# LATE CARBONIFEROUS NONMARINE SEQUENCE STRATIGRAPHY AND PETROLEUM GEOLOGY OF THE CENTRAL MARITIMES BASIN, EASTERN CANADA

by

Trent A. Rehill

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

at

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## Dedication

To

Nicole Renée, Joan, and Don Rehill

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## Abstract

Based on interpreted seismic, lithostratigraphic, and biostratigraphic analyses, a detailed stratigraphic framework is presented for the thick (>10km) succession of Late Carboniferous strata preserved in the offshore portion of the Maritimes Basin. The offshore comprises more than 70% of the total area (~215 000 $km^2$) of the Maritimes Basin and was previously poorly understood in terms of regional tectono-stratigraphic history. Consequently, although the 20 exploration wells drilled in the offshore area had strong indications of gas, there is little understanding of regional petroleum potential and documentation of play types.

Offshore, the Late Carboniferous stata was deposited in an asymmetrical basin that developed within a Continental Wrenched Foldbelt tectonic regime. The majority of the restricted-marine to alluvial basin fill consists of a thick (>8km) succession of Cumberland and Pictou Group strata that can be subdivided into 7 newly proposed, formation level, lithostratigraphic units.

Within the post Namurian basin fill, four 2nd-3rd order depositional sequences are recognized, bounded by regionally identifiable sequence boundaries. Each sequence consists of a basal coarse grained facies overlain by a fine grained facies. The 200-500m thick sequences contain smaller, higher frequency sequences, hence are divided into sequence sets. The progradational basal facies are interpreted to be forestepping systems sets. Retrogradational backstepping systems sets overlie both the basal unit and a transgressive surface. These cyclic sequences developed in response to episodic allocyclic tectonic processes related to renewed Alleghanian thrusting in the Appalachians and increased tectonic subsidence. Interaction of these mechanisms controlled relative rates of change of accommodation and sediment supply in the basin.

The derived stratigraphic framework, used in conjunction with modern basin analysis techniques, allowed the reconstruction of subsidence, compaction, thermal and maturation histories for 14 exploration wells. Burial rates on the order of 100-200 m/My led to rapid organic maturation and expulsion of hydrocarbons (ca 310-280 Ma). This timing information confirms that a viable petroleum system developed in the basin with favourable source, reservoir, seal and overburden dynamics. Hydrocarbon play types include; subsalt, salt piercement, fault related, basin-centre gas, stratigraphic pinchout, and unconformity.

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# CHAPTER 1 - INTRODUCTION

## 1.1 General Statement

The offshore region underlying the southern Gulf of St. Lawrence and Laurentian Channel (Fig. 1.1) has received relatively little attention from either the academic, industry, or government geologic communities. Only a handful of studies have incorporated offshore geologic data of any kind from the Gulf of St. Lawrence (Table 1.1). More than 70% of the Atlantic region's Late Paleozoic strata, collectively referred to here as the Maritimes Basin, lies offshore (Fig. 1.2), and as a result relatively little is known about the regional stratigraphy, tectono-stratigraphic history and hydrocarbon potential of the Maritimes Basin as a whole (Fig. 1.3).

The presence of oil seeps in coeval onshore strata, sourced from the Lower Carboniferous Horton Group, led to the drilling of twenty offshore exploration wells and the acquisition of more than 80 000 line-kilometres of offshore seismic data. Most of the wells showed indications of gas, but all (except the East Point E-49 gas discovery) were classified dry and abandoned.

The discovery and subsequent mapping of a thick Upper Carboniferous coal-bearing package underlying much of the Gulf of St. Lawrence (Grant and Moir, 1992) along with suggestions that these Coal Measures have the potential to source hydrocarbons (Mossman, 1992), provoked renewed interest in the resource potential of the region. In addition, recent studies of agglutinated foraminifera indicate that sections of the coal measures were deposited in marine-influenced environments, enhancing the possibility of sourcing hydrocarbons from type II and III kerogens.

The few studies dealing specifically with the offshore database are restricted to areas where petroleum companies have had interests. The absence of a detailed synthesis of the offshore database has imposed severe restrictions on evaluations of the petroleum system dynamics and hydrocarbon potential of the offshore Maritimes Basin. It is crucial that the offshore database be addressed to advance the understanding of the regional geologic framework of the Maritimes Basin.

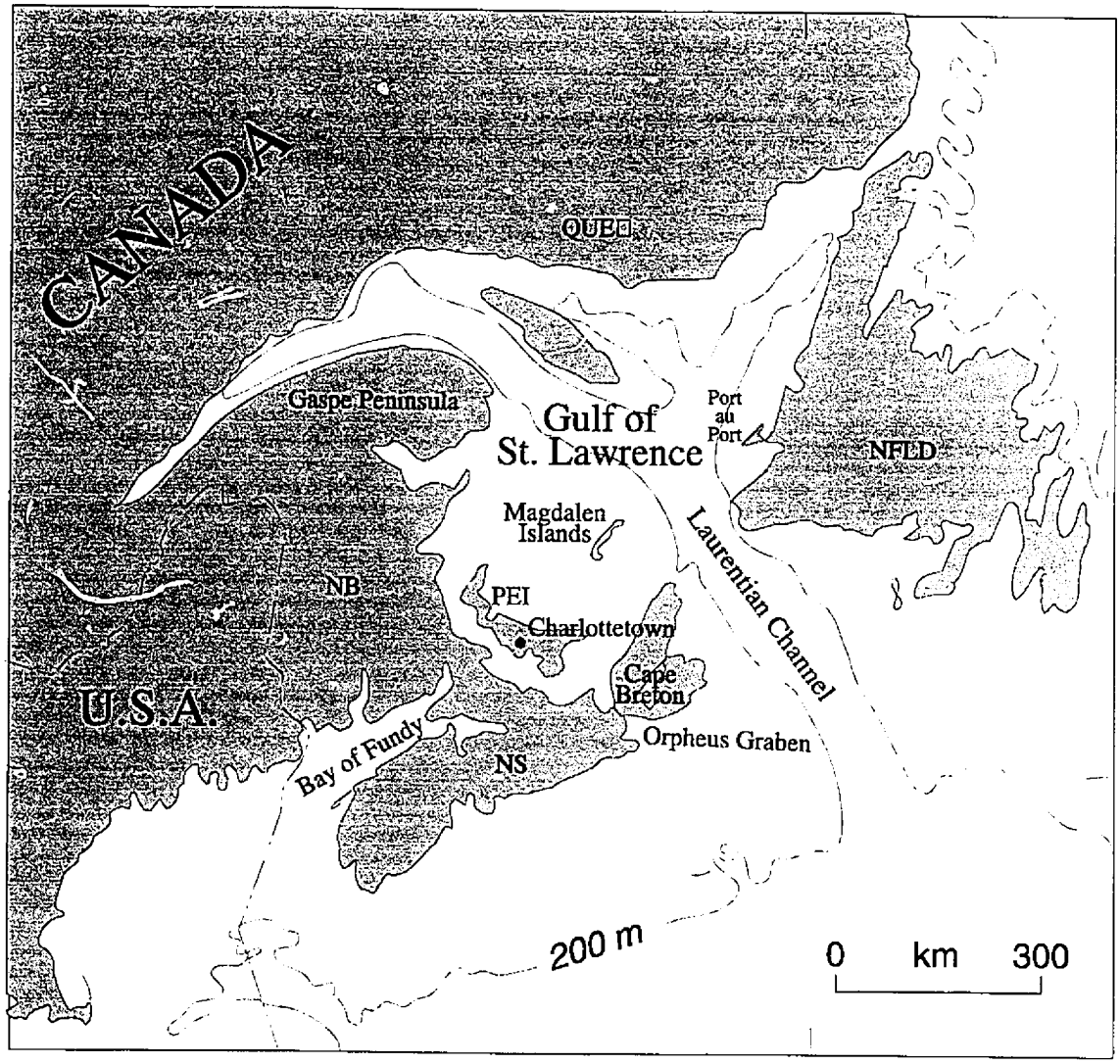



Figure 1.1 Location of the main geographic features and stratigraphic type section locations in Atlantic Canada. The 200m water depth contour is indicated. Abbreviations are; NB = New Brunswick; NS = Nova Scotia; QUE = Quebec; P.E.I. = Prince Edward Island; NFLD = Newfoundland.

Table 1.1 Geologic studies by previous workers in the Maritimes Basin. Key studies that dealt specifically with the offshore Gulf of St. Lawrence database are shown in **bold**.

| STRATIGRAPHY/ SEDIMENTOLOGY | TECTONIC/BASIN DEVELOPMENT | ECONOMICS/BASIN ANALYSIS |
|---|---|---|
| Allen, 1995 | Belt, 1968b, 1969 | Bell, 1958 |
| Bali *et al.*, 1981 | Bradley, 1982 | Bell and Howie, 1990 |
| Bell, 1927, 1944, 1958 | **Durling and Marillier, 1990, 1993b** | Fleming, 1970 |
| Belt, 1964, 1965 | Eisbacher, 1969 | **Grant and Moir, 1992** |
| Fralick and Schenk, 1981 | Gibling *et al.*, 1987 | **Grist *et al.*, 1995** |
| Gersib and McCabe, 1981 | Hamblin and Rust, 1989 | **Hacquebard and Cameron, 1989** |
| Gibling *et al.*, 1992b | Hyde *et al.*, 1988 | Hacquebard and Donaldson, 1970 |
| Giles, 1981 | Keppie, 1982, 1989 | Hacquebard *et al.*, 1989 |
| **Grant, 1994** | **Langdon and Hall, 1994** | Hamblin *et al.*, 1995 |
| Gussow, 1953 | McCutcheon and Robinson, 1987 | Hendriks *et al.*, 1993 |
| Hacquebard, 1972, 1986 | Nance, 1987 | Howie, 1966 |
| Hacquebard *et al.*, 1989 | Naylor *et al.*, 1989 | **McCamis, 1973** |
| Haites, 1952 | Poole, 1967 | Martel, 1987 |
| Howie, 1988 | **Quinlan *et al.*, 1988** | Mukhopadhyay *et al.*, 1991 |
| **Howie and Barss, 1975** | Reed *et al.*, 1993 | Ravenhurst and Zentilli, 1987 |
| Hyde *et al.*, 1991 | Ryan and Zentilli, 1993 | **Ryan, 1993** |
| Kelly, 1967 | St. Peter, 1993 | **Ryan *et al.*, 1990** |
| Knight, 1983; | **Stockmal *et al.*, 1990** | Sinclair, 1992 |
| Le Gallais, 1983 | Webb, 1969 | **SOQUIP, 1987** |
| Naylor *et al.*, 1989 | Yeo and Ruixiang, 1987 | **Williams, 1973, 1974** |
| **Rehill et al, 1995** | | |
| Rolif, 1962 | | |
| Ryan and Boehner, 1994 | | |
| Ryan *et al.*, 1991 | | |
| Sanford and Grant, 1990 | | |
| Utting, 1978 | | |
| van de Poll, 1966, 1973, 1989 | | |
| van de Poll *et al.*, 1995 | | |
| **Wightman *et al.*, 1994a** | | |

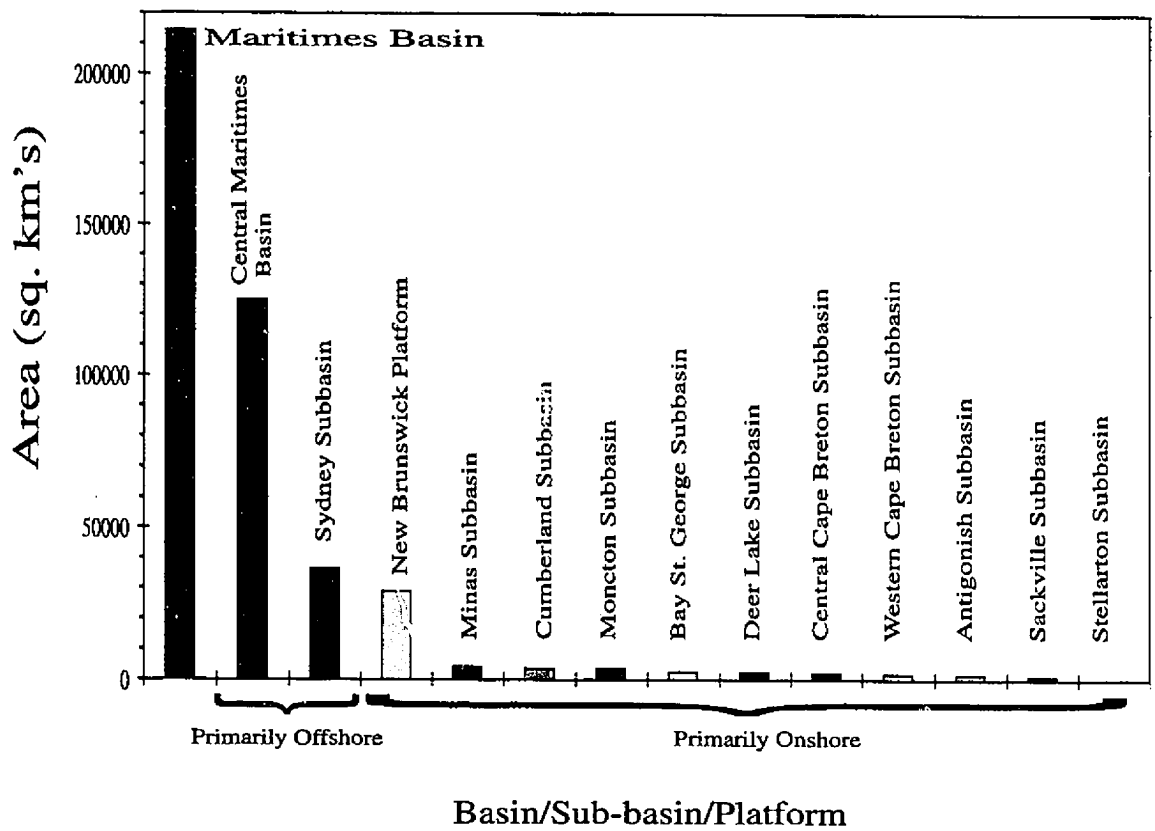



Figure 1.2 Plot of basin, subbasin, and platform areas in square kilometres. The indicated subbasins and platforms correspond to Figure 1.3. The principle offshore and onshore areas of the Maritimes Basin are indicated. The St. Anthony Subbasin is not included in area calculations.

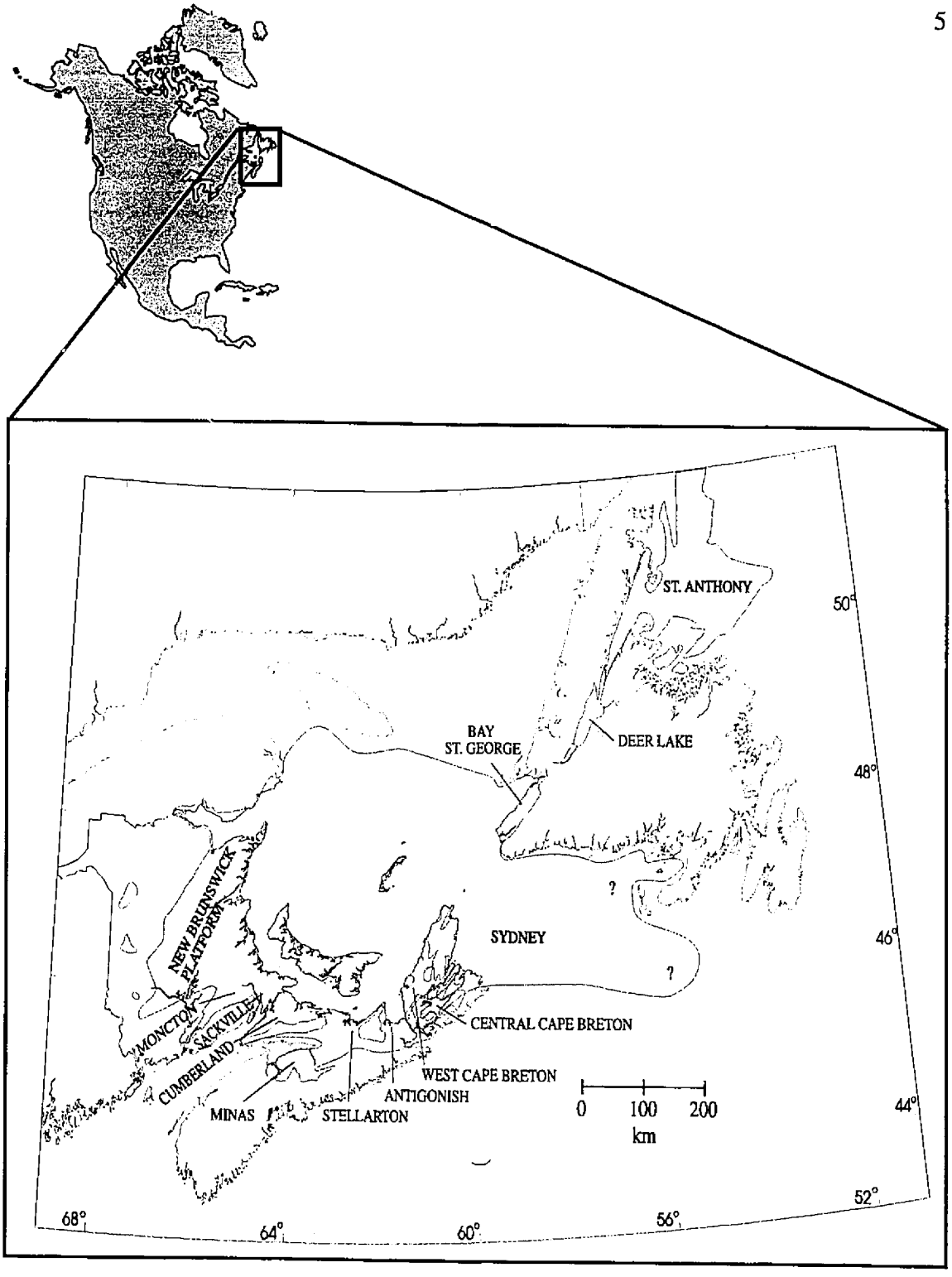



Figure 1.3 Location of the Maritimes Basin (shaded light grey) of Eastern Canada, with major onshore subbasins indicated (from Gibling et al, 1987; Howie and Barss, 1975; Hyde et al., 1988: McCutcheon and Robinson, 1987 and van de Poll et al., 1995). The question marks indicate where present boundaries are poorly defined.

## 1.2 Objectives and Scope of this Study

1) Construct detailed stratigraphic correlations of southern Gulf of St. Lawrence offshore wells tied to onshore wells, seismic data and representative onshore sections, to provide a regional lithostratigraphic framework.

2) Place the stratigraphic framework in a sequence stratigraphic context and interpret any stratigraphic trends, cycles, and sequences in the offshore Late Paleozoic basin fill package and investigate how these compare to onshore sections.

3) Investigate the causes or controls of any cyclic fill in the strata underlying the southern Gulf of St. Lawrence at various scales. Are the controls autocyclic or allocyclic?

4) Develop a provisional basin depositional model with analogues to other basins based on sedimentologic, stratigraphic, seismic, micropalaeontologic and tectonic data.

5) Identify and interpret the major petroleum system components in the Late Paleozoic basin fill underlying the southern Gulf of St. Lawrence.

6) Develop a hydrocarbon charge model for the offshore southern Gulf of St. Lawrence that constrains both erosion and thermal assumptions, and addresses the quantification of risk involved with further exploration in the area.

Completion of these objectives will help address the fundamental questions being investigated by this regional basin analysis project:

**A)** Are the Maritimes Basin onshore exposures found around the southern periphery of the Gulf of St. Lawrence representative of what underlies the offshore area?

**B)** Why, if the Carboniferous strata underlying the Gulf of St. Lawrence have been charged with hydrocarbons, did the offshore exploration wells not encounter significant quantities of hydrocarbons? Does the offshore area lack good reservoirs and/or seals? Was there a problem with the timing of hydrocarbon generation?

## 1.3 Organization of this Work

This basin analysis project, which specifically addresses the offshore database from the southern Gulf of St. Lawrence, has two main components: stratigraphic analysis and petroleum system analysis. The stratigraphic analysis component has three stages: developing a stratigraphic framework for the offshore, putting the stratigraphic framework in a sequence stratigraphic context, and investigating potential controls on basin fill patterns. These stages are described in Chapters 2, 3 and 4, respectively.

The investigation of the offshore petroleum system will require the integration of all available data with the three stages of stratigraphic analysis. This synthesis of data will be the platform from which the petroleum systems of the offshore Maritimes Basin will be outlined in the first part of Chapter 5. The second part of Chapter 5 will deal with the timing associated with hydrocarbon generation. The completion of the two main components will provide the first detailed investigation and documentation of petroleum geology/basin modelling in the offshore Maritimes Basin. The last chapter (Chapter 6) will summarize and recommend further directions of work.

The remaining sections of Chapter 1 will first outline the database used for the

study, followed by an introduction to the study area, then an overview of the tectonic history/basin development and stratigraphic framework of the onshore Maritimes Basin. The chapter will conclude with a brief review of previous work done in the study area.

## 1.4 Database

Modern techniques of basin analysis require the integration of geoscientific data using numerous analytical procedures. For offshore basins, the primary data sources tend to be the information recovered from drilling hydrocarbon exploration wells (well data) and conducting reflection/refraction seismic surveys.

According to Canadian law, petroleum companies that drill offshore wells are required to provide sets of their well and seismic data to the Government of Canada for archiving and future research. The data on the east coast are archived with either the Canada Nova Scotia Offshore Petroleum Board (CNSOPB) or the Canada Newfoundland Offshore Petroleum Board (CNOPB). In addition to these databases, the Geological Survey of Canada (Atlantic) in Dartmouth has a large database of offshore well data. The majority of the data for this study came from the GSC Atlantic and CNSOPB.

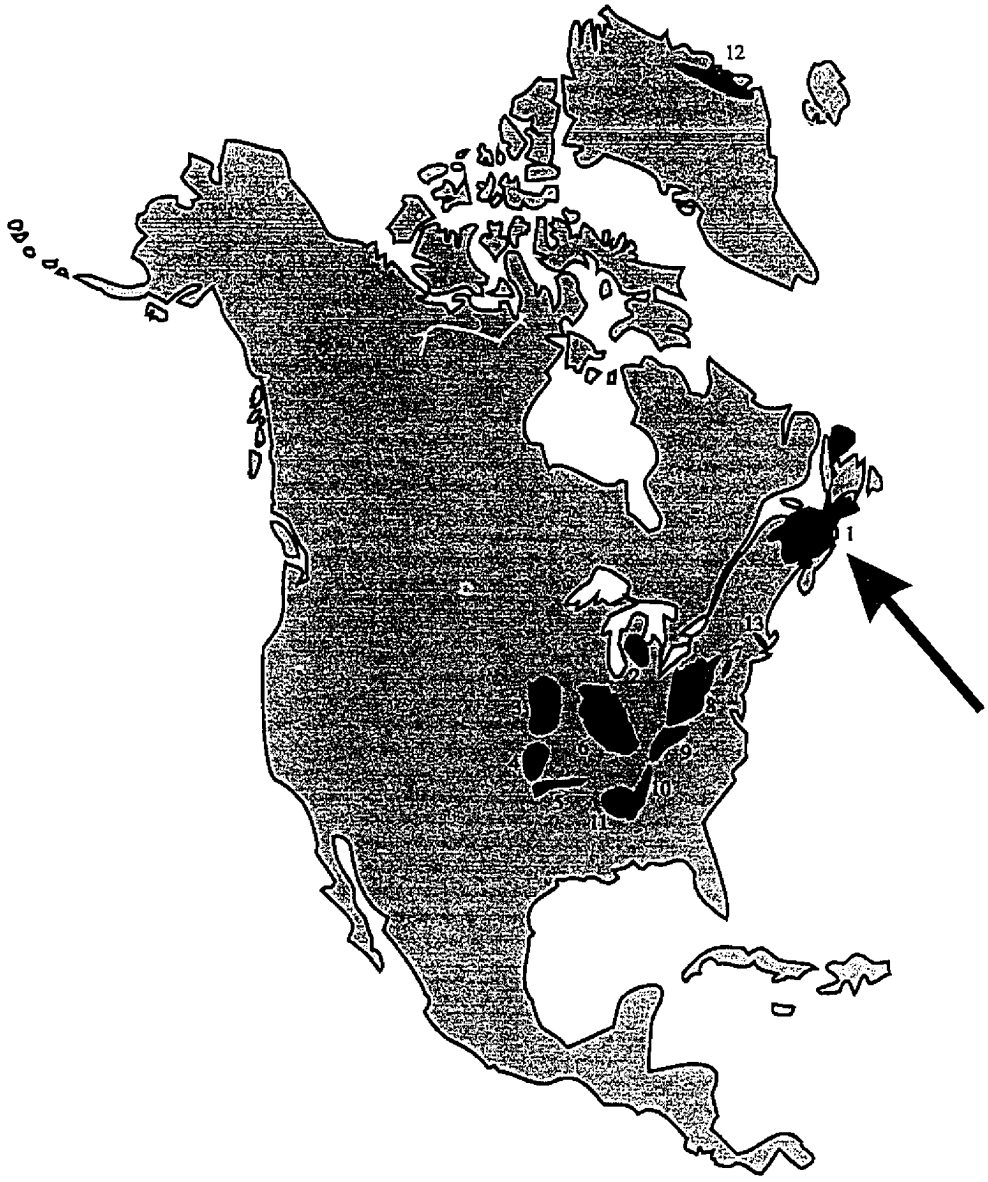
Initially a relatively small amount of geological data in both digital and paper form was available to study the Central Maritimes Basin. During the course of this study an extensive collection of geological data has been amassed into one database. All available lithologic, thermal maturation (Ro/TAI), apatite fission track, Rock-Eval pyrolysis, clay mineralogy, biostratigraphic-palynological, micropalynological-foraminifera, and temperature data have been compiled and entered into a computer database. Additionally, a comprehensive suite of digital well logs has been assembled for stratigraphic correlations and petrophysical analyses. This collection of well data has been complemented by a substantial amount of seismic data and notes from regional geologic reconnaissance around the study area. The technical details of the database will be further outlined in later chapters.

## 1.5 The Maritimes Basin

The Maritimes Basin is located in the northeastern part of the Appalachian mountain system of North America (Fig. 1.4). It is one in a series of Late Paleozoic Basins that extend along the eastern margin of North America. The basin fill outcrops in all the Atlantic Canadian Provinces and underlies the southern Gulf of St. Lawrence (Fig. 1.1). With an estimated area of 215 000 km$^2$, the Maritimes Basin ranks as one of North America's largest preserved Late Paleozoic depocentres, presently comparable in size to the Illinois Basin of the eastern United States. However, according to apatite fission track and coal rank analysis, between 1-4 km of strata have been removed by erosion since the Late Permian (Ryan, 1993; Hacquebard and Cameron, 1989). These data suggest that the present areal extent of the Maritimes Basin strata is only an erosional remnant of a formerly much larger Carboniferous basin.

The Maritimes Basin, a large composite basin, comprises a complicated series of subbasins and platforms (Fig. 1.3) which were interconnected during the Carboniferous (Bradley, 1982). The subbasins and platform locations shown in Figure 1.3, reflect original Carboniferous depocentres. The large faults and highland areas, which today separate the subbasins and platform areas, form arbitrary subbasin boundaries, creating a complex study area similar to a "basin and range" or "horst and graben" type of geographic setting.

Previous workers have referred to all or parts of the Maritimes Basin by a variety of names, including the Fundy Geosyncline (Bell, 1944), the Fundy Basin (Bell, 1958), the Late Paleozoic Folded Zone (Poole *et al.*, 1970), the Maritimes Carboniferous Basin (Rolif, 1962), the Fundy Basin Rift (Belt, 1968b), the Maritime Rift (Belt, 1969), the Fundy Epieugeosyncline (Poole *et al.*, 1970), the Maritimes Basin (Williams, 1973), the Fundy Aulacogen (Keppie, 1977), the Magdalen Pull-Apart Basin (Bradley, 1982) and the Gulf of St. Lawrence Basin (Hacquebard, 1986). Recently, the term "Maritimes Basin" has been widely accepted as the collective term for all Late Paleozoic strata in the Atlantic provinces (Boehner *et al.*, 1988).




1 Maritimes Basin
2 Michigan Basin
3 Forest City Basin
4 Cherokee Basin
5 Arkoma Basin
6 Illinois Basin
7 Anthracite Basin
8 Northern Appalachian Basin
9 Central Appalachian Basin
10 Southern Appalachian Basin
11 Black Warrior Basin
12 East Greenland Basin
13 Narragansett/Norfolk Basins

Figure 1.4 Location of the Maritimes Basin with respect to other late Carboniferous basins in eastern North America and Greenland (from Phillips et al., 1985).

### 1.5.1 The Central Maritimes Basin

The term Central Maritimes Basin (CMB), as used in this study, refers to the strata underlying the southern Gulf of St. Lawrence (Fig. 1.5). The boundaries are not typically structural in origin but instead follow the modern coastlines of New Brunswick, eastern Gaspé Peninsula, northern Nova Scotia and southwest Newfoundland, outlining an area of the Maritimes Basin that has undergone minimal tectonic activity from the Middle Carboniferous to the Permian. Technically, it could be called a subbasin of the Maritimes basin, but its large size, almost 125 000 $km^2$, warrants classification as a basin. The CMB completely underlies both Prince Edward Island and the Magdalen Islands. Present day water depths are generally less than 100m except in the Laurentian Channel where depths can exceed 500m.

The depocentre, located east of the Magdalen Islands (Fig. 1.1), presently has more than twelve kilometres of Late Paleozoic basin fill (Durling and Marillier, 1990). The basin axis trends southwest to northeast, oriented approximately along a line from Charlottetown, Prince Edward Island to 50 kilometres east of the Magdalen Islands. Morphology of the Central Maritimes Basin can be thought of as a broad asymmetrical basin with a basement gently sloping from the northern New Brunswick and eastern Gaspé Peninsula areas towards the basin axis, and then a rapidly increasing basement gradient towards the coast of Cape Breton Island, Nova Scotia.

## 1.6 Regional Tectonic Setting and Basin Development

The Acadian Orogeny is generally associated with the compressional events leading up to and including the accretion of the Avalon and Meguma terranes to the North American Craton (van de Poll *et al.*, 1995). This deformation, which was a major orogenic event in the development of the Appalachian Fold Belt (Poole, 1967), started to wane by the Early Devonian, such that by the Middle to Late Devonian the Appalachian Orogen was essentially assembled (Hamblin and Rust, 1989). According to prevailing interpretations, the Maritimes Basin developed as a direct result of late stage Acadian collisional events and, at least in its early stages, can be considered a "successor basin"

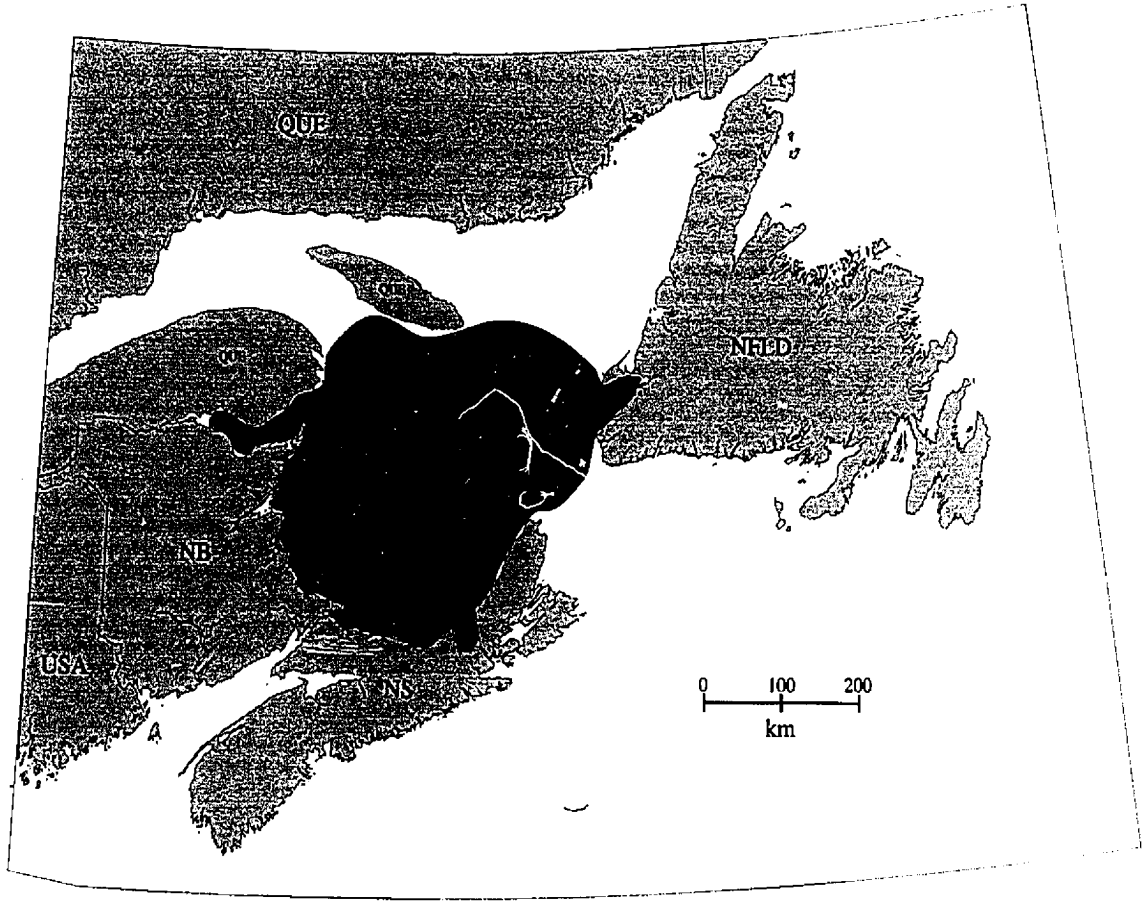



Figure 1.5 The offshore Central Maritimes Basin (shown in dark grey).

(St. Peter, 1993). The presence of Late Paleozoic fill lying unconformably on the Late Precambrian to Middle Paleozoic deformed basements of all defined tectono-stratigraphic zones or terranes (Fig. 1.6) implies that the accretion of terranes was complete before sediment deposition took place in the early Maritimes Basin (van de Poll *et al.*, 1995).

The origin of the basin has been a constant source of debate for the local geological community. The onshore geology has been dissected by at least nine major faults or fault zones (Fig. 1.7). The timing of movement on each is only partially understood, complicating the onshore structural geology. Early basin formation has been attributed to either rifting (Belt, 1968b) or strike-slip pull apart (Bradley, 1982) and the literature suggests that most additional models tend to be a revision or combination of the rift or strike-slip models (Ryan, 1993). Two of the more recent suggestions explaining the development of the Maritimes Basin are the passive subsidence model (McCutcheon and Robinson, 1987), which suggests that the basin formed due to continental rifting caused by Acadian crustal loading, and the Quinlan *et al.* (1988) model which proposes that the Maritimes Basin formed as a result of the re-extension/relaxation of older Acadian thrust faults. A common theme to most of the more recent models is the belief that the basin has undergone two major, linked stages of development: an early phase of extension (possibly associated with strike-slip motion) followed by a period of rapid thermal subsidence, which later slowed with time.

The Maritimes Basin underwent a period of extension during the Late Devonian - Early Carboniferous in a cratonic-scale structural environment possibly due to rifting, strike-slip pull apart, or both. This major zone of extension/strike-slip extended through a series of regional fault systems active during the Late Paleozoic. The zone in which the Maritimes Basin formed extended from Southern New England, through the Bay of Fundy up into Newfoundland and into the Midland Valley Rift in Scotland (Belt, 1969).

On a relatively local scale, an increased understanding of basin fill geometries, and availability of quality seismic data, allows for a more comprehensive tectonic history to be developed. Recent deep seismic LITHOPROBE studies by Quinlan *et al.* (1988), Stockmal *et al.* (1990) and Marillier *et al.* (1989) suggest that movements of lower crustal

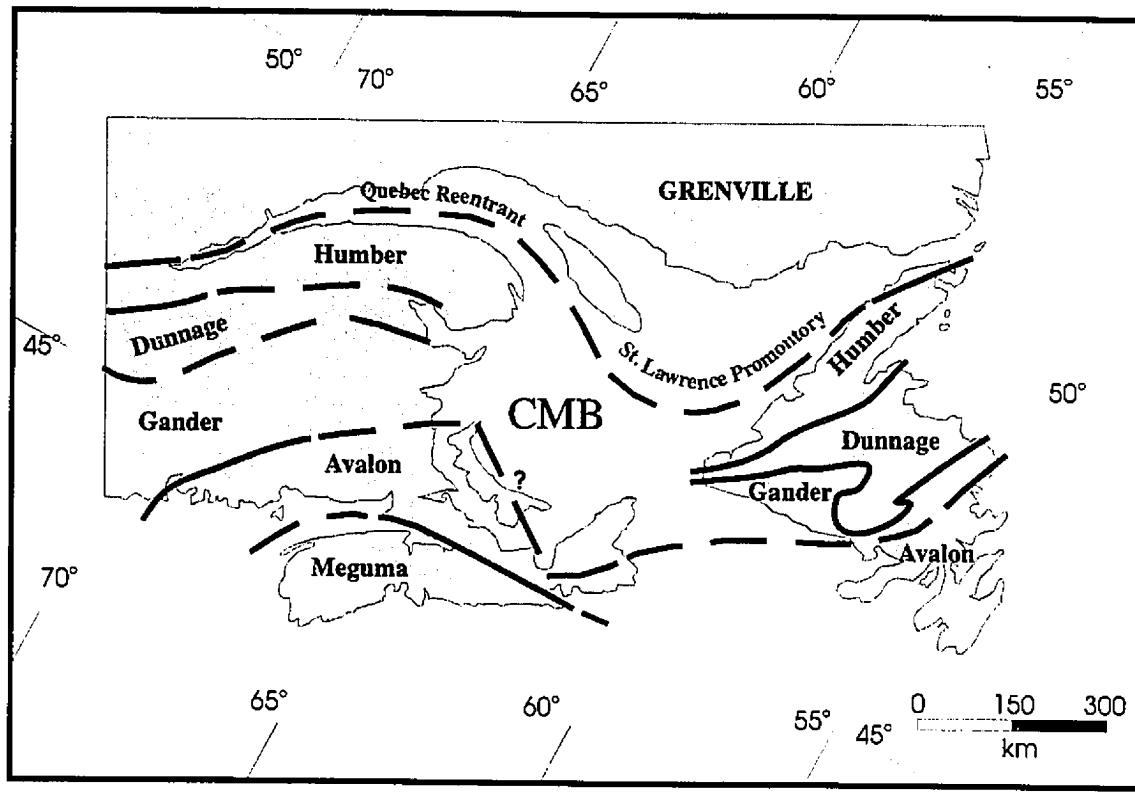



Figure 1.6 Canadian tectonic-stratigraphic zones (heavy lines) underlying the strata of the Maritimes Basin (modified from Stockmal et al., 1990). Refer to Figure 1.3 for location of Late Paleozoic basin fill.

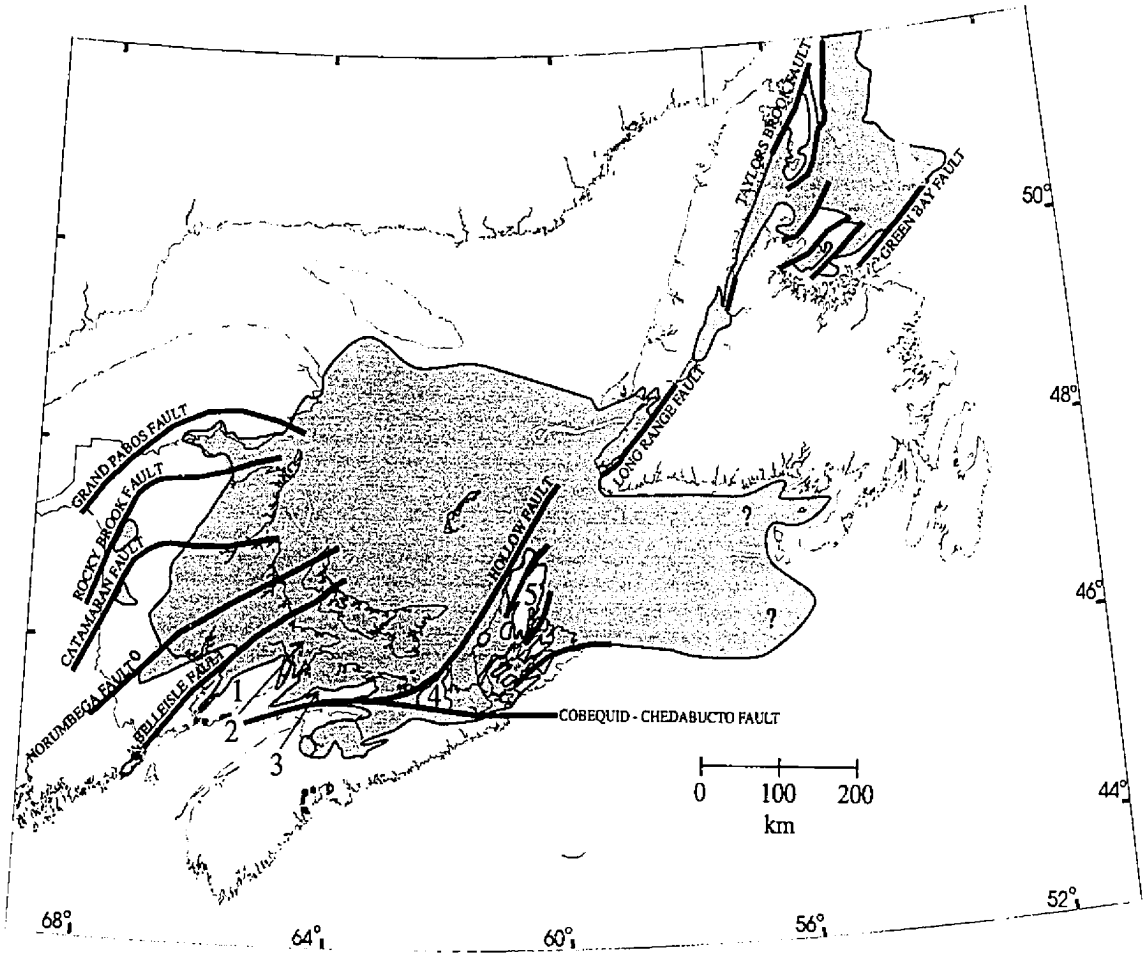



Figure 1.7 Map showing the distribution of major faults that presently cut strata of the Maritimes Basin (from McCutcheon and Robinson, 1987; Martel, 1987; St. Peter, 1993; Stockmal et al., 1990; van de Poll et al., 1995). Highland areas indicated; 1 = Caledonia Highlands; 2 = Westmorland Highlands; 3 = Cobequid Highlands; 4 = Antigonish Highlands; 5 = Cape Breton Highlands.

blocks (LCB) after Acadian orogenic thrusting, in conjunction with strike-slip faulting (Bradley, 1982), were responsible for the initial development of the Maritimes Basin. The re-extension of Acadian thrust faults resulted in subsidence of the crust. In association with LCB movement, near vertical strike-slip (normal?) movement may have occurred on the Hollow Fault (Fig. 1.7), which helped relieve stress in the system. This stress release led to the second stage of development, consisting of initially rapid, followed by slower, thermal subsidence from the Late Carboniferous to the Early Permian. This model also explains the asymmetric crustal subsidence observed in the offshore Maritimes Basin (Durling and Marillier, 1990).

Minor strike-slip movements may have persisted well into Mesozoic time (Webb, 1969). Subsidence of the Maritimes Basin had ceased by the Early Triassic (Ryan *et al.*, 1990), at which point the basin was subject to uplift, resulting in the removal of one to four kilometres of sediment by erosion (Ryan *et al.*, 1990; Hacquebard and Cameron, 1989).

## 1.7 Regional Stratigraphic Overview

The Maritimes Basin preserves the thickest and most widespread occurrences of Late Paleozoic deposits in eastern Canada (Bell and Howie, 1990). Onshore geologic work has been extensive; however, most studies lack a comprehensive regional scope. Over the past 147 years, stratigraphic classification of the onshore strata has been accomplished using combinations of biostratigraphy, chronostratigraphy and lithostratigraphy (Boehner *et al.* 1986).

The pioneering stratigraphic and paleontological studies of Bell (1944, 1948, 1958) remain the foundation for all subsequent work in the region. Bell recognized the paleontological limitations of working with Maritimes Basin strata, which generally lack ubiquitous marine marker beds. Despite this difficulty he was able to develop a stratigraphic nomenclature consisting of (in ascending stratigraphic order) the Horton, Windsor, Canso, Riversdale, Cumberland and Pictou groups based on a combination of lithostratigraphy and biostratigraphy.

Although workers have attempted to modify Bell's nomenclature, this basic division of onshore strata has, except for slight revisions, stood the test of time. One such revision was by Belt (1964, 1965), who replaced the Canso and part of the Riversdale Groups with the Mabou Group. Built on Bell's stratigraphic framework, the studies done by Norman (1941) and Gussow (1953) remain the primary references for Late Paleozoic work in New Brunswick. In Newfoundland, the findings of Hayes and Johnson (1938) and Bell (1948) continue to be used today.

Ryan *et al.* (1991) proposed the most recent revision of onshore stratigraphic nomenclature, resulting from their work with Cumberland subbasin stratigraphy which focused on lithostratigraphy, emphasizing the Formation component. Their proposed revisions formally apply only to the Upper Carboniferous to Lower Permian strata found in the Cumberland subbasin; however, the authors suggest a general applicability to the regional Maritimes Basin (Ryan *et al.*, 1991).

Parts of the onshore stratigraphic nomenclature have been applied to the offshore portions of the Maritimes Basin (Ryan, 1993; Hacquebard, 1986), but not in a comprehensive manner. As a direct result of this study, a series of new formations for the Central Maritimes Basin is defined and introduced in Chapter 2. Nevertheless, the offshore stratigraphy does correspond reasonably well with onshore stratigraphy at the group level. In light of this relationship, the following sections will summarize and define previously interpreted onshore Late Paleozoic strata (Fig. 1.8) which have been assigned to the following lithostratigraphic packages: Fountain Lake Group, Horton Group, Windsor Group, Mabou Group, Cumberland Group and Pictou Group.

### 1.7.1 Fountain Lake Group

**Type Section Location:** The 950m type section, defined by Donohoe and Wallace (1980), is located in the Cumberland subbasin.

**Typical Lithology:** The group consists of interbedded volcanics and nonmarine

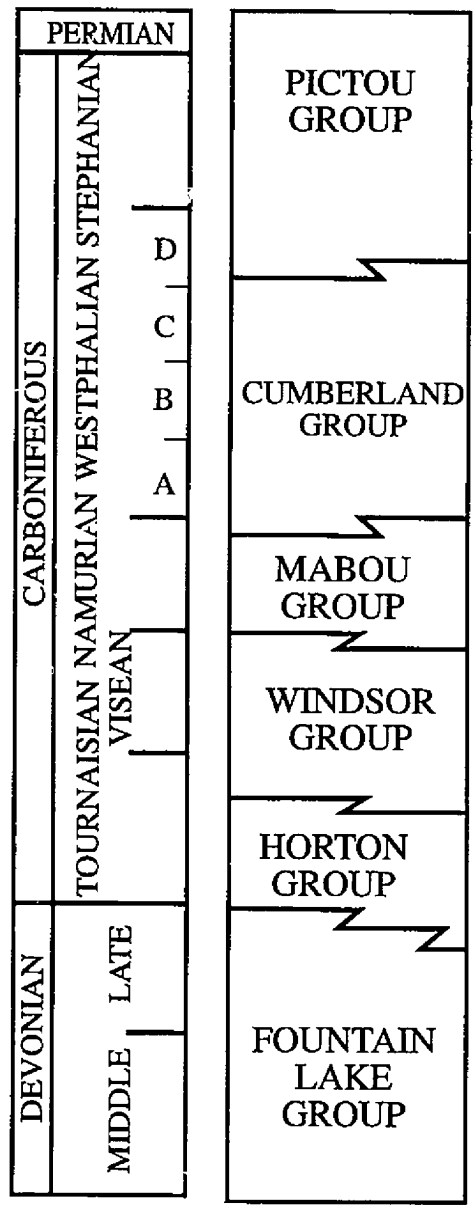



Figure 1.8 General stratigraphic nomenclature for the Upper Paleozoic rocks in the Maritimes Basin (from Ryan et al., 1991).

sedimentary rocks (Bell and Howie, 1990). The subaerial volcanics tend to have a bimodal (basalt and rhyolite) composition and exhibit textures, chemistries and stratigraphic relationships commonly found in non-marine settings related to intraplate continental rifting (Gibling *et al.*, 1992a). The sedimentary package comprises red to grey conglomerates, sandstones, and shales (Fralick and Schenk, 1981; Hamblin and Rust, 1989).

**Onshore Distribution:** Outcrops are generally scarce. The Cumberland subbasin Fountain Lake Group has equivalent strata in the Sydney, Antigonish and West Cape Breton subbasins. These rocks include the McAdams Lake, McAras Brook, and the Fisset Brook formations, respectively (Hamblin and Rust, 1989; Fralick and Schenk, 1981; Barr and Raeside, 1986).

**Contact Relationships:** Unconformably overlies the faulted, deformed and metamorphosed rocks of the Acadian Orogen and older basement rocks (Ryan *et al.*, 1991; Kelly, 1967). The overlying Horton Group rests conformably to unconformably on the Fountain Lake Group (Gibling, 1995).

**Age:** Typically, Late Devonian to Early Carboniferous (Bell and Howie, 1990).

### 1.7.2 Horton Group

**Type Section Location:** The type section, redefined by Bell (1929), is located in the Minas subbasin, Nova Scotia.

**Typical Lithology:** The Horton Group consists of a continental sequence of non-marine alluvial, lacustrine and intermontane sediments which are generally red and grey to black (Kelly, 1967; Hacquebard, 1972). The group consists of a lower and upper coarse-grained alluvial facies with a finer-grained lacustrine unit in the middle (Martel, 1990).

Marine to brackish water sediments occur in the upper section of the group (Hacquebard, 1972).

**Onshore Distribution:** Onshore, the Horton Group has a highly variable thickness ranging from less than ten metres to a maximum of 3291 metres on Cape Breton Island (Kelly, 1967). It is spatially restricted unit, pinching out onto the New Brunswick and Nova Scotia onshore areas (Boehner *et al.*, 1986). The group was deposited in a series of fault bounded basins, typically half-graben in nature, according to Hamblin and Rust (1989), Sanford and Grant (1990) and Bell and Howie (1990).

**Contact Relationships:** The Horton Group strata rest conformably to unconformably on the Fountain Lake Group. In the absence of Fountain Lake Group strata, the Horton Group has a non-conformable boundary with the Acadian or older basement rocks (Gibling, 1995). The upper boundary separating the Horton Group from the Windsor Group is conformable to disconformable, and occasionally unconformable (St. Peter, 1993; Kelly, 1967).

**Age:** At the type section, Latest Devonian to Tournaisian (Martel *et al.*, 1993).

**General Comments:** The coarse basal rocks of the Horton Group indicate deposition in a piedmont environment (Howie and Barss, 1975). The presence of cyclic packages may suggest that regional tectonics, associated with a mid-crustal decollement (Martel and Gibling, in press), controlled sedimentation, conversely, in other localities, rapid vertical and lateral facies changes in addition to thick packages of sediment suggest that sedimentation was controlled by local tectonics (Hamblin and Rust, 1989; Boehner *et al.*, 1986).

Data obtained from the Horton Group and Fountain Lake Group in the Cobequid Hills have yielded broadly the same radiometric and biostratigraphic dates (Piper, 1995). However, Fountain Lake Group equivalent strata in Cape Breton Island have yielded a U-

Pb age of 389 Ma which is significantly older than the typical Horton Group succession (Barr *et al.*, 1996). In view of these new data, and maintaining the traditional classification of Bell (1944), this thesis simply uses the term "Horton Group" to include both original Horton Group strata and all strata formally assigned to the Fountain Lake Group.

### 1.7.3 Windsor Group

**Type Section Location:** The 920 metre thick type section is located in the Minas subbasin near Windsor, Nova Scotia (Kelly, 1967; Boehner, 1984) and was originally defined by Bell (1929).

**Typical Lithology:** Red sandstone, red and minor grey siltstone, limestone, minor dolomite and gypsum constitute the lithology of the type area (Howie and Barss, 1975). In the subsurface, full sections of Windsor Group are characterized by thick packages of red to reddish brown sandstone, siltstone and shale interbedded with gypsum, anhydrite, halite, potash salts, and thin sequences of limestone and dolomite (Howie and Barss, 1975; Boehner, 1984). The group also has characteristic fanglomerate units adjacent to the subbasin margins (Boehner et al, 1986; Howie and Barss, 1975; Kelly, 1967).

Visean age volcanics are found on the Magdalen Islands in the form of cap rocks on salt diapirs. The volcanics have continental tholeiitic to alkalic chemical signatures (Barr *et al.*, 1985). Occurrences of trachyte porphyry of Windsor Group age are found in the southern area of the Antigonish - West Cape Breton subbasins (Howie and Barss, 1975).

**Onshore Distribution:** On the surface and in the shallow subsurface, the salts characteristic of the Windsor group have either been dissolved, eroded or deformed so that full surface exposure of the Windsor group is unavailable (Bell and Howie, 1990). Estimates by Ryan and Boehner (1994) suggest the Windsor Group was originally

between 1000 to 1500 metres thick.

**Contact Relationships:** In the Cumberland subbasin, the Windsor Group either conformably or unconformably overlies the Horton Group and unconformably overlies older basement rocks (Ryan and Boehner, 1994). Onshore, the group is conformably overlain by the Mabou Group (Giles, 1981).

**Age:** Assigned a Middle to Late Visean age (Utting, 1978).

**General Comments:** The Windsor Group represents the only open marine succession in the Maritimes Basin (Kelly, 1967; Howie and Barss, 1975). Windsor Group deposition occurred during periodic flooding of the Maritimes Basin by the Hercynian Ocean (Fralick and Schenk, 1981; Boehner et al, 1986; Howie and Barss, 1975). The flooding events are thought to have been caused by either local subsidence or glacioeustasy (Fralick and Schenk, 1981). The initial flooding event was both rapid and areally extensive (Sanford and Grant, 1990), prompting some authors to suggest that a major hiatus exists between the Horton Group and the overlying Windsor Group (Kelly, 1967; Utting, 1978; Geldsetzer, 1978).

Strong evidence for post-depositional Windsor Group salt flowage exists both offshore and onshore (Howie and Barss, 1975; Bell and Howie, 1990). In the southern part of the Gulf of St. Lawrence the bedded salts have moved to form ridges walls, and diapirs of variable sizes (Sanford and Grant, 1990: Bell and Howie, 1990). Some diapirs in the southern gulf have risen to penetrate Quaternary deposits at the sea floor. The majority of the Maritimes Basin offshore petroleum wells have been drilled on salt structures (Williams, 1974).

### 1.7.4 Mabou Group

**Type Section Location:** The Mabou Group type section, defined by Belt (1964,1965), is

located on the west coast of Cape Breton Island.

**Typical Lithology:** Typically the Mabou Group consists of a nonmarine fine grained clastic sequence of red and grey sandstones, siltstones and mudstones deposited in a range of fluvial, floodplain and lacustrine environments (Belt, 1964; Ryan and Boehner, 1994). Locally the sequence contains conglomerates and volcanics at the subbasin margins (Bell and Howie, 1990; Sanford and Grant, 1990; Ryan *et al.*, 1990). The group can be broken into two regional lithofacies, a lower grey lacustrine facies and an upper red fluviatile facies (Allen, 1995).

**Onshore Distribution:** Mabou Group rocks are widely distributed across most of the onshore Maritimes Basin (Gussow, 1953; Hayes and Johnson, 1938; Gibling *et al.*, 1987). Exposures of the Mabou Group are typically about 2 km in thickness (Boehner *et al.*, 1986).

**Contact Relationships:** The Mabou Group conformably to unconformably overlies the Windsor Group and represents the regional transition from marine to fluviatile and lacustrine conditions (Utting, 1978). Towards subbasin margins, the Mabou Group may locally overlap the Windsor Group and onlap older basement rocks (Sanford and Grant, 1990). Mabou strata also may be transitional basinward with both the Windsor and the overlying Cumberland Group (Boehner *et al.*, 1986: Gibling, 1995).

**Age:** Latest Visean, Namurian and Westphalian A in age (van de Poll *et al.*, 1995).

**General Comments:** Historically, several authors (Kelly, 1967; Hacquebard, 1972; Howie and Barss, 1975) found the Mabou Group unsuitable for regional mapping and continued to use the more traditional Canso and Riversdale Group terminology defined by Bell (1944). Recently, the usage of the Mabou Group, previously assigned to the Canso and lower Riversdale Groups, has been preferred by Ryan *et al.* (1991) who suggested

that the Mabou Group is a distinct and laterally extensive rock unit that can be further divided into the Middleborough and Shepody Formations in the Cumberland subbasin.

### 1.7.5 Cumberland Group

**Type Section Location:** The type area for the Cumberland Group is found in the western part of the Cumberland Basin (Ryan and Boehner, 1994) along the northeastern coast of the Bay of Fundy.

**Typical Lithology:** The type section outlined by Ryan *et al.* (1991) has a heterogeneous lithology consisting of red and grey conglomerate, sandstone and mudstone, coal seams and thin bituminous, locally fossiliferous, limestone and shale beds. The coal seams are up to 4.3m thick (Ryan *et al.*, 1991). Thick fanglomerates and sand dominated sequences are found locally adjacent to the highland areas (Ryan *et al.*, 1990).

Depositional environments represented by the Cumberland Group include alluvial fan, meandering, anastomosed and braided fluvial regimes. Lacustrine units occur throughout the section but tend to be thin. The Cumberland Group as defined by Ryan *et al.* (1991) consists of all grey coal-bearing strata in the Maritimes Basin, however, outside the type area, upper Cumberland Group strata commonly consist of predominantly red strata interbedded with grey coal-bearing strata (Gibling *et al.*, 1987).

**Onshore Distribution:** The group may locally exceed a thickness of 5000m with the incomplete type section measuring 3700m in thickness (Ryan and Boehner, 1994). Cumberland Group equivalents are widely distributed across the entire Maritimes Basin (Gussow, 1953; Hayes and Johnson, 1938; Gibling *et al.*, 1987).

**Contact Relationships:** The predominantly alluvial Cumberland Group conformably to unconformably overlies the Mabou Group and unconformably onlaps older basement rocks (Ryan *et al.*, 1991). The Pictou Group conformably to disconformably overlies the

Cumberland Group (Ryan and Boehner, 1994).

**Age:** The group at the type section is assigned a Late Namurian - Westphalian A to Late Westphalian C - Early Westphalian D age (Ryan *et al.*, 1991), however, equivalent strata in the Sydney subbasin may extend to the basal Stephanian (Gibling *et al.*, 1987).

**General Comments:** By improving and modifying the stratigraphic nomenclature of Bell (1944), Ryan *et al.* (1991) revised the Cumberland Group. Rocks previously assigned to the upper part of the Riversdale Group (Bell, 1944) and the Coarse Fluvial Facies (Belt, 1964,1965) are now assigned to the revised Cumberland Group. It is proposed that the Cumberland Group will now include also all the strata formally assigned to the Morien and Stellarton Groups of the Sydney and Stellarton subbasins, respectively (Gibling, 1995; Ryan *et al.*, 1991).

Ryan *et al.* (1991) assigned seven formations to the Cumberland Group in the type area; Claremont, Boss Point, Polly Brook, Joggins, Springhill Mines, Ragged Reef and Malagash formations. For a more detailed account of the stratigraphic nomenclature, the reader is referred to Ryan *et al.* (1991).

Sparse marine agglutinated foraminifera collected from Cumberland Group strata in the Sydney (Wightman *et al.*, 1993) and Cumberland (Archer *et al.*, 1995) subbasins indicate the presence of marine waters during Cumberland Group deposition: the first such marine incursion since the open marine conditions that existed during the deposition of the Windsor Group. Paleoflow for the Westphalian section tends to be generally in a north-northeasterly direction (Gibling *et al.*, 1992b).

### 1.7.6 Pictou Group

**Type Section Location:** The type section for the Pictou Group lies in the western portion of the Cumberland subbasin (Ryan *et al.*, 1991).

**Typical Lithology:** In the type area, the Pictou Group is typically a sequence of fluvial rocks predominantly composed of redbeds, with varying proportions of sandstone and mudstone (Ryan and Boehner, 1994). The sequences locally contain thin grey limestones, rare thin coals and conglomerates (Ryan *et al.*, 1991). The formations are alluvial in character and show a broadly upward fining trend (Gibling, 1995). Ryan *et al.* (1991) have suggested that in general the Pictou Group includes all predominantly red non-coal bearing strata that overlie the Cumberland Group.

The upper Pictou Group strata on P.E.I. are generally composed of grey to red quartz and mud-pellet conglomerates, coarse- to fine-grained sandstones, orange to red siltstones and mudstones and rare grey limestone (van de Poll, 1989; Howie, 1977). Deposition of the terrestrial redbeds likely occurred in either a deltaic or low alluvial plain environment (Howie, 1977).

**Onshore Distribution:** Pictou Group equivalents are widely distributed across the entire southern Maritimes Basin (Gussow, 1953; van de Poll, 1989; Gibling *et al.*, 1987). The type section has a thickness of 1650m, however the Pictou Group reaches a thickness of 3000m on Prince Edward Island and reaches much greater thickness near the depocentre of the Maritimes Basin (Ryan *et al.*, 1991; Howie and Barss, 1975).

**Contact Relationships:** The group may overlie any older Carboniferous unit or older basement rocks with disconformity, angular unconformity or nonconformity relationships (Ryan and Boehner, 1994).

**Age:** The group has been assigned an age of Westphalian D to Early Permian (Ryan *et al.*, 1991).

**General Comments:** The Pictou Group red bed succession blankets the Maritimes Basin and is the most poorly understood stratigraphic package. Its red bed character and lack of paleontological specimens have created longstanding problems with stratigraphic

classification. To help resolve problems with Pictou Group classification Ryan *et al.* (1991) proposed a revised group which can be further divided into three formations. In ascending order these are the Balfron, Tatamagouche and Cape John formations.

The Pictou Group outlined by Ryan *et al.* (1991) includes the redbeds of the offshore Sydney subbasin, the Cap-aux-Meules Formation and the Tormentine Formation of the Magdalen Islands and New Brunswick, respectively. Confusion as to how the Prince Edward Island redbeds fit into the revised Pictou Group exists due to poorly defined boundary conditions between the Nova Scotia and P.E.I. exposures investigated by Ryan *et al.* (1991) and van de Poll (1989), respectively. It is possible that the Cumberland Basin Pictou Group is transitional and time transgressive with the Prince Edward Island Redbeds (van de Poll, 1989). Some of the youngest Pictou Group strata exist on Prince Edward Island where tetrapod tracks found on the southwestern coast have been recently dated as late Early Permian (Mossman and Place, 1989).

## 1.8 Previous Work on the CMB

The geology of onshore exposures of Maritimes Basin strata has been well documented (Table 1.1). Table 1.1 compiles key studies that have contributed to understanding Maritimes Basin geology. The publication list of papers dealing specifically with the offshore data base is short (Table 1.1) but is complemented by a limited number of company reports and government open file reports.

Petroleum geologic activity in the Central Maritimes Basin has been at best sporadic. Activity in the 1970's led to the drilling of most of the offshore wells from which came a flow of data. At approximately the same time as the major phase of drilling activity, three notable studies on the offshore basin fill were conducted by Williams (1973, 1974) and McCamis (1973), primarily in the form of hydrocarbon resource assessments. More recent assessments have been provided by SOQUIP (1987) and Grant and Moir (1992).

Few stratigraphic or sedimentologic studies have been published that utilize well or seismic data from the offshore. The notable exceptions are the studies by Hacquebard

(1986), Ryan *et al.* (1990), Wightman *et al.* (1994a), Grant (1994) and Rehill *et al.* (1995), which used combinations of well logs, chip samples, core and seismic data in their geologic investigations of the Central Maritimes Basin fill.

Most structural investigations of the Maritimes Basin have been based on onshore exposures and fault traces. The large seismic data base offshore has only been used as a key to understanding the genesis of the basin in the last ten years. The studies by Durling and Marillier (1990, 1993b), Quinlan *et al.* (1988) and Stockmal *et al.* (1990) employed both multichannel and LITHOPROBE seismic data from the Gulf of St. Lawrence and presented intriguing perspectives on the tectonic history of the Maritimes Basin.

Over the last five years, a renewed interest in the offshore hydrocarbon potential has raised questions with regard to the subsidence/uplift, thermal and hydrocarbon maturation histories of the offshore Maritimes Basin. Preliminary solutions to such questions have been proposed by Hacquebard and Cameron (1989), Ryan *et al.*, (1990), Ryan (1993) and Grist *et al.* (1995).

# CHAPTER 2 - CENTRAL MARITIMES BASIN STRATIGRAPHY

## 2.1 General Statement

As a significant portion of the Maritimes Basin lies offshore (Fig. 2.1), geological studies of its Carboniferous fill tended to focus on preserved onshore portions. This contributed to the development of a complex stratigraphic nomenclature and tectonic history, clearly illustrated by a recent compilation of regional chronostratigraphy (Langdon and Hall, 1994). Their summary diagram (Fig. 2.2) shows the intricate stratigraphies developed for the various subbasins of the Maritimes Basin. However, the column set aside for the offshore Gulf of St. Lawrence (Central Maritimes Basin, CMB) lacks any detailed stratigraphic definition.

The stratigraphy, sedimentology and tectonic origin of onshore strata has been well documented (Bell, 1927, 1944, 1958; Belt, 1964, 1965; Kelly, 1967; Ryan *et al.*, 1991; St. Peter, 1993; Ryan and Boehner, 1994). In general, these studies dealt with the stratigraphy and tectonics of individual onshore subbasins, and sometimes applied their findings to the regional basin framework. As a result, unique stratigraphic nomenclatures have become associated with each subbasin. Although quite effective at the local scale, they typically cannot be applied and correlated basin-wide.

Not only do these individual subbasins and platform areas represent a very small portion of the total Maritimes Basin area (Figs. 1.2 and 2.2), the onshore record is further obscured by complex local tectonics, that may bias our account of the basin stratigraphic record when considered regionally.

The main focus of this thesis therefore is: What is the underlying geology of the southern portion of the Gulf of St. Lawrence? If the regional Maritimes Basin depocentre lies offshore near the Magdalen Islands (Howie and Barss, 1975) (Fig. 2.1), the thickest and most complete stratigraphic record should also lie offshore. As shown by the Langdon and Hall (1994) chronostratigraphic summary, even though the CMB represents the largest single geological area in the Maritimes Basin, it is the most poorly understood stratigraphically. The complexities of the onshore stratigraphy and the lack of detailed

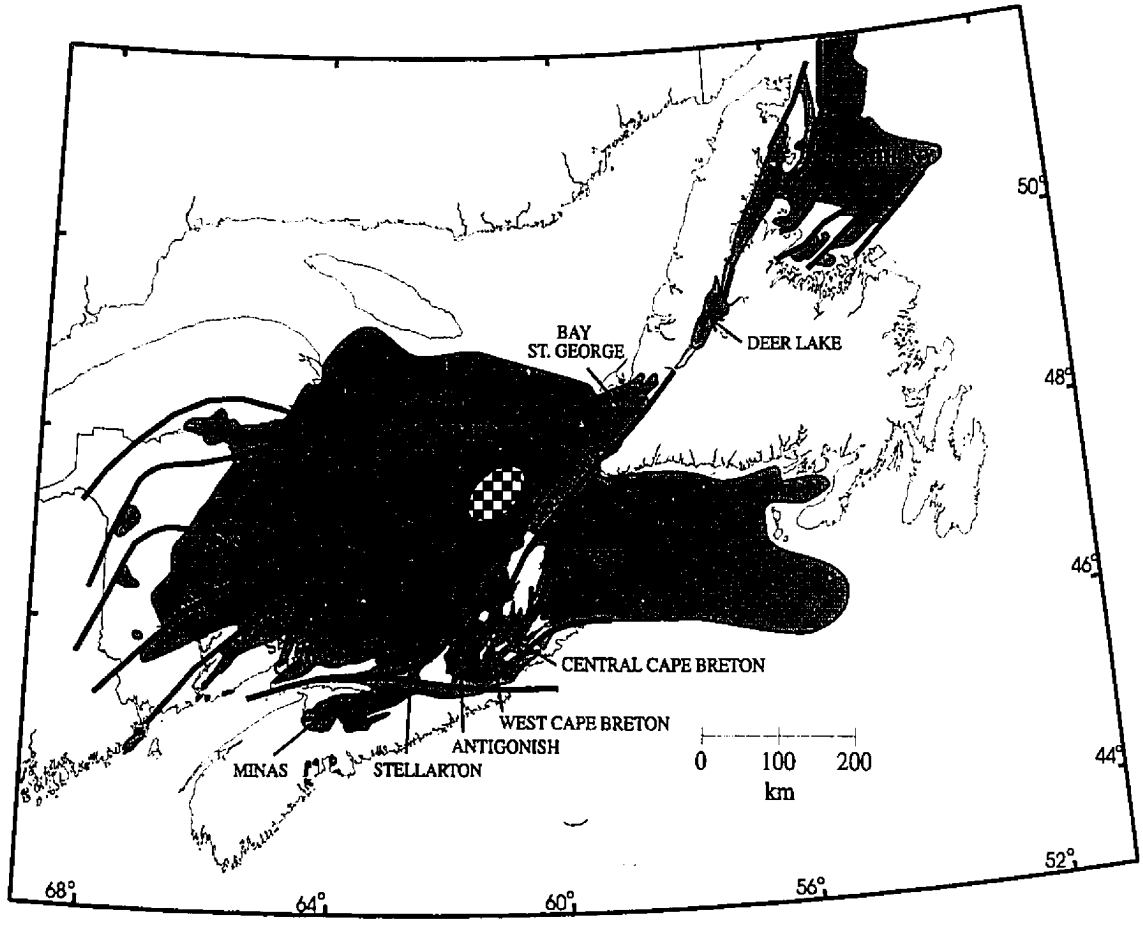



Figure 2.1 Map showing the location of the main subbasins, platform areas, and major faults which collectively make up the Maritimes Basin. The approximate location of the present depocentre is marked by a checker board pattern and the axis of the CMB is designated by the large arrow. The smaller arrows show the approximate direction of stratigraphic thickening. Refer to Figure 1.7 for fault identification.

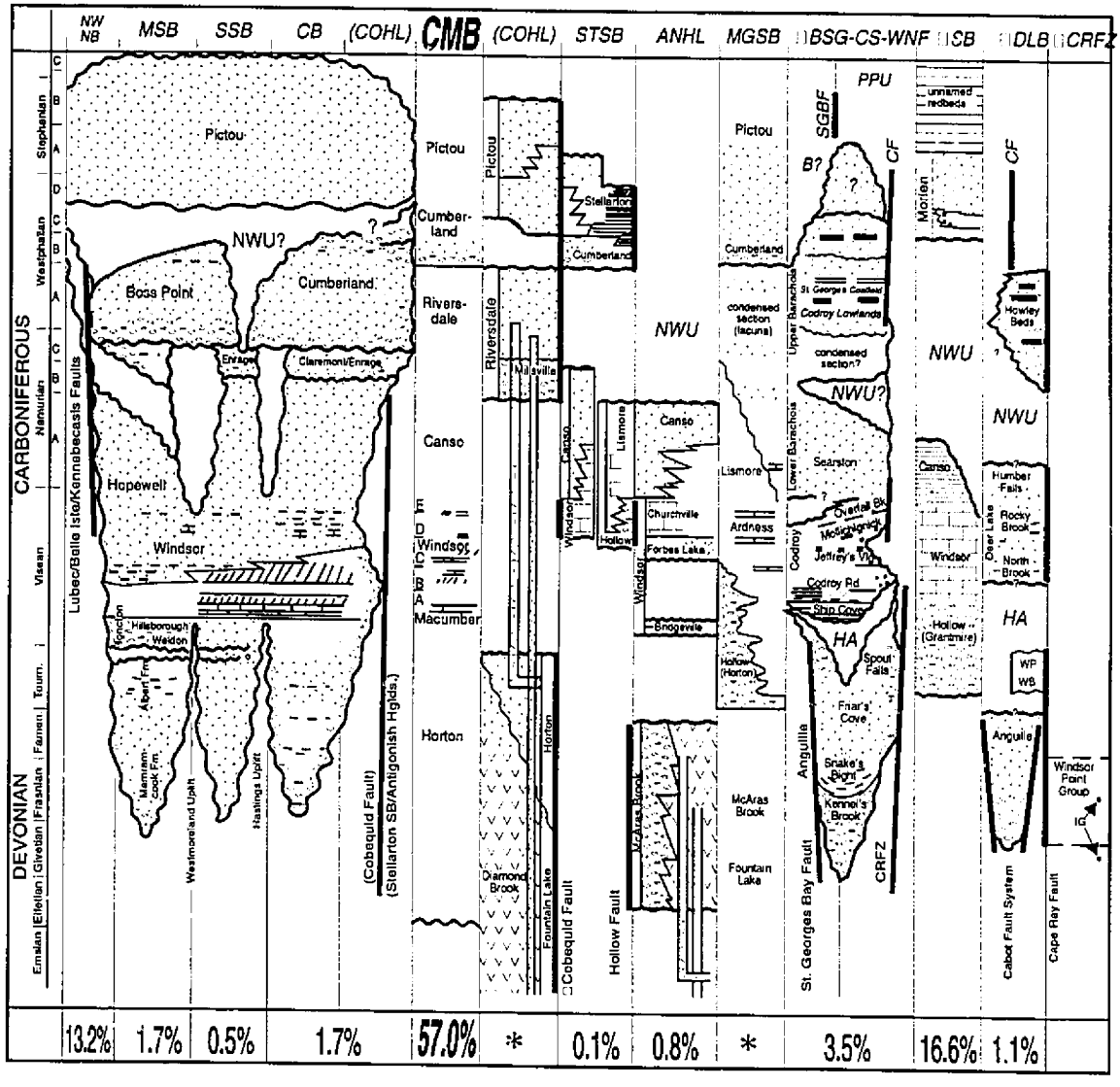



Figure 2.2 A recent compilation (after Langdon and Hall, 1994) of regional chronostratigraphy for the Maritimes Basin. Relative areas (as a percentage) of the basins/subbasins which make up the regional Maritimes Basin complex are shown at the bottom of each stratigraphic column. Abbreviations are; NWNB = northwestern New Brunswick (New Brunswick Platform); MSB = Moncton Subbasin; SSB = Sackville Subbasin; CB = Cumberland Subbasin; COHL Cobequid Highlands (*Cumberland Subbasin); CMB = Central Maritimes Basin; STSB = Stellarton Subbasin; ANHL = Antigonish Highlands (Antigonish Subbasin); MGSB = Merigomish Subbasin (*Cumberland Subbasin); BSG-CS-WNF = Bay St. George-Cabot Strait-western Newfoundland; SB = Sydney Subbasin; DLB = Deer Lake Subbasin; CRFZ = Cape Ray Fault Zone; IG = ignimbrites used in dating the Windsor Point Group. Abbreviations for unconformities; HA = top Horton-Anguille unconformity; NWU = Namurian-Westphalian unconformity; B = top Barachois unconformity; PPU = post-Pennsylvanian or post-early Permian unconformity.

stratigraphy for the offshore, has resulted in a poorly defined Late Carboniferous regional stratigraphic nomenclature that has not kept up with improved understandings of basin fill processes and sequence stratigraphic development.

The purpose of this chapter is to introduce, define and document the stratigraphic framework of the Central Maritimes Basin which consists of nine regionally extensive stratigraphic units. The nomenclature for some of the units proposed herein has been reserved with the Geological Survey of Canada and will be formally proposed in an appropriate publication.

The scope of stratigraphic investigations in this study encompass post-Windsor Group strata only. The older rocks (Horton and Windsor Groups) in the Central Maritimes Basin are not generally penetrated by a significant number of wells ($< 10$) and tend to be poorly imaged on available seismic records.

## 2.2 General Methodology: CMB Stratigraphic Analysis

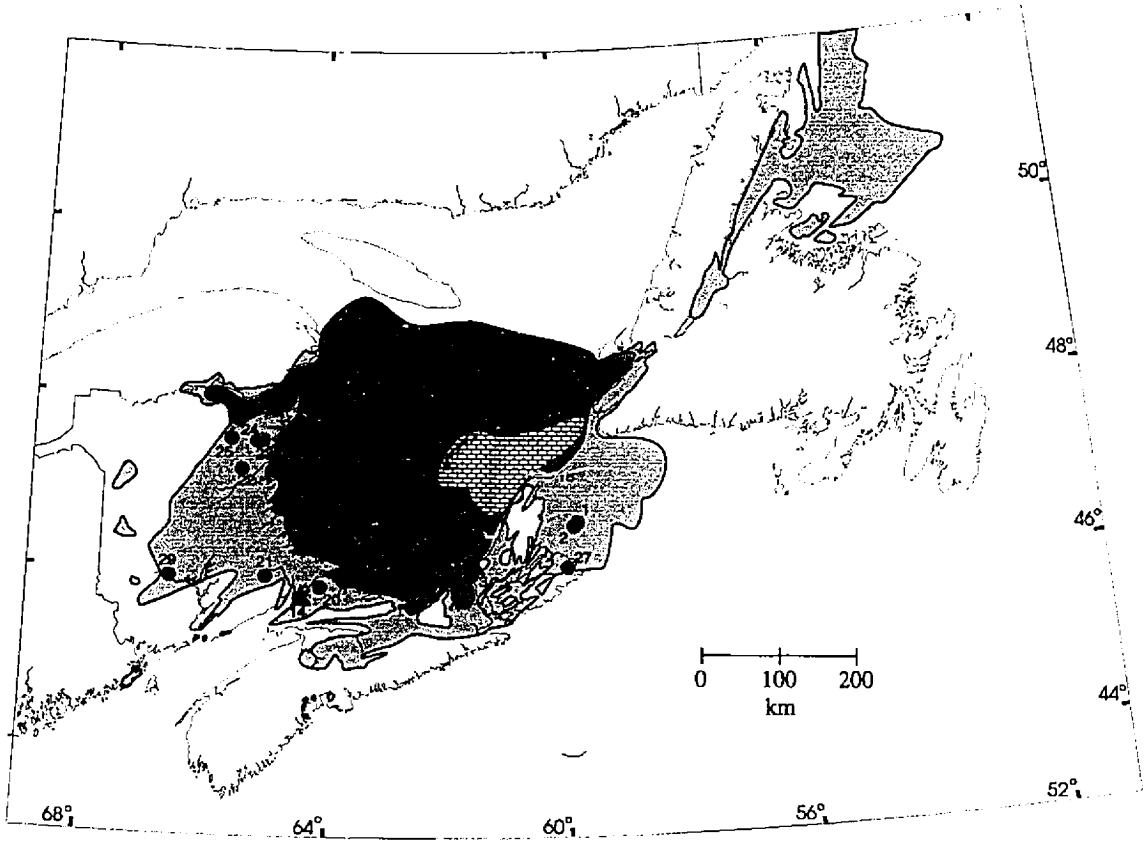
Regional analysis of the Central Maritimes Basin presented here uses several diverse data sets and applies several different methods to accomplish the primary goals of the thesis. The two primary data sets consist of information gathered from exploration wells (geological well data) and reflection seismic data. The two main styles of basin analysis consist of lithostratigraphic and seismo-stratigraphic correlation.

### 2.2.1 Geological Well Data

Geological well data obtained from exploration wells forms the primary source of data. Twenty-eight well locations (Fig. 2.3) were included in this study based on the following criteria:

- Each well must have penetrated a significant section (>500m) of Upper Carboniferous rocks
- Geophysical well logs had been run.
- Well logs were available for examination.

The well database compiled includes 17 wells drilled in the CMB, 3 wells in the




1. NORTH SYDNEY P-05
2. NORTH SYDNEY F-24
3. MABOU COASTAL SECTION
4. NSDME M-1
5. NSDME M-2A
6. EAST POINT E-47
7. EAST POINT E-49
8. BEATON POINT F-70
9. NAUFRAGE #1
10. TYRONE #1
11. GREEN GABLES #1
12. IRISHTOWN #1
13. WELLINGTON STATION #1
14. CUMBERLAND COASTAL SECTION
15. CABLE HEAD E-95
16. BRION ISLAND #1
17. BRADELLE L-49
18. ST. PAUL P-91
19. NSDME PH-3
20. HASTINGS #1
21. MIDDLESEX #1
22. BARTIBOG #1
23. ST. ISIDORE #1
24. ST. ISIDORE #2
25. BLANCHARD #1
26. HILLSBOROUGH #1
27. BIRCH GROVE #1
28. N. STRAIT F-25
29. FREDERICTON #2
30. NSDME P-58

Figure 2.3 Location map for the 28 wells and two major coastal reference sections referred to in this study. The triangular "limestone" shaded zone near the Magdalen Islands is the principal zone of evaporite tectonism (Grant and Moir, 1992).

Sydney subbasin (2 offshore, 1 onshore) and 8 wells drilled onshore around the periphery of the CMB. Locations and technical details of these wells are outlined in Table 2.1; additional data on each well are available from the CNSOPB. The onshore wells were chosen to complement the offshore database and to address questions regarding offshore to onshore stratigraphic links. Two well-known coastal sections, the Cumberland Group type sections situated on the shores of the Bay of Fundy and the Inverness Formation section at Mabou Mines western Cape Breton Island, were also included to help link subsurface units with the onshore geology (Table 2.1). In addition to well logs for each study well location, selected geologic data (Table 2.2) were available from the Government of Canada archives (GSC Atlantic) and published literature.

### 2.2.1.1 Geophysical Well Logs

To supplement the limited amount of digital and analog well log data that were initially available for this study twelve additional wells were added to the database during the course of the project. The original analog well data from these wells were digitized to complement the existing digital well log database. The complete set of CMB digital well logs used for this study resides in the GSC Atlantic Oracle database; BASIN.

The vintage of well data varies between wells (1944-1986) as does the quantity and quality of data from each well location. More data tend to be available from more recent exploration wells. The type of well logs for each well location varies, but typically consists of Gamma Ray (GR), Sonic (AU), Density (DEN), Spontaneous Potential (SP), Deep Induction (ID) and Short Normal Resistivity (SN) logs. A complete list of well logs available for individual wells can be acquired from the GSC Atlantic Basin Analysis Sub-division.

Since their development in the 1930's, well logs have become a critical element to any subsurface geologic study. In the absence of outcrop and core, well logs provide the only complete physical geological link to the subsurface stratigraphic column. With correlations established, well log data can be used to address questions concerning the lithology, sedimentology, fluid content, structural orientation, porosity and permeability

Table 2.1 List of wells with associated technical details. "+" values are above sea level.

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 08-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 09-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 09-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 01-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 04-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 05-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 03-Mar-58 | 03-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 07-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 07-Sep-73 | 01-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 02-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 06-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 04-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 05-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 02-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 07-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 03-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |

Table 2.2 List of study locations and the types of data available for each location. Brackets indicate poor data, multiple "X's" indicate multiple data sets.

| Well # | Well Name | Wireline Logs | Biostratigraphic Data | Mineralogic Data | Protozoan Data |
|---|---|---|---|---|---|
| 1 | Murphy *et al.* North Sydney P-05 | X | XX | X | |
| 2 | Shell *et al.* North Sydney F-24 | X | XX | | |
| 3 | Mabou Coastal Section | | | | |
| 4 | NSDME Borehole M-1 | X | X | | |
| 5 | NSDME Borehole M-2A | X | X | | |
| 6 | Hudson's Bay *et al.* East Point E-47 | X | X | | |
| 7 | Hudson's Bay-Fina East Point E-49 | X | XX | X | X |
| 8 | Hudson's Bay *et al.* Beaton Point F-70 | X | XX | | |
| 9 | Soquip *et al.* Naufrage No.1 | X | XX | X | |
| 10 | Soquip *et al.* Tyrone No.1 | X | XX | X | |
| 11 | Hudson's Bay-Fina Green Gables No.1 | X | XX | X | |
| 12 | Hudson's Bay-Fina Irishtown No.1 | X | XX | X | |
| 13 | Imperial Wellington Station No.1 | X | X | | |
| 14 | Cumberland Coastal Section | | (X) | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | X | XX | | X |
| 16 | Sarep H.Q. Brion Island No.1 | X | XX | X | X |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | X | XXXX | X | X |
| 18 | Petro-Canada *et al.* St. Paul P-91 | X | (X) | | |
| 19 | NSDME PH-3 | X | X | | |
| 20 | Gulf *et al.* Hastings No.1 | X | X | | |
| 21 | Irving Chevron *et al.* Middlesex #1 | X | (X) | | |
| 22 | Hudson's Bay Bartibog No.1 | X | | | |
| 23 | Hudson's Bay St. Isidore No.1 | X | | | |
| 24 | Hudson's Bay St. Isidore No.2 | X | | | |
| 25 | Hudson's Bay Blanchard No.1 | X | (X) | | |
| 26 | Island Development Company Hillsborough No.1 | X | (X)X | | |
| 27 | Murphy *et al.* Birch Grove No.1 | X | X | | |
| 28 | Hudson's Bay *et al.* Northumberland Strait F-25 | X | X | (X) | |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | X | (X) | | |
| 30 | NSDME P-58 | X | X | | |

of individual stratigraphic units.

Well logs used in this study are all in digital format, making them easier to manipulate and analyze than standard paper logs. Stratworks, a Unix based commercial software package developed by Landmark Graphics Corporation, was used to manage the digital log database. This software package helps the user perform correlation, mapping and rudimentary petrophysical analyses using digital well log data.

Primary lithologic analysis was performed using well logs in conjunction with Canadian Stratigraphic Services Logs and company well history reports. For instance, probable coal zones were identified based on a combination of low, high and low responses from the gamma-ray, sonic and density logs, respectively (Alberty, 1992) in conjunction with reported occurrences of coal from CanStrat logs and cuttings reports. For each well location, the sandstone/shale ratios for key stratigraphic units were calculated using the gamma-ray well log and designating a shale baseline (Alberty, 1992; Slatt, 1992).

#### 2.2.1.1.1 Correlation Using Well Logs

Stratigraphic correlation is the cornerstone of subsurface geologic work, the ultimate goal of which is to determine stratigraphic equivalence between wells and other representative geologic sections. Recognizing similar wireline data signatures (or markers) from each well provides the basic means of linking stratal units between wells. It is crucial that all available data be utilized to help support the correlations so that a strong foundation exists from which to conduct further study.

In addition to well log data, correlation of subsurface stratal units was assisted by biostratigraphic data. Similar to standard industry projects (Putnam, 1993), the primary well logs used in this study were the gamma ray and sonic (acoustic) logs. Well log signatures and biostratigraphy of each well were first compared with the nearest wells to see what, if any, relationships existed, then the search was extended outwards to more distant wells. Commonly, subsurface geologic investigations deal with the correlation of stratal units a few metres to tens of metres thick (Church and Gawthorpe, 1994). The

long distances (1.5 to 150 km) between CMB study wells required correlations of units hundreds of metres thick. The multiple well correlation process first concentrated on linking common shale dominated sequences that were presumed to be more uniformly distributed (Visher, 1984; Cant, 1992). This stage was followed by examining the relationships between the coarser grained sequences. After the main stratigraphic relationships were identified, linked between individual wells, and tied to available seismic data, the stratal units found in the CMB wells were correlated with the onshore wells and representative sections.

#### 2.2.1.1.2 Depositional Environment Using Well Logs

In addition to helping link subsurface stratal units, well log signatures can be used to infer depositional environments (Fig 2.4). Wireline tools respond to the changing physical properties of rocks and fluids in the subsurface and these properties are directly related to the depositional and post-depositional histories of the subsurface strata (Alberty, 1992). Characteristic responses by individual tools have led geologists, over the past 50 years, to speculate that curve shapes correspond to certain depositional environments.

It is common practice to place, or mirror, the sonic or resistivity logs opposite a gamma ray log. This configuration often results in distinctive shapes which correspond to "characteristic" depositional environments (Cant, 1992), although many types of depositional environments can be attributed to any one curve shape (Fig. 2.4). Individual well logs were examined for characteristic curve shape with special attention paid to the coarser grained sequences. The available supporting data (e.g. lithology {cores and chip samples}, seismic, protozoan analysis) were used in conjunction with the curve shape analysis to constrain the types of depositional environments.

### 2.2.1.2 Micropalynological Data (*Biostratigraphy*)

The continental to restricted marine nature of the younger Maritimes Basin fill restricts biostratigraphical analysis to examination of terrestrial palynomorphs which are

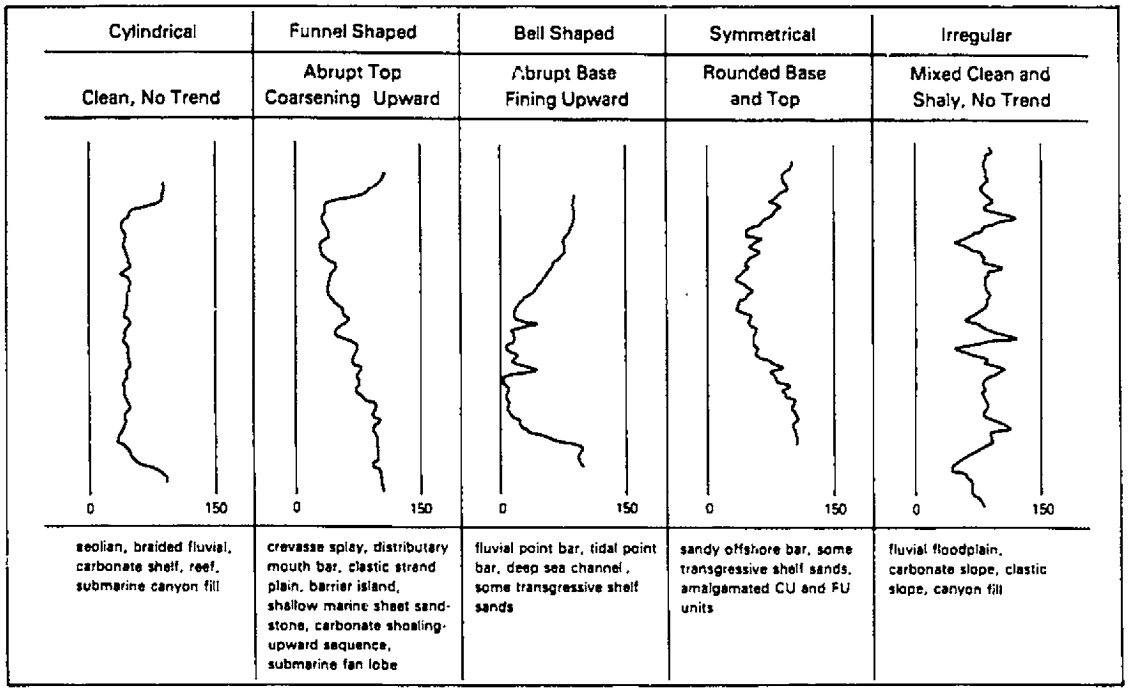



Figure 2.4 Representative gamma-ray well log shapes used to interpret depositional environment. Using the resistivity or sonic logs opposite a gamma ray log results in the classic bell, funnel and cylinder shapes which correspond to "characteristic" depositional environments. Using curve shape alone is not diagnostic; as shown below the curves, many types of depositional environment can be attributed to any one curve shape (from Cant, 1992).

of limited use for high resolution age-depth determinations. In general, the offshore basin fill is Visean to Early Permian in age (53.8 million year span) and, more specifically, the thick (>8km) Westphalian to late Stephanian strata, which make up more than 80% of the basin fill, represent approximately 17 million years (based on the timescales of Hess and Lippolt, 1986; AGSO, 1996; Claoe-Long *et al.*, 1992). These strata lie within eleven spore assemblage zones each of which is represented by hundreds of metres of strata. There is great potential for spore zone overlaps, especially as reworking of palynomorphs has been documented in many samples. The presence of redbeds compounds this problem because they tend to be barren of palynomorphs. As a result, palynological age dating from Maritimes Basin strata is at times uncertain and zone boundaries tend to be poorly defined.

A primary concern when dealing with borehole derived biostratigraphic information is the possibility that the material has been caved from younger strata above in the wellbore. Biostratigraphic reports rarely indicate when samples are caved; usually only the zones/assemblages and depths are documented. Additionally, samples are taken typically every 10 to 100 m, resulting in biostratigraphic resolution that may be less than the stratigraphic units to be correlated. Little can be done (besides retesting the section) about these inherent problems except to recognize the limitations and apply the data with caution.

Previous palynological investigations dealing with CMB study wells (Table 2.2) have been compiled from several sources (APPENDIX I). In addition, biostratigraphic investigations (Dolby, 1994) of six offshore well locations (Naufrage No.1, Beaton Point F-70, East Point E-47, Cable Head E-95, Bradelle L-49, NSDME Boreholes M-1 and M-2A; Fig. 2.3 and Table 2.1) were conducted to assist with this study. All age-depth pairs have been plotted against the vertical well profiles for selected CMB study wells, facilitating multi-well correlation.

The Carboniferous absolute time scale used exclusively in this study is defined by Hess and Lippolt (1986). The Devonian-Tournaisian and Visean-Namurian boundary ages are from Claoe-Long *et al.* (1992) and AGSO (1996), respectively. Although

numerous absolute time scales are available, the Hess and Lippolt scale, based on measurements from tuffs very close to biostratigraphic stage boundaries, was assumed to be the most reliable for the Carboniferous. The Harland *et al.* (1989) absolute time scale was used for pre and post Carboniferous ages.

### 2.2.1.3 Protozoan Data

The post-Windsor Group Maritimes Basin strata have traditionally been associated with fluvio-lacustrine environments of deposition (Howie and Barss, 1975). Thibaudeau and Medioli (1986) and Wightman *et al.* (1993) in the Sydney sub-basin, however, documented restricted-marine agglutinated foraminifera in the Westphalian-aged Coal Measures. Following up these onland investigations Wightman *et al.* (1994a) examined selected CMB wells for evidence of marine influence in the coal-bearing sections. The investigation focussed on 65 samples collected from the East Point E-49 (13 samples), Brion Island No.1 (19 samples), Cable Head E-95 (16 samples), and Bradelle L-49 (17 samples) offshore wells (Table 2.2)(see Fig. 2.3 for locations) with the specific number of samples per stratigraphic unit outlined in APPENDIX II. Besides freshwater thecamoebians, the investigation was successful in identifying the foraminiferal genera *Trochammina*, *Ammotium* and *Ammobaculites* (Table 2.3) in a significant portion of the study intervals, suggesting that portions of the CMB Westphalian-aged strata were deposited under restricted-marine conditions. Detailed reports of materials, methods and results are outlined in APPENDIX II.

To examine the timing of marine incursions with respect to specific CMB stratigraphic sections, for each well the proportion of agglutinated foraminifera to thecamoebians was plotted against depth. These four profiles (APPENDIX II) were then combined to make one composite Central Maritimes Basin vertical profile which can be considered a semi-quantitative indicator of relative marine influence (Wightman *et al.*, 1994a): the higher the ratio the higher the relative sea level. This schematic sea level curve was plotted against the CMB stratigraphic framework to indicate any relationship between the degree of marine influence and stratigraphic position.

Table 2.3 Agglutinated foraminifera and thecamoebians that are typically found in modern estuaries, salt and freshwater marshes (from Wightman *et al.*, 1994b). The genera that were identified during the CMB protozoan study are in boid. Relative proportions of specific foraminifera for each sample interval are detailed in APPENDIX II.

| | Environment | | | |
|---|---|---|---|---|
| | Estuary | Lower salt marsh | Upper salt marsh | Freshwater marsh |
| Tidal Range | Sub/inter tidal | 0-70cm above MSL | 70-110cm above MSL | N/A |
| Salinity (%) | 1-35 | 15-32 | 1-25 | 0 |
| Fauna | Agglutinated Foraminifera | Agglutinated Foraminifera | Agglutinated Foraminifera | Thecamoebians |
| | ***Milammina fusca*** | ***Ammotium salsum*** | ***Trochammian inflata*** | *C. constricta* |
| | ***Ammotium salsum*** | *Milammina fusca* | *T. macrescens* | *Nebela collaris* |
| | ***Ammobaculites* spp.** | ***Ammobaculites* spp.** | *Tiphotrocha comprimata* | ***Centropyxix aculeata*** |
| | | | | ***Difflugia* spp.**[1] |
| | *Eggerella advena* | | ***Haplophragmoides* spp.** | |
| | ***Reophax* spp.** | | | |

[1]Also endemic to floating marsh environment.

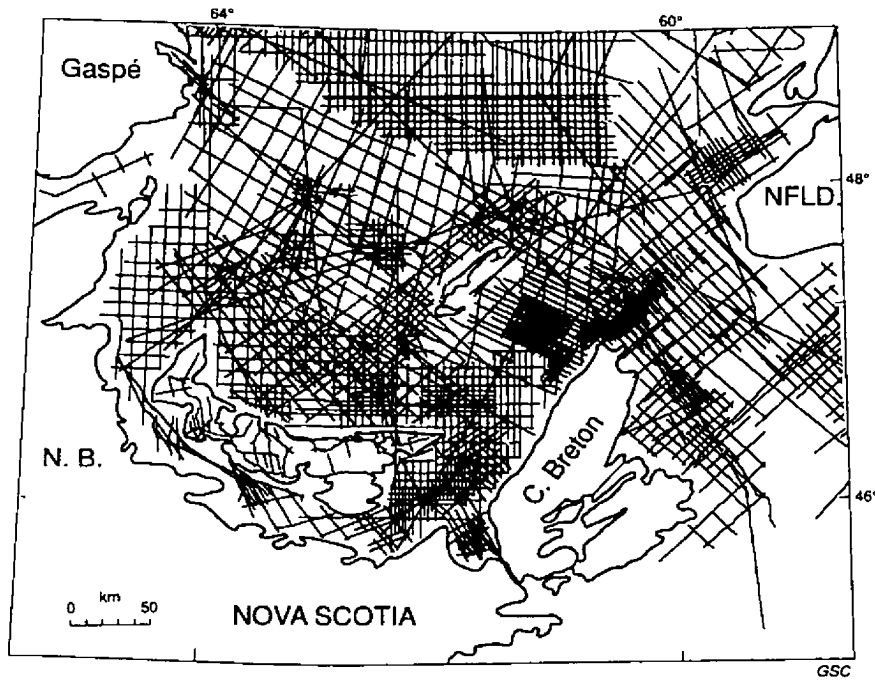
#### 2.2.1.4 Clay Mineralogic Data

During the peak phase of industry activity in the early 1970's, INRS-Petrole (1975a, 1975b, 1975c) selected several CMB wells for detailed X-ray diffraction analysis (Table 2.2). The findings were informally published in company reports which consisted of a short report and a series of semi-quantitative profiles of major minerals (quartz, calcite, dolomite), lithology, bulk clay mineralogy (chlorite, illite, kaolinite, mixed illite/smectite) and individual clay mineral peak ratios (chlorite and illite) versus depth. Sampling for the study was carried out over relatively large intervals (one sample/30-100m). A difficulty with the data set was that all the individual paper profiles were detached, fragmented and plotted at different depth scales, making it extremely hard to link data from well to well. To address these problems, each mineralogic profile was digitized using AutoCad software. Once each profile was in digital form, the data were imported into an Excel spreadsheet for manipulation and plotting. This provided a means for visually comparing and correlating major variations in mineral content on a well-to-well basis. The software also aided in the overlay of key stratigraphic boundaries on the mineralogic profiles.

### 2.2.2 Seismic Data

Over the last 30 years, approximately 80 000 line-km of industry seismic data, LITHOPROBE and high resolution seismic surveys have been collected over the Gulf of St. Lawrence (Fig. 2.5). Most data are available to the general public from the CNSOPB, CNOPB and Provincial Government of Quebec.

Thirty lines were chosen from the larger data set (Fig. 2.5; Table 2.4) to complement the offshore geological well database. These lines were chosen specifically to provide a regional view of the basin fill character across and along strike, similar to the geological cross sections. Each line was examined for characteristic seismic stratigraphic reflector patterns and where possible was linked to well bore data using synthetic seismograms (see below).



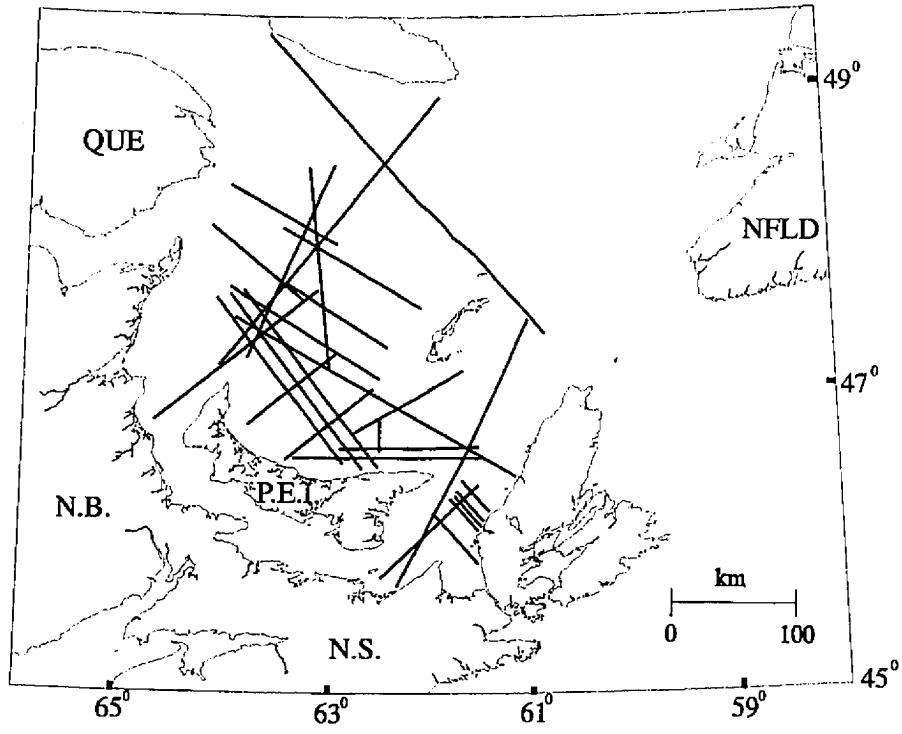




Figure 2.5 (Top) Location of industry multichannel seismic lines currently available in the offshore Maritimes Basin. From Grant and Moir (1992). (Bottom) Location of multichannel seismic lines used in this study: see Table 2.3 for a detailed listing of industry line numbers and a brief overview of technical details.

Table 2.4 List of industry multichannel seismic lines used for seismic stratigraphic analysis. Line numbers in **bold** are used in figures in the thesis. Seismic lines that are underlined contain designated seismo-stratigraphic type sections. The reader is referred to the CNSOPB for more detailed information regarding the seismic data base.

| Line # | Year | Operator | Contractor | Source | Quality |
|---|---|---|---|---|---|
| **86-1** | 1986 | GSC | G.S.I | Air Gun | Good |
| 86-2 | 1986 | GSC | G.S.I | Air Gun | Good |
| 82-49-21H | 1982 | Chevron | Chevron Geosciences Co. | Air Gun | Fair to Good |
| 81-51-11L | 1981 | Chevron | Western | Air Gun | Fair to Good |
| 81-25-11MA | 1981 | Chevron | Western | Air Gun | Fair to Good |
| 81-25-11M | 1981 | Chevron | Western | Air Gun | Fair to Good |
| **81-67-11L** | 1981 | Chevron | Western | Air Gun | Good |
| 81-59-11L | 1981 | Chevron | Western | Air Gun | Good |
| 81-63-11L | 1981 | Chevron | Western | Air Gun | Good |
| **81-75-11F** | 1981 | Chevron | Western | Air Gun | Good |
| XAU-001 | 1971 | E. Coast Participation Survey | Catalina Expl. and Dev. | Vibrator | Fair to Good |
| XAU-008 | 1971 | E. Coast Participation Survey | Catalina Expl. and Dev. | Vibrator | Fair to Good |
| HAA-006 | 1967 | Conoco | Delta | Vibrator | Poor to Fair |
| HAA-007 | 1967 | Conoco | Delta | Vibrator | Poor to Fair |
| **ST-82-02** | 1982 | G.S.I | G.S.I | Air Gun | Good |
| ST-82-02B | 1982 | G.S.I | G.S.I | Air Gun | Good |
| GSL-51 | 1980 | Chevron | Western | Air Gun | Fair to Good |
| GSL-60 | 1980 | Chevron | Western | Air Gun | Fair to Good |
| GSL-31X | 1980 | Chevron | Western | Air Gun | Fair to Good |
| GSL-91 | 1980 | Chevron | Western | Air Gun | Fair to Good |
| **GSL-71** | 1980 | Chevron | Western | Air Gun | Fair to Good |
| GSL-50 | 1980 | Chevron | Western | Air Gun | Fair to Good |
| **GSL-70** | 1980 | Chevron | Western | Air Gun | Fair to Good |
| GSL-51A | 1980 | Chevron | Western | Air Gun | Fair to Good |
| 71-2130 | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |
| 71-2140 | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |
| 71-1060 | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |
| 71-2170 | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |
| **71-2100** | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |
| 71-2090 | 1971 | SOQUIP | S.S.C | Vibrator | Fair to Good |

### 2.2.2.1 Seismic Stratigraphy

The approach used during this phase of the project follows the seismic stratigraphy methods developed by Vail *et al.* (1977), who documented a two-step process for seismic interpretation; primary seismic sequence analysis and secondary seismic facies analysis.

Seismic sequence analysis is underpinned by the depositional sequence concept, originally defined by Vail *et al.* (1977) as a relatively conformable succession of genetically related strata bounded at its top and bottom by unconformities or their correlative conformities. Applying this definition to seismic reflection data, a seismic sequence is simply a depositional sequence identified on a seismic section. It is formally defined as a relatively conformable succession of reflections, interpreted as a group of genetically related strata, which are bounded at the top and bottom by surfaces of discontinuity marked typically by reflector terminations. The discontinuities are interpreted to be unconformities or their correlative conformities which have chronostratigraphic significance (Vail *et al.*, 1977).

The key element in defining seismic sequences is the identification of bounding discontinuities or seismic sequence boundaries (Vail *et al.*, 1977). Typically, sequence boundaries are identified where the velocity-density of strata above and below the surface of discontinuity vary (acoustic impedance contrast) causing a pronounced seismic irregularity or reflection. The larger the contrast between packages of strata, the more easily the sequence boundary is identified. Reflection terminations are important for identifying angular sequence boundaries, however non-angular discontinuities, where there is no obvious termination of reflections, are commonly identified by the strong velocity-density contrast between genetically different packages of parallel strata above and below the disconformity (Vail *et al.*, 1977).

Seismic facies analysis involves detailed examination of the configuration, continuity, relief and amplitude of individual reflections within the seismic sequences (Vail *et al.*, 1977), and integration with any available geologic or timing information. Such seismic stratigraphic analysis provides information regarding stratification processes

and erosional surfaces. Reflection configurations, continuity and relief help to interpret depositional processes, bedding patterns and paleotopography. The amplitude of the reflectors is associated with bed thicknesses and variations in reflection coefficient magnitude between different lithologies. The facies analysis component is subjective and commonly open to alternative interpretations (Visher, 1984).

Paper copies of each study line, obtained from the GSC Atlantic archives, were examined and the major seismic sequence boundaries were identified based on the criteria of Vail *et al.* (1977) and, where possible, were tied to other seismic lines. The characteristics (reflector termination and geometry, continuity, relief and amplitude) of each sequence boundary were noted and reflectors were highlighted. The seismic data were then re-examined and a series of type sections were selected as representative of the data set. Their seismic facies characteristics were recorded and the designated type sections were then digitally scanned.

### 2.2.2.2 Synthetic Well Ties

An important goal of this project was to calibrate the physical geologic well data with the extensive offshore seismic database in order to extend geological interpretations away from the individual boreholes. A problem in dealing with the two distinctly different databases is the different resolutions and the fact that one is collected as a function of depth and the other of time. The solution to this problem is to invert well log depths to time, create time-depth tables, and construct a synthetic seismogram, or "synthetic", which allows the merging of data sets.

Construction of synthetic seismograms requires an estimate of sonic velocity and rock density. These data can be obtained from the sonic and density logs for the well location that is being tied to the seismic section. The sonic log, data in combination with data from the density log, are used to calculate a vertical two-way-travel time profile of acoustic impedance contrasts which in turn gives reflection coefficient sequences. These sequences are then convolved with a suitable seismic wavelet to construct the synthetic seismogram profile, which is then compared with the seismic section to calibrate depths

and stratigraphic boundaries.

Synthetics were created for selected CMB wells (NSDME Borehole M-2A, Bradelle L-49, East Point E-49, Beaton Point F-70 and Cable Head E-95) (see Fig. 2.3 for locations) using the Landmark Graphics Corporation's MIRA SynTool v. 2.50 software package. The digital sonic and density well logs from each well were used to create preliminary acoustic impedance profiles. An appropriate seismic wavelet was chosen (a Ricker wavelet) and convolved with the acoustic impedance profiles. Replacement velocities (1500-1700 m/s) were applied to the synthetics to correct for water depth and casing effects (i.e., absence of well log data). This process resulted in a set of synthetics which closely matched the seismic reflection data in close proximity to the wells.

Synthetics previously created, by Sonigram, were available for several CMB wells (North Sydney F-24, Northumberland Strait F-25, East Point E-49, East Point E-47, Cap Rouge F-52 and Bradelle L-49). There was no appreciable difference between the newly generated and older commercial synthetic seismograms. The commercial synthetic seismograms are available from the GSC Atlantic Basin Analysis Subdivision.

The time-depth curves constructed during the process of making the synthetic seismograms were used to convert the two-way travel times to depths. This enabled a quick approximation of both stratigraphic thicknesses and stratigraphic boundary depths directly from the seismic data.

### 2.2.3 Field Work

Approximately three weeks of geological reconnaissance surveying was conducted during the course of this project. The work consisted of traversing important onshore stratigraphic successions to become familiar with regional Carboniferous geology. The type sections of the Cumberland and Pictou Groups were visited in the Cumberland subbasin (Fig. 2.1), as was a key coastal exposure of the Mabou Group. An excursion was made to P.E.I. to examine the redbed succession. On Cape Breton Island, strata examined include Westphalian-aged rocks in the Sydney subbasin (Fig. 2.1), the type section of the Port Hood Formation on the western coast, and the Broad Cove,

Inverness, Mabou and Windsor stratigraphic successions. In the Bay St. George subbasin of Newfoundland (Fig. 2.1), the type section of the Searston Formation (Mabou-Early Cumberland Group age equivalent), and significant portions of both the Barachois (Middle Cumberland Group age equivalents) and Codroy Groups (Windsor Group age equivalent) were investigated. The Visean to Namurian Deer Lake Group and Early Westphalian Howley Formations were examined in the Deer Lake subbasin (Fig. 2.1).

## 2.3 Results of Litho, Bio and Seismo Stratigraphic Analyses

The construction of cross-sections linked to the seismic data led to identification of ten regionally extensive stratigraphic successions. Offshore equivalents of the Windsor and Mabou Groups were easily recognized based on the distinct lithologic contrast between the two groups. Overlying the Mabou Group, eight distinctive units have been identified and given the formal names (in ascending order) Brion Island Formation, Bird Rock Formation, Bradelle Formation, Green Gables Formation, Magdalen Formation, Seacow Formation, Cable Head Formation and the Naufrage Formation (Fig. 2.6). The next two subsections will consider bio/lithostratigraphic relationships and regional basin fill characteristics, respectively.

### 2.3.1 Cross-Sections

Six geologic cross-sections were constructed; four perpendicular to the basin axis and two parallel to the basin axis (Fig 2.7). Enclosures 1 to 6 indicate stratigraphic correlations between the study wells. They consolidate available biostratigraphic data and are not shown with horizontal scale. Enclosures 7 to 12 are scaled horizontally to illustrate structural relationships between wells and general unit lithology correlations. A complete set of geologic tops for the CMB well locations is located in APPENDIX III. Enclosure 13 displays the interpreted correlations between the CMB stratigraphic framework and the set of onshore wells. This is not an attempt to redefine the established stratigraphic nomenclature for these areas, but instead, to link the offshore CMB to the preserved onshore strata. All cross-sections focus exclusively on post-Windsor Group

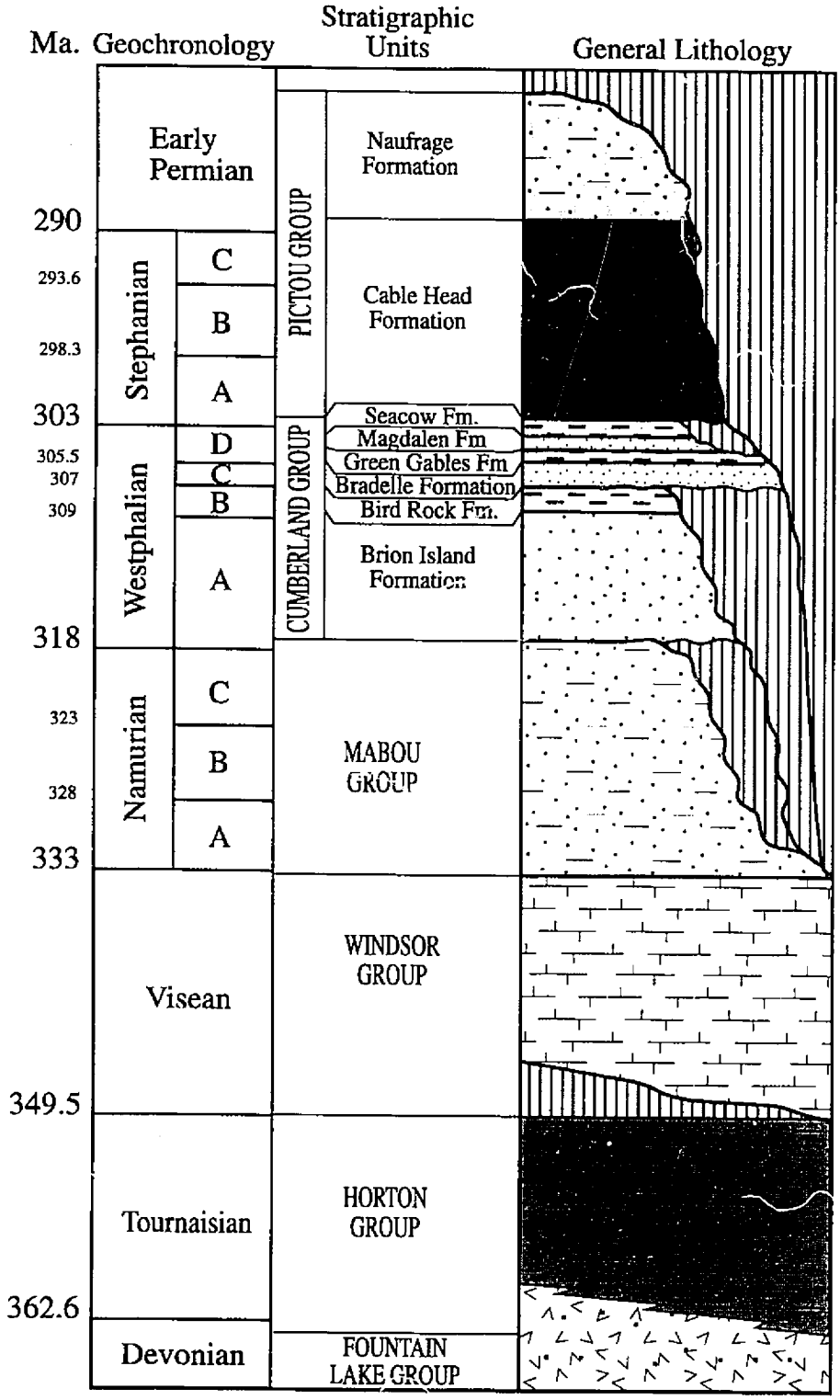
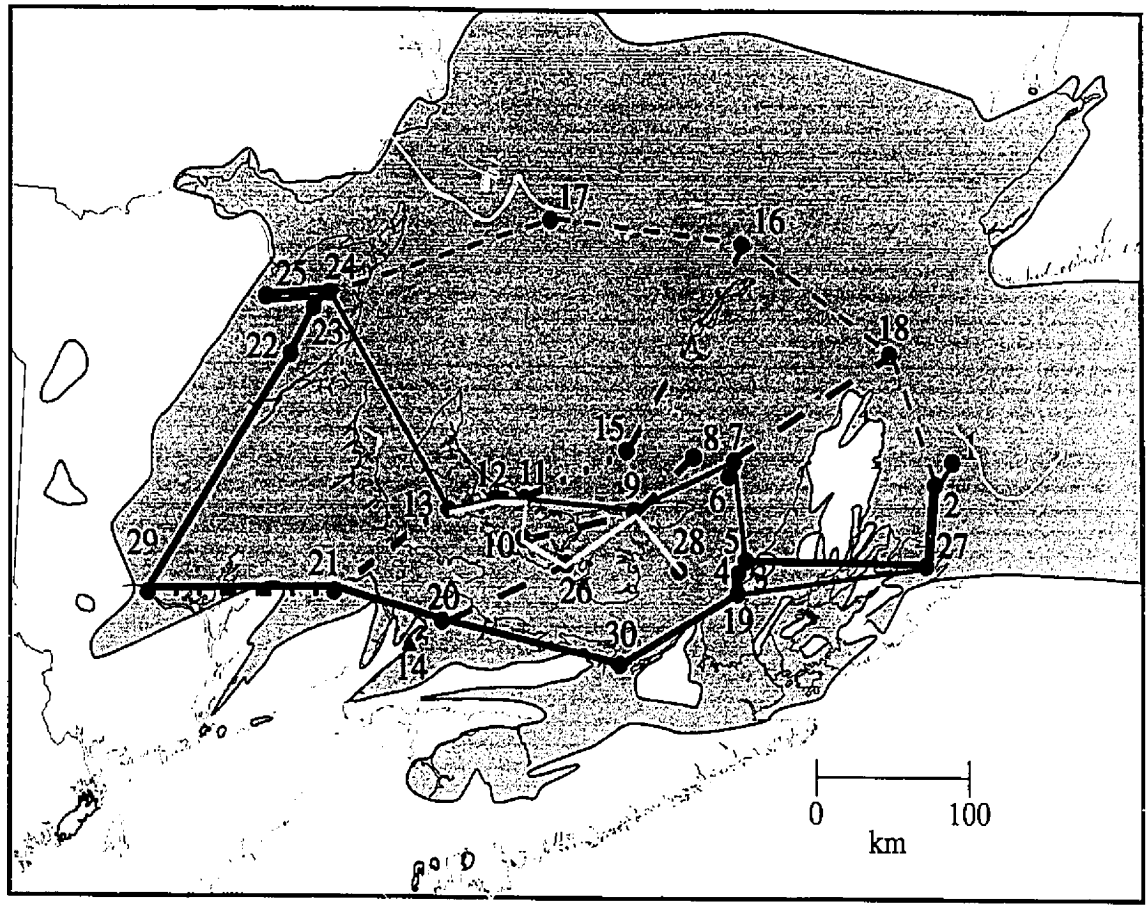
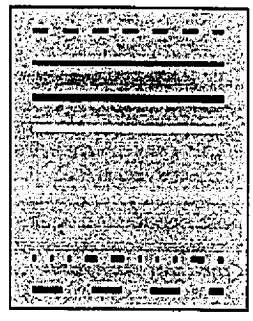



Figure 2.6 Late Paleozoic stratigraphic column for the Central Maritimes Basin: see Figure 2.9 for unit lithologies. Time scale from Hess and Lippolt (1986), AGSO (1996) and Claoe-Long et al. (1992).



Perpendicular to Basin Axis

Cross-Section A - A'
Cross-Section B - B'
Cross-Section C - C'
Cross-Section D - D'

Parallel to the Basin Axis

Cross-Section E - E'
Cross-Section F - F'

Figure 2.7 Map showing the location of geological cross-sections. A complete set of detailed bio/lithostratigraphic correlation and strctural cross-sections is found in the pocket at the back of the thesis as Enclosures 1 to 13.

strata and use sea level as a datum.

#### 2.3.1.1 CMB Bio/Lithostratigraphic Correlation Cross-Sections

The synthesis of CMB palynological and well log data has resulted in the identification of three important hiatuses: near the Namurian-Westphalian, Late Westphalian B-Early Westphalian C (Mid-Westphalian), and the Westphalian-Stephanian boundaries (Fig. 2.8).

The Namurian-Westphalian event is clearly identified in both the Brion Island No.1 and Bradelle L-49 exploration wells. In the Brion Island No.1 well (well #16, Enclosure 5), strata of Westphalian A age lie directly on Namurian A strata (Sarep Ltd, 1971; INRS-Petrole, 1973), suggesting that the Namurian B and C portions of the Mabou Group were eroded, not deposited or faulted out at this location. The stratal loss is associated with a sharp lithological discontinuity at the base of the Brion Island Formation. Bradelle L-49 (well #17, Enclosure 1) has Westphalian B strata lying directly on Namurian C strata (Dolby, 1994) implying a similar relationship.

Of the three inferred time gaps, the Mid-Westphalian event is the most easily identified; however, this could reflect a greater abundance of data over this particular interval (Fig. 2.8). Nevertheless, the event is evident in several wells (Table 2.1, wells #1, #2, #7, #10, #12 and #19) over a large geographic area. In the southwestern portion of the CMB, the Irishtown No.1 (well #12, Enclosure 5) well has Westphalian B - Westphalian C strata directly overlying Late Visean - Early Namurian strata (INRS-Petrole, 1975c).

The data at several locations suggest that the Mid-Westphalian event locally incises down to, or merges, with the underlying Namurian-Westphalian event (Fig. 2.8). In the Sydney subbasin, the North Sydney F-24 well (well #2, Enclosure 3) has Namurian A strata overlain by Early Westphalian C strata (Shell Canada Resources Ltd, 1976). In the eastern portion of the CMB, the East Point E-49 exploration well (well #7, Enclosure 6) shows evidence of Westphalian D overlying Late Visean - Early Namurian strata (Barss *et al.*, 1979). Relatively close to the East Point well, the NSDME PH-3 well (well

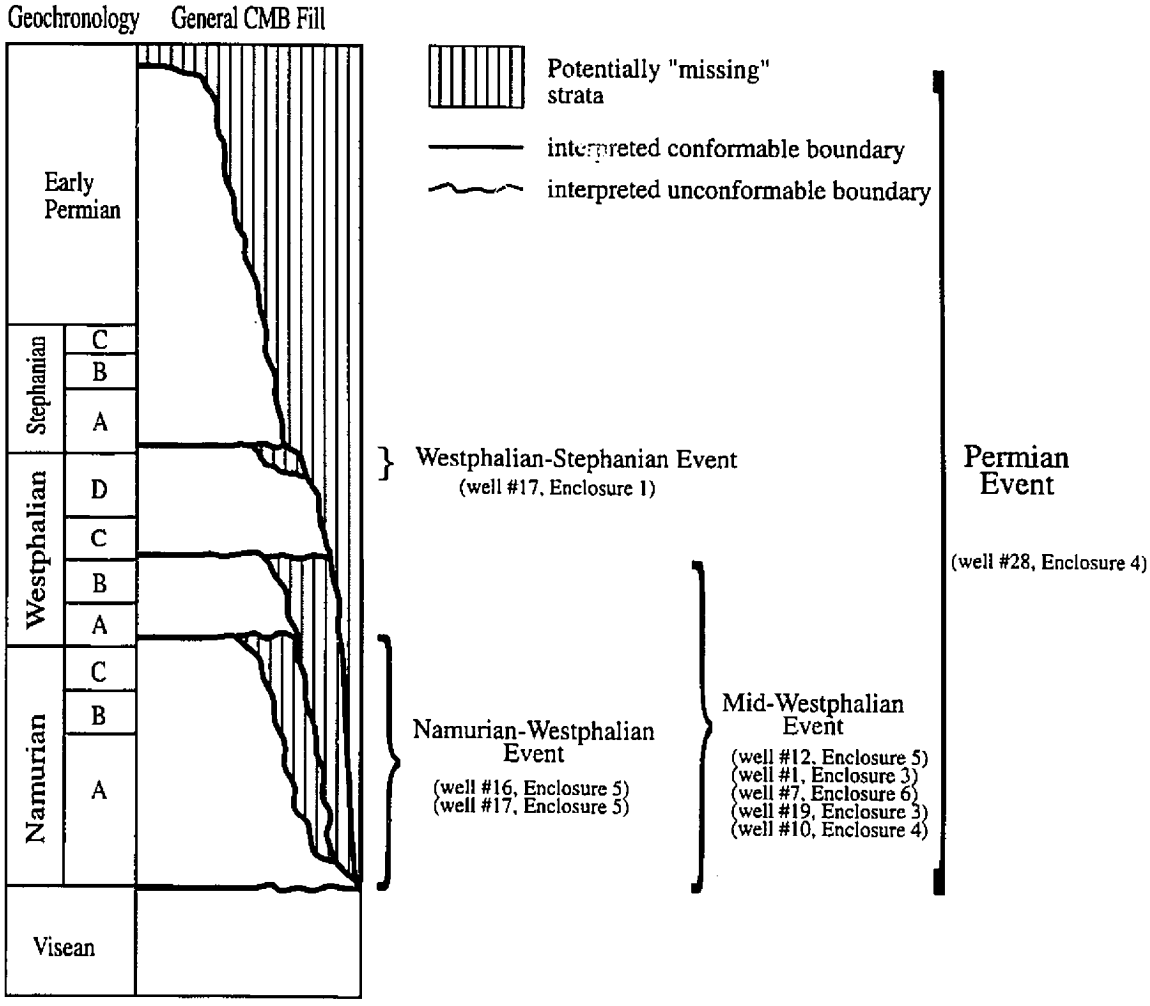



Figure 2.8 Locations and approximate durations of biostratigraphic gaps, or events, identified from the bio/lithostratigraphic correlation cross-sections. Bracketed enclosures and well numbers refer to the data contained in Enclosures 1 to 6 in the back pocket of the thesis.

#19, Enclosure 3) has indications of Early Westphalian C strata overlying Westphalian A strata (Dolby, 1994; Giles, P., 1995, pers. comm.).

All the above examples exhibit biostratigraphic data that clearly suggest that portions of Westphalian A and Early to Middle Westphalian B strata have either been removed by erosion, not deposited or faulted out at these locations. Based on an abrupt lithologic change in these wells, the Mid-Westphalian event is associated with the base of the Bradelle Formation (Figs. 2.6, 2.8).

The uppermost biostratigraphic gap is less obvious than the older ones. Evidence for a time gap across the Stephanian - Westphalian boundary is found in the Bradelle L-49 well (well #17, Enclosure 1) where Stephanian strata lie directly on Late Westphalian C - Early Westphalian D strata (Barss *et al.*, 1979). These data suggest that, at this location, a portion of Westphalian D strata was either eroded, not deposited or faulted (Fig. 2.8). Strict interpretation of the biostratigraphic data, however, suggests that Westphalian D strata are present in almost all the other study wells.

It is important to recognize that the transition from the Westphalian to the Stephanian is associated with the deposition of the Cable Head Formation (Fig. 2.6), a significant coarse-grained redbed sequence that is uniformly distributed across the entire basin. As mentioned previously, redbed successions are commonly barren of palynomorphs, so an erosional event, implied by the Bradelle L-49 well data, may be present at this boundary but has yet to be resolved using current palynostratigraphy. The regional identification of a major unconformity at this surface, using seismic profiles for example, is further frustrated by the typically concordant base of the Cable Head Formation.

An important aspect of the correlations shown in Enclosures 1 to 6 is the inclusion of biostratigraphic information plotted along the well logs. As mentioned previously, the locations of chronostratigraphic boundaries is commonly uncertain in the Maritimes Basin fill. For example, a section of more than 600m in well #12 (Enclosure 2) is broadly dated as Stephanian to Westphalian (Barss *et al.*, 1979), and 1200m of section in well #18 (Enclosure 1) has been identified as Namurian A (Utting, 1984). Well #8 (Enclosure 6)

shows a more average CMB boundary relationship of 400m of section dated as Late to Middle Westphalian C (Dolby, 1994). However, the Westphalian-Namurian boundary is placed at 2428 metres in Well #11 (Enclosure 4). These data indicate that, instead of providing definitive age-depth pairs, most chronostratigraphic boundaries lie within zones of tens to hundreds of metres of strata. As no explicit geologic boundaries can be identified (e.g. Well #12, above), placement of boundaries in many cases must be done through an interpretive process based on a combination of all available data, and not exclusively based on any one set of palynological data.

### 2.3.1.2 CMB Structural Cross-Sections

This section describes structural cross-sections E-E' (Fig. 2.9) and B-B' (Fig. 2.10) which are representative of the sections parallel (Enclosures 11 and 12) and perpendicular (Enclosures 7, 8, 9 and 10) to the basin axis. Section E-E' begins onshore on the New Brunswick Platform and extends 517 km towards the Maritimes Basin depocentre. The B-B' cross-section is 737 km long and begins onshore on the New Brunswick Platform, goes through the Central Maritimes Basin and into the Sydney subbasin. Both cross-sections exhibit six primary features: regionally mappable units, thickening of strata basinward, onlap relationships, erosional truncations, and the development of two units near the depocentre that are not identified elsewhere.

These sections reveal the large areal extent of the subsurface units. Thick (50 - 600 m) stratigraphic units together with their bounding surfaces are correlatable over tens to hundreds of kilometres. On the New Brunswick Platform, the units are generally flat-lying and can be traced considerable distances with minor changes in thickness. In the Central Maritimes Basin, however, the thickness of the units increases over relatively short distances towards the depocentre. Despite the changes in stratigraphic thickness from the platform area towards the depocentre, the units and bounding surfaces are still correlatable and overall are uniformly distributed throughout the basin.

Two depocentres have been identified from the cross-sections. A localized depocentre is identified on cross-section C-C' (Enclosure #9). A solitary study well

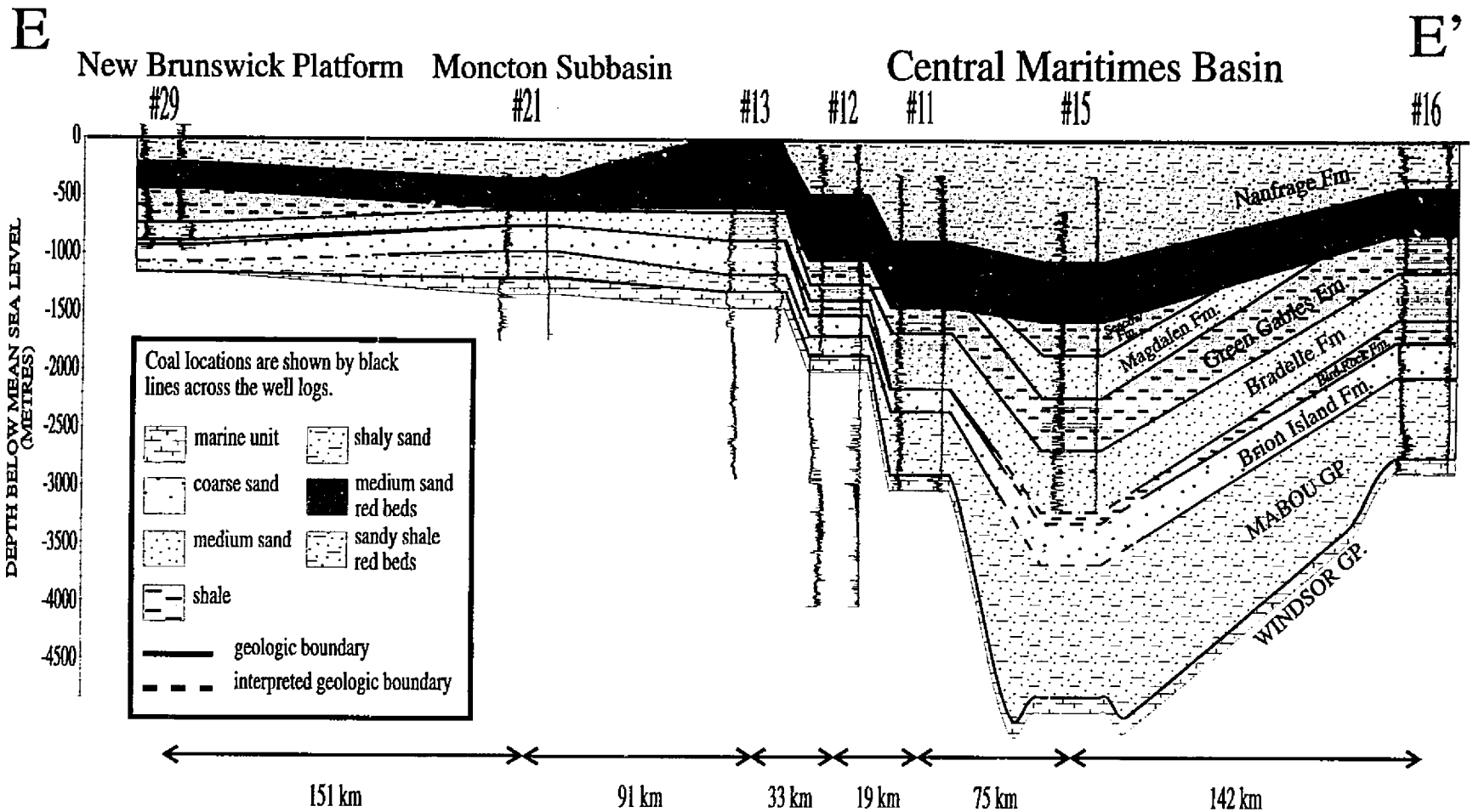



Figure 2.9 CMB structural cross-section E-E' (location shown in Fig. 2.7) was constructed parallel to the main SW-NE basin axis. The cross section shows a thickening of units towards the northeast, erosional truncation of the Magdalen and Seacow formations in the central portion of the section, slight onlap and stratigraphic convergence of most units towards the New Brunswick Platform and the "thinning", or removal, of strata between wells 11 and 21. The section uses a sea level datum.

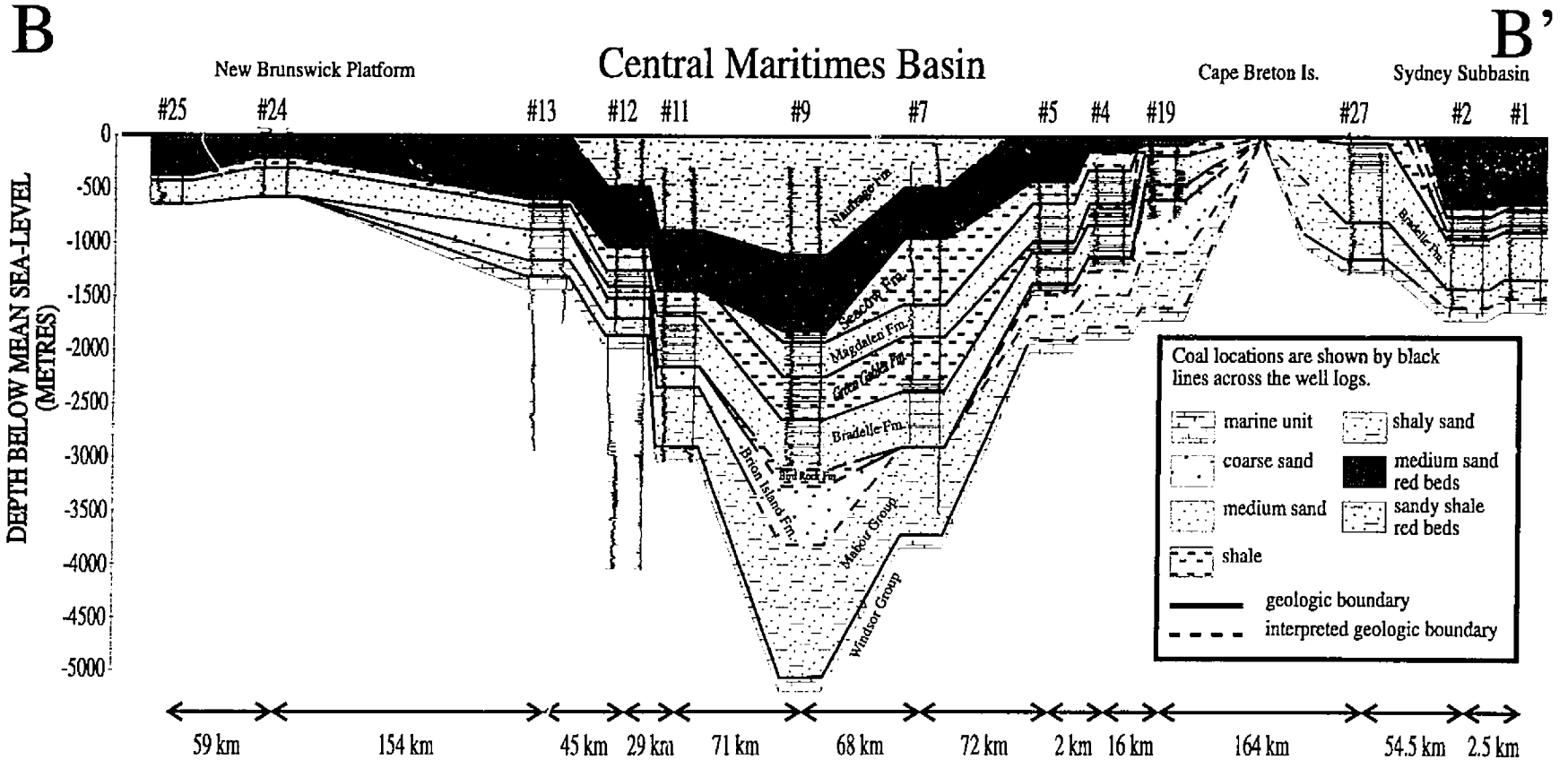



Figure 2.10 Geological cross-section B-B' across the Maritimes Basin (location shown in Fig. 2.7) was constructed perpendicular to the SW-NE oriented basin axis. The stratigraphic units (central part of the section) are interpreted to be regionally mappable lithostratigraphic units. The cross-section suggests erosional truncation of the Magdalen and Seacow formations (between wells #9 and #11), complete removal of the Brion Island and Bird Rock formations (wells #7, #27, #2 and #1), onlap of all units onto the New Brunswick Platform, slight convergence of stratal units towards Cape Breton Island and a substantial thickening of the stratigraphic column from the flanks towards the basin axis. The stratigraphic relationships shown towards Cape Breton Island indicate a local pinching out of strata, however, this need not be true everywhere. Interpreted geologic boundaries are supported by additional geologic and geophysical data. The section uses a sea level datum.

located in the Cumberland subbasin (well #20, Enclosure #9) shows the development of a thick section equivalent to the Brion Island Formation (1430m). Comparison with other well data, where the Brion Island Formation averages 300m in thickness, suggests that the development of such a thick succession is anomalous. On a more regional scale, the area outlined as the depocentre of the Maritimes Basin (Howie and Barss, 1975) is obscured by the presence of extensive evaporite tectonism (Fig. 2.3) (Grant, 1994). The absence of significant well data in this area and problems with interpretations of seismic data (due to the salt) have led to a general uncertainty as to the geologic history of this area (Durling and Marillier, 1993a). The cross-sections show the CMB strata thickening towards the tectonized evaporite zone. The Coal Measures facies mapped by Grant and Moir (1992) have also been identified in this deformed zone (Grant, A., 1996, pers. comm.). The distinct thickening of all upper CMB stratal units towards the tectonized salt zone and the continued presence of the Coal Measures within the deformed zone supports the proposed location (50 km east of the Magdalen Islands) of the regional Maritimes Basin depocentre (Fig. 2.1).

Sections E-E' and B-B' suggest that the Windsor, Mabou, Brion Island and Bird Rock stratigraphic successions eventually onlap the New Brunswick Platform with the overlying Bradelle Formation lying directly on basement at the well #24 location. Strata above the Bird Rock Formation show thinning toward the platform, but any onlapping relationships are outside the limits of the well data. An onlapping relationship like that shown towards the New Brunswick platform is not observed where the same package of strata approaches Cape Breton Island. Instead, the strata that have been penetrated (post Brion Island Formation) show only minor signs of stratigraphic convergence.

Numerous erosional relationships are implied by the cross-sections. On both cross sections E-E' and B-B' a distinctive zone of thinning is shown in wells #13, #12, #11, and #21 (Figs. 2.9 and 2.10) for the Mabou Group, Brion Island, Bird Rock, Bradelle and the Green Gables Formations (Fig 2.6). The thinning of Mabou Group strata in wells #13 and #12 is interpreted to be the result of the Namurian-Westphalian event located at the base of the Brion Island Formation. In the same series of wells, thinning of the

overlying Brion Island and removal of the Bird Rock Formation is interpreted to be the result of the Mid-Westphalian event located stratigraphically at the base of the overlying Bradelle Formation. In wells #7, #2 and #1 (Fig. 2.10) the Brion Island and Bird Rock formations have been completely removed and portions of the upper Mabou Group are missing from the stratigraphic section. This places the Bradelle Formation directly on top of Mabou strata suggesting the merging of the Mid-Westphalian event with the underlying Namurian-Westphalian event. Portions of the Green Gables Formation have been removed in wells #13 and #21 (Fig. 2.9) resulting in a thinner stratigraphic succession. This erosion, which is most obvious on the southwest flanks of the CMB and the New Brunswick Platform, is interpreted to be the result of the Stephanian-Westphalian event, located at the base of the overlying Cable Head Formation.

Two stratigraphic units have been identified that were developed primarily in the offshore portion of the Maritimes Basin: the Magdalen and Seacow formations (Fig. 2.6). Distribution of both units is presently restricted to the southeast-northeast quadrants of the Central Maritimes Basin in an area broadly bordered by northern P.E.I., the Magdalen Islands and the western coast of Cape Breton Island. Identification of the units is easiest in areas closest to the basin axis and depocentre (Fig. 2.1); however, both stratigraphic units have been *tentatively* identified in the Sydney subbasin (wells #1 and #2; Fig. 2.10). The Magdalen and Seacow formations have either been erosionally truncated in the south-southwest by the Stephanian-Westphalian event or may pinch out between the overlying Cable Head and underlying Green Gables Formations.

### 2.3.2 Seismic Stratigraphic Analysis

Seismic interpretation indicates that the Central Maritimes Basin fill is cyclic in nature. Several typical lines (Fig. 2.11) have been chosen to demonstrate that the offshore basin fill consists of four primary seismo-stratigraphic packages constrained by four regionally identifiable seismic sequence boundaries (Fig. 2.12). Within this regional framework, and on a relatively smaller scale, four seismic sub-sequence boundaries have been identified which bound five distinctive seismo-stratigraphic sub-packages. The

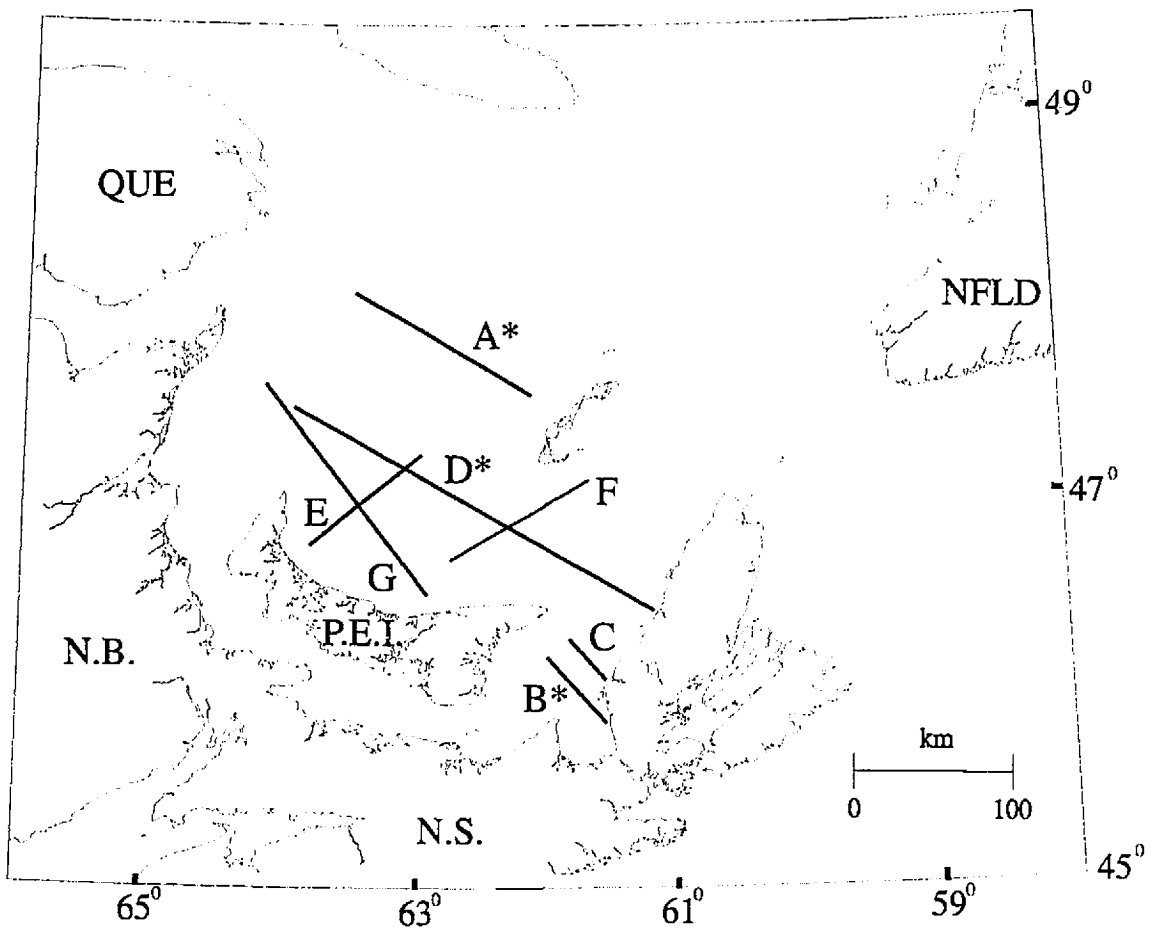



Figure 2.11 Location map of representative seismic lines used for illustrating the Central Maritimes Basin fill. Those lines containing designated CMB seismo-stratigraphic type sections are marked with asterisks (*).

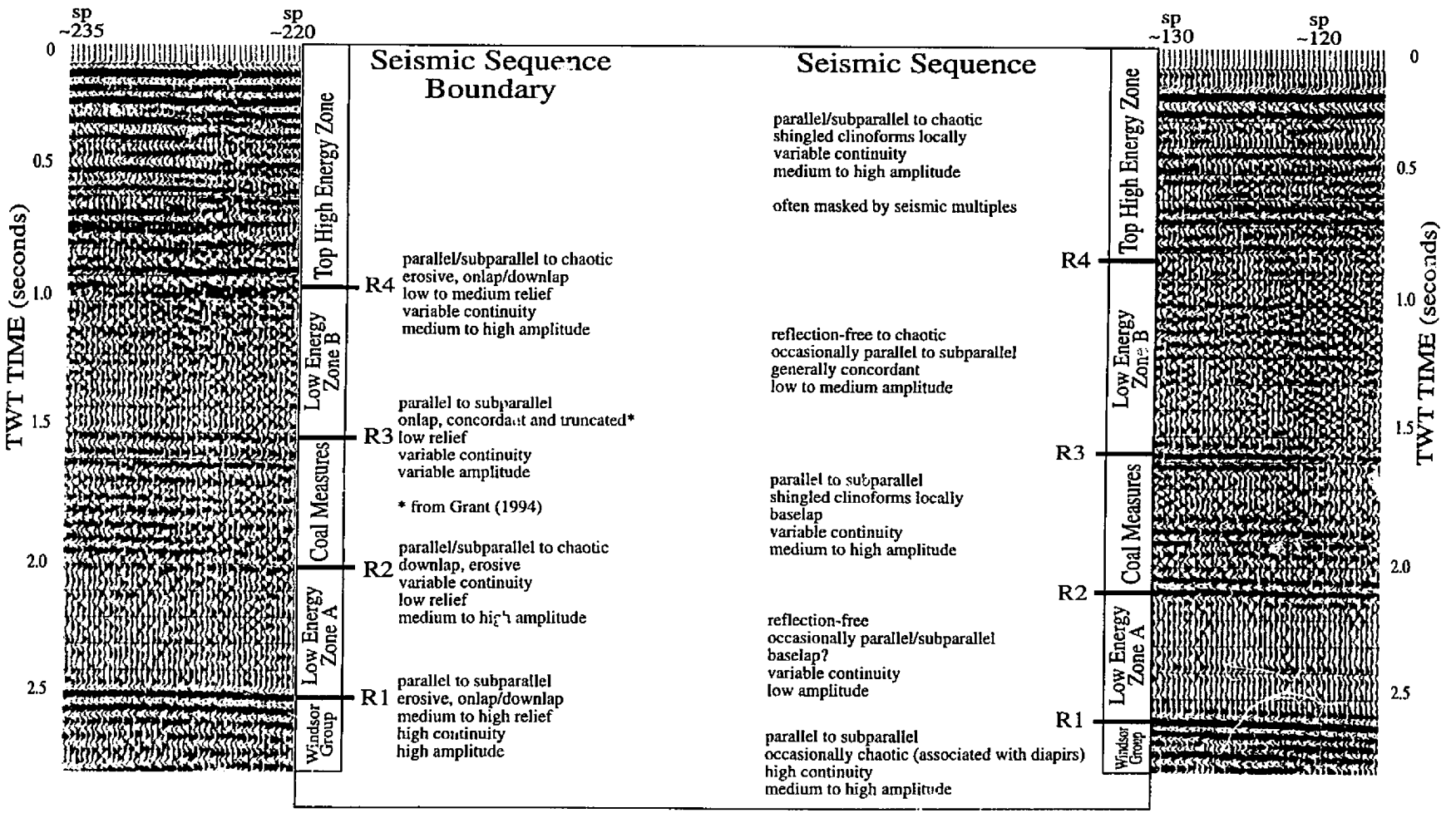



Figure 2.12 Type section of seismo-stratigraphic units and major seismic sequence boundaries identified in the CMB. Both units (right side) and boundaries (left side) are outlined with their seismic characteristics identified. Seismic sections shown are from Figure 2.13 (top): the original seismic section was modified, by removing the middle portion, to demonstrate the variability of the reflectors over short distances.

following sections will first define the characteristics of the seismic sequence boundaries, followed by a facies description of the seismo-stratigraphic sequences.

### 2.3.2.1 Primary Boundaries and Sequences

The seismic sequence analysis focused almost exclusively on the post-Windsor Group stratigraphic section preserved in the CMB. Pre-Mabou Group strata will be only briefly discussed.

The fill of the Maritimes Basin lies unconformably on deformed Precambrian to Devonian rocks (St. Peter, 1993). The seismic character of the boundary that separates the sediments from the metamorphic terrane is highly variable and at times unresolvable on seismic profiles (Grant, A., 1995, pers. comm.). Durling and Marillier (1993b) interpreted the boundary at the point where there is an abrupt change from the discordant reflections of the fill to the chaotic reflections of the basement. Locally the boundary displays erosional truncations, with clear angular relationships between the basal Maritime Basin reflectors and the chaotic basement reflectors (Durling and Marillier, 1993b). Lying above this seismic boundary is the Horton/Fountain Lake Group equivalent seismo-stratigraphic package.

An easily identified seismic sequence boundary is associated with the base of the overlying Windsor Group. The boundary is strongly continuous, low relief in nature and has a very high amplitude. The sequence boundary displays baselap relationships with the underlying seismic stratigraphic packages and the basement (Soquip, 1987). Locally the sequence boundary erosionally truncates the underlying sedimentary fill (Durling and Marillier, 1993b).

#### R1

On the seismic lines used for this study, the most easily identified boundary is seismic sequence boundary R1 (Figs. 2.12, 2.13). R1 is associated with the top of the Windsor Group seismo-stratigraphic succession and is a highly continuous reflector that generally displays low relief. However, the relief of R1 increases in proximity to

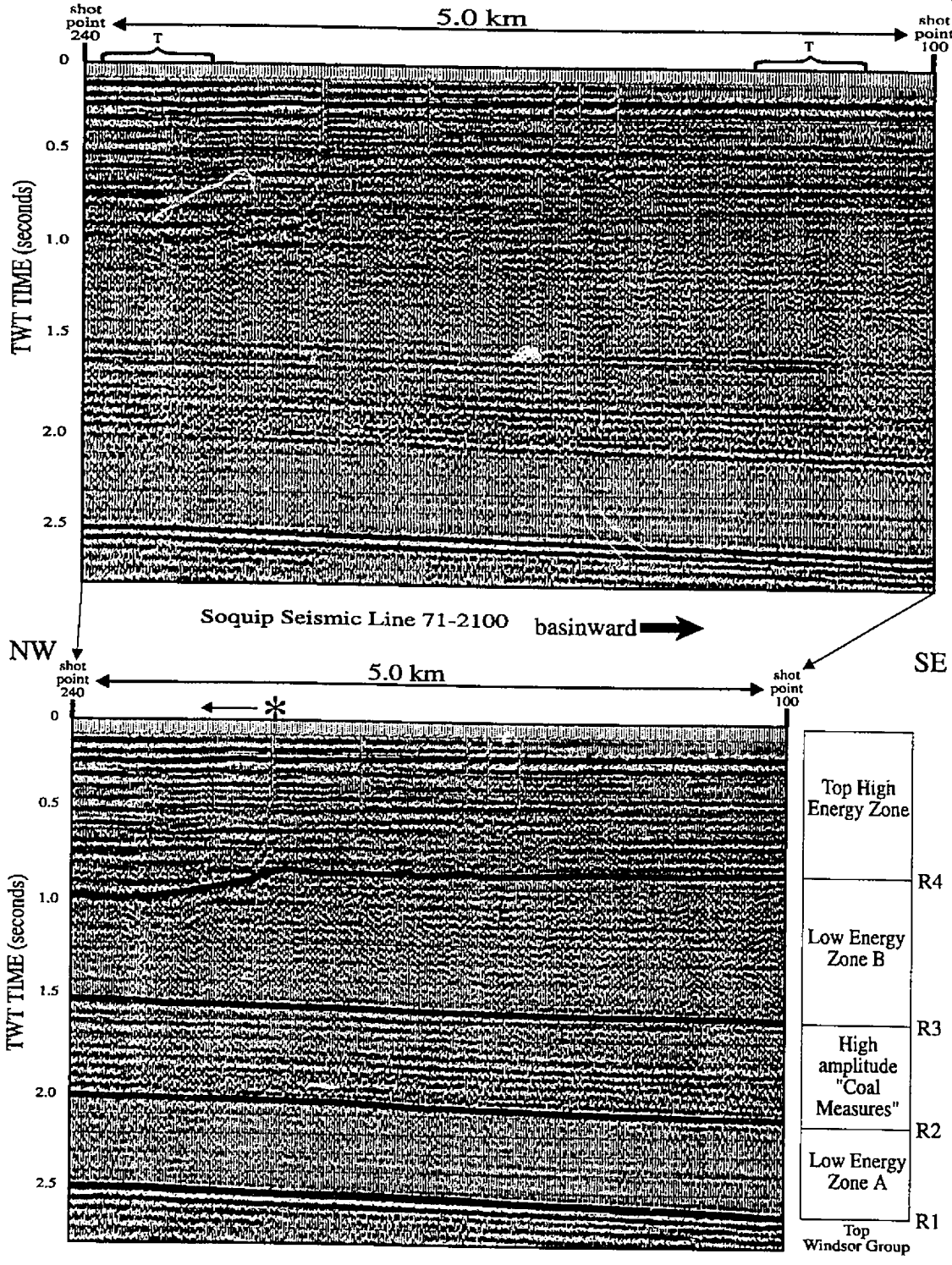



Figure 2.13 (Top) Uninterpreted record Soquip line 71-2100 (line A, Fig. 2.11). (Bottom) Interpretation, showing the primary seismic sequence boundaries and seismo-stratigraphic packages that are commonly identified in the cyclic CMB fill. At the R4 reflector level, an erosive channel scour is interpreted. The scour extends from shot point 240 to the "star" symbol and is based on a change in amplitude and dip of reflections. The locations of the Figure 2.12 seismic records are indicated by "T"s.

Windsor Group salt structures. The R1 sequence boundary is overlain by the Low Energy Zone (LEZ) A seismic sequence, which is in turn bounded above by seismic sequence boundary R2.

**R2**

The R2 sequence boundary (Figs. 2.12, 2.13) is easily identified due to the large contrast in acoustic impedance between the underlying LEZ A and the overlying high energy Coal Measures seismic sequence. R2 exhibits erosive as well as downlapping relationships with the underlying low energy seismo-stratigraphic package.

**R3**

R3 is the upper boundary of the Coal Measures seismic sequence (Figs. 2.12, 2.13). This boundary is often hard to place precisely due to highly variable continuity; it is usually picked at the level of the most significant seismic character change between the underlying Coal Measures and the overlying Low Energy Zone B (LEZ B) seismic sequence. The boundary between these units was mapped over an area of approximately 66 000 $km^2$ by Grant and Moir (1992). It is highly variable in amplitude and exhibits onlapping, concordant and truncated relationships with the underlying seismic successions (Grant, 1994).

**R4**

The stratigraphically youngest sequence boundary identified is R4 which is the basal boundary of the Top High Energy Zone seismo-stratigraphic unit (Figs. 2.12, 2.13). Relief on the R4 boundary varies between low to medium and is commonly associated with erosional scours and truncations. The R4 boundary exhibits a baselapping relationship with the underlying seismo-stratigraphic packages towards the basin flanks.

The mapping of each seismic sequence boundary was not the objective of this analysis, however, the seismic data analyzed show that the four primary CMB seismic sequences and their boundaries are regionally mappable features. Oriented perpendicular

to the basin axis (Fig. 2.14), LITHOPROBE line 86-1 demonstrates that sequence boundaries can be recognized laterally over distances of more than 150km. Seismic line ST-82-02 (Fig. 2.15), at right angles to the LITHOPROBE line, shows that the seismic sequence boundaries and sequences also extend in opposite directions, implying that individual sequence boundaries and the sequences they bound extend for hundreds of kilometres in all directions. On all lines studied, the primary sequence boundaries and sequences onlap the New Brunswick Platform and are generally parallel with increasing depth towards the zone of Windsor Group salt tectonism (Fig 2.3).

### 2.3.2.2 Sub-Boundaries and Sub-Sequences

The process of dividing the seismic sections into discrete packages of genetically related reflectors resulted in the identification of a series of sequence boundaries and sequences contained within the primary cyclic fill described in the above section. Figure 2.16 places four sub-sequence boundaries in a stratigraphic context within the primary seismo-stratigraphic framework. In contrast to the primary boundaries and sequences, the series of sub-sequence boundaries and sub-sequences tend to be regionally less extensive, however, they do display a range of relationships similar to the primary boundaries and sequences.

Sub-sequence boundaries R2a and R2b (Figs. 2.16, 2.17) are identified near the western coast of Cape Breton Island where a thick section of post-Windsor Group strata overlies the basal R1 sequence boundary. In this area the stratigraphic succession is expanded, allowing the identification of distinct sub-boundaries and sub-sequences between primary boundaries R2 and R3.

Seismic data in this area indicate that the primary R2 boundary is overlain by a LOWER Coal Measures seismic sub-sequence (Figs. 2.16, 2.17). Defining the top of this sub-sequence is sub-sequence boundary R2a, which is a low relief reflector that displays potential baselapping relationships. Lying directly above the R2a boundary is Low Energy Zone A1 (LEZ A1). The interpreted top of this sequence is sub-sequence boundary R2b, which is locally hard to place precisely due to highly variable continuity.

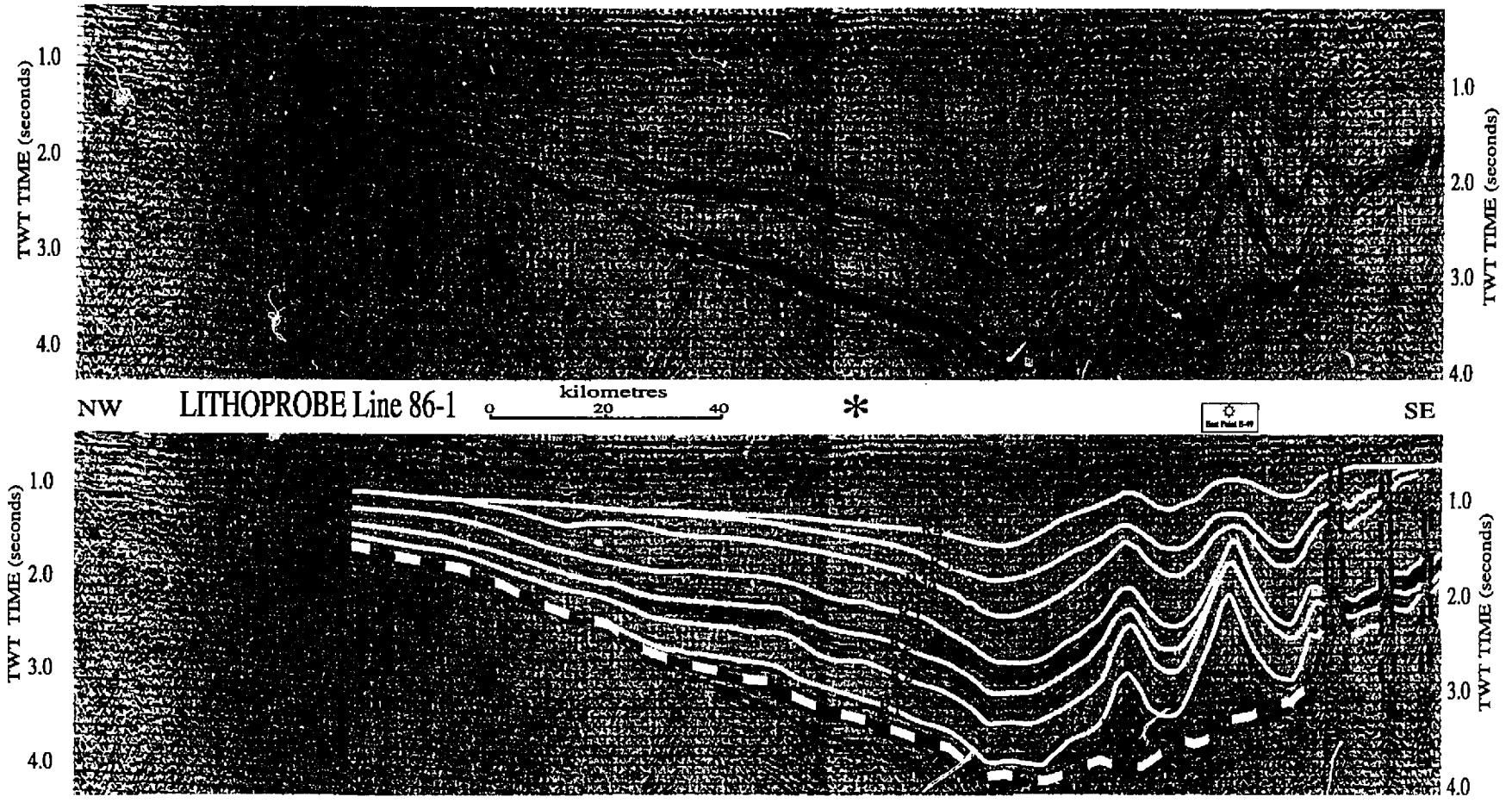



Figure 2.14 (Top) Uninterpreted LITHOPROBE seismic line 86-1 (line D, Fig. 2.11) showing that, apart from salt tectonism, the CMB Late Carboniferous basin fill is essentially undeformed. (Bottom) Interpreted seismic record showing the regional extent of the primary seismic sequence boundaries and the seismo-stratigrapahic packages identified in the CMB fill. The sequence boundaries suggest an onlapping relationship with the New Brunswick Platform to the NW and slight stratigraphic convergence toward Cape Breton Island (SE). Seismic sequence boundaries 3a and 3b are areally restricted to the right hand portion of the seismic record and are then truncated by reflection R4 near the middle of the panel. Windsor Group salt tectonism in the form of salt pillows and diapirs is evident on bottom right side of the record. Vertical scale near the basin axis is approximately 8-9 km. Tie point location for line ST-82-02 is shown with an asterisk(*). The seismic record has been horizontally compressed and is "warped" as a result of the scanning and digitizing process.

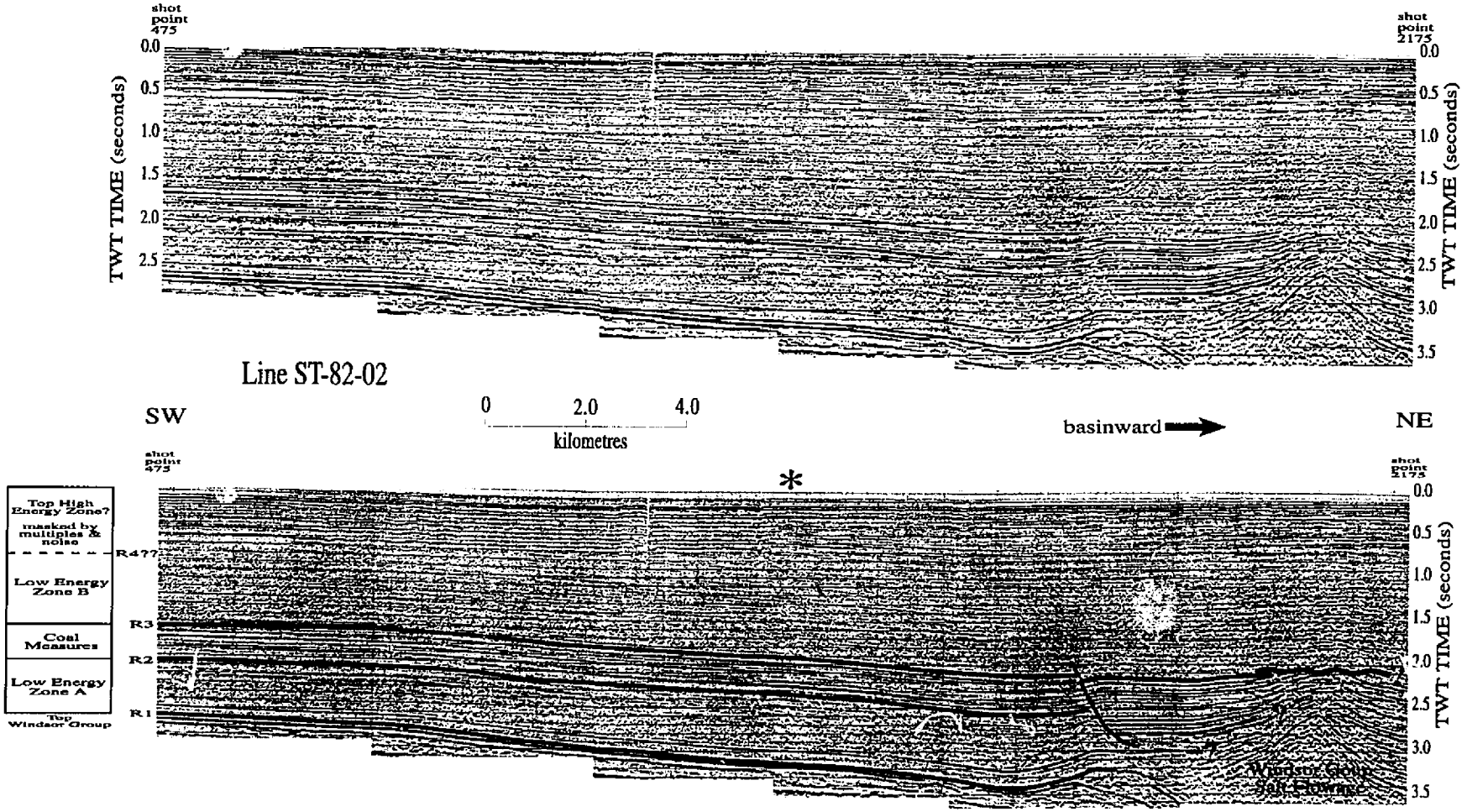



Figure 2.15 (Top) Uninterpreted G.S.L. seismic line ST-82-02 (line F, Fig. 2.11) showing the relatively undeformed nature of the CMB fill parallel to the basin axis (SW-NE). (Bottom) The primary sequence boundaries and sequences contained in the CMB fill are identified. The basin fill is thickening towards the NE, where there are indications of salt tectonism as the seismic line approaches the Windsor Group salt flowage zone (as shown on Fig. 2.3) Tie point location for line 86-1 is shown with an asterisk (*).

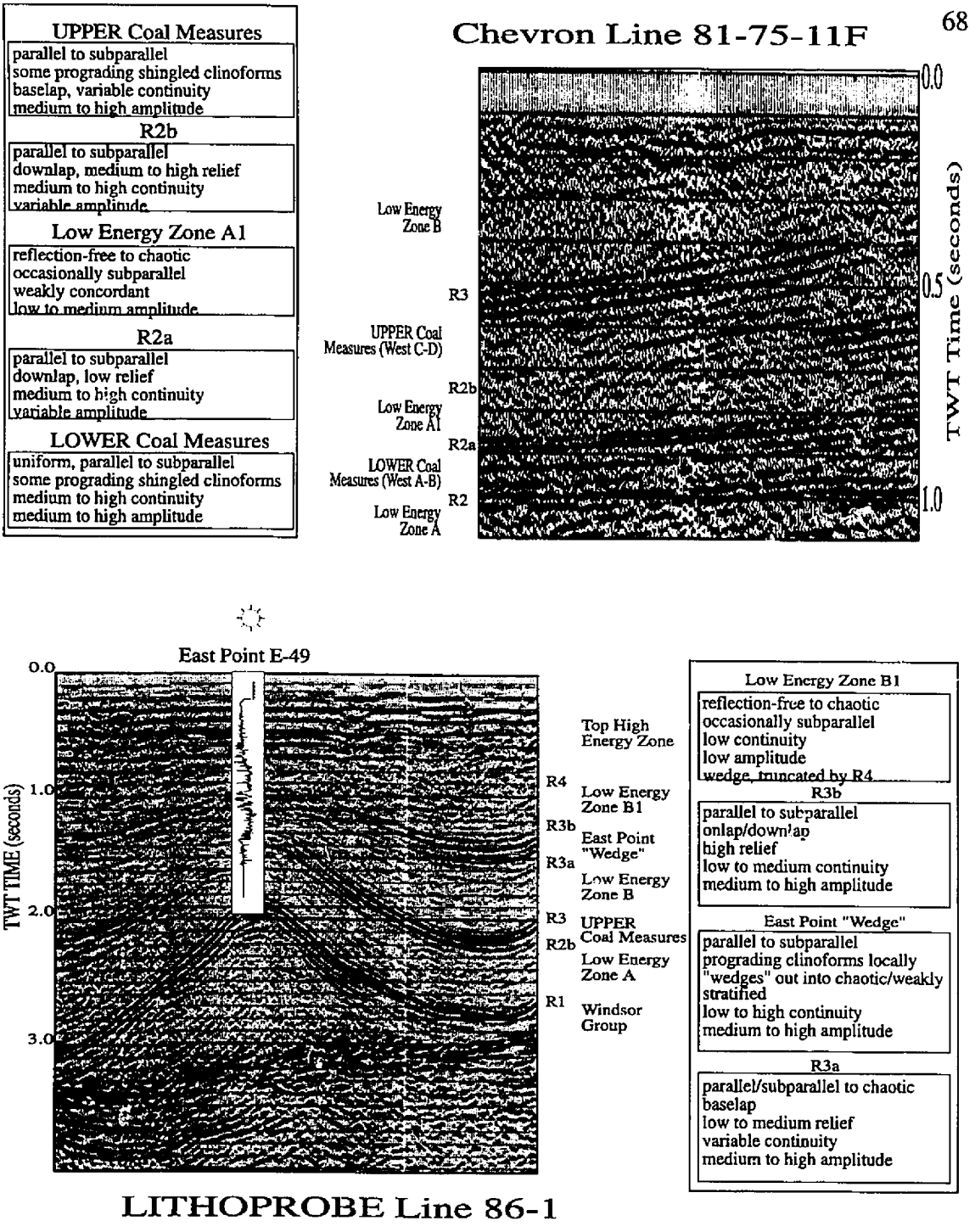



Figure 2.16 Type sections for seismic sub-sequence boundaries and seismo-stratigraphic sub-sequences identified in the Central Maritimes Basin with seismic characteristics displayed. (Top) Three seismic sub-sequences (LOWER Coal Measures, Low Energy Zone A1 (LEZ A1), and UPPER Coal Measures) and two sub-sequence boundaries (R2a and R2b) interpreted within the primary Coal Measures seismic sequence in the Central Maritimes Basin (SE end of line B, Fig. 2,11). (Bottom) Portion of Line 86-1 (Fig. 2.14) through the East Point E-49 well site (with SP log) showing two seismo-stratigraphic sub-units (East Point "Wedge" and Low Energy Zone B1, LEZ B1) and two seismic subsequence boundaries (R3a and R3b) which have been identified only in the south-southeastern portions of the Central Maritimes Basin. Refer to Figures 2.17 and 2.18 for approximate horizontal scales.

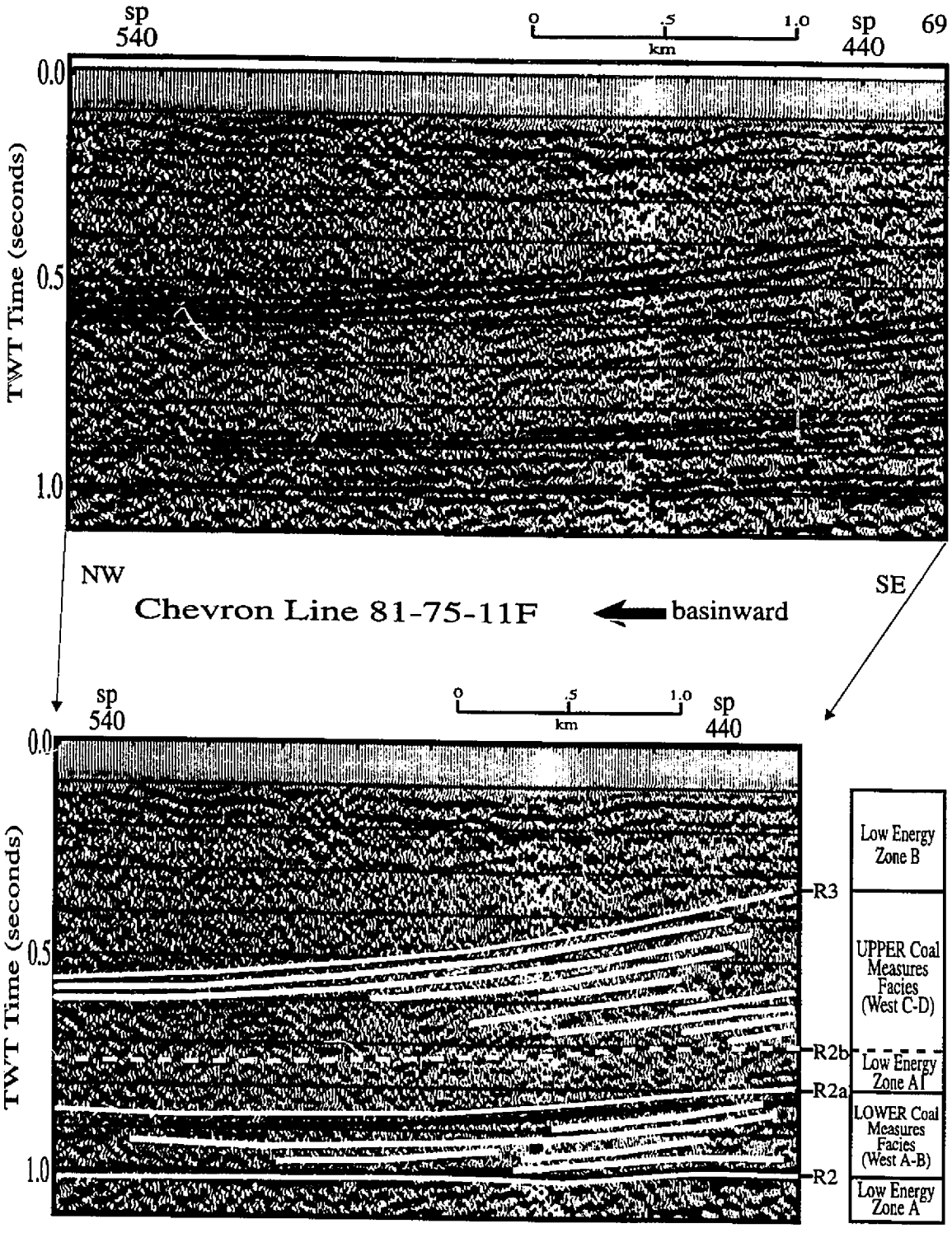



Figure 2.17 (Top) Uninterpreted Chevron seismic line 81-75-11F (SE end of line B, Fig. 2.11). (Bottom) Interpreted seismic record showing the identification of two major reflectors (R2a and R2b) between primary seismic sequence boundaries R2 and R3. The two zones of high energy reflectors (LOWER and UPPER Coal Measures) are separated by a lower energy zone (LEZ A1); the three zones are collectively known as the primary Coal Measures seismo-stratigraphic unit in the CMB. From the right, reflectors within the UPPER Coal Measures seismic sub-sequence are shown prograding basinward (NW).

R2b is usually placed at the level of the most significant seismic character change between the underlying LEZ A1 and the overlying UPPER Coal Measures seismic sequence, however, where reflectors of the UPPER Coal Measures are strongly prograding (Fig. 2.17) the boundary is interpreted at the terminus of the downlapping reflectors. The R2b boundary is typically a medium to highly continuous reflector that displays variable amplitudes and locally shows a strong downlapping relationship with the underlying seismo-stratigraphic packages. In the vicinity of the East Point E-49 well (Fig. 2.3) the R2b sub-sequence boundary, interpreted on LITHOPROBE line 86-1 (Fig. 2.14), truncates the R2a sub-sequence boundary and both the LEZ A1 and LOWER Coal Measures seismic sub-sequences. This relationship results in the UPPER Coal Measures directly overlying the LEZ A seismic sequence, suggesting a local merger between the R2b seismic sub-sequence and the primary R2 seismic sequence boundary (Fig. 2.16).

Biostratigraphic control indicates that the LOWER and UPPER Coal Measures seismo-stratigraphic units are approximately Westphalian A to B and C to D in age, respectively. The primary Coal Measures seismic sequence is generally of the same ages in the CMB further offshore. Based on the well data, this suggests that the sub-boundaries and sub-sequences are present in the greater CMB but are collectively grouped in the primary Coal Measures seismic stratigraphic unit (Fig. 2.12). The sub-sequences and sub-boundaries further offshore are difficult to resolve in a substantially thinner stratigraphic succession.

Sub-Sequence boundaries R3a and R3b were identified between primary boundaries R3 and R4 (Figs. 2.16, 2.18) in the vicinity of the East Point E-49 well. Slightly more regional in nature than R2a and R2b, R3a and R3b are distributed in close proximity to the main basin axis (Fig. 2.14) and display convergence to the southeast towards Cape Breton Island. Collectively, boundaries R3a, R3b and R4 define a "wedge" of seismo-stratigraphic packages. R3a and R3b, respectively, define the bottom and top sequence boundaries of the East Point Wedge seismo-stratigraphic succession (Fig. 2.16). Stratigraphically highest, the Low Energy Zone B1 (LEZ B1) seismic sequence is defined by the R3b and R4 sequence boundaries on the bottom and top, respectively. Primary

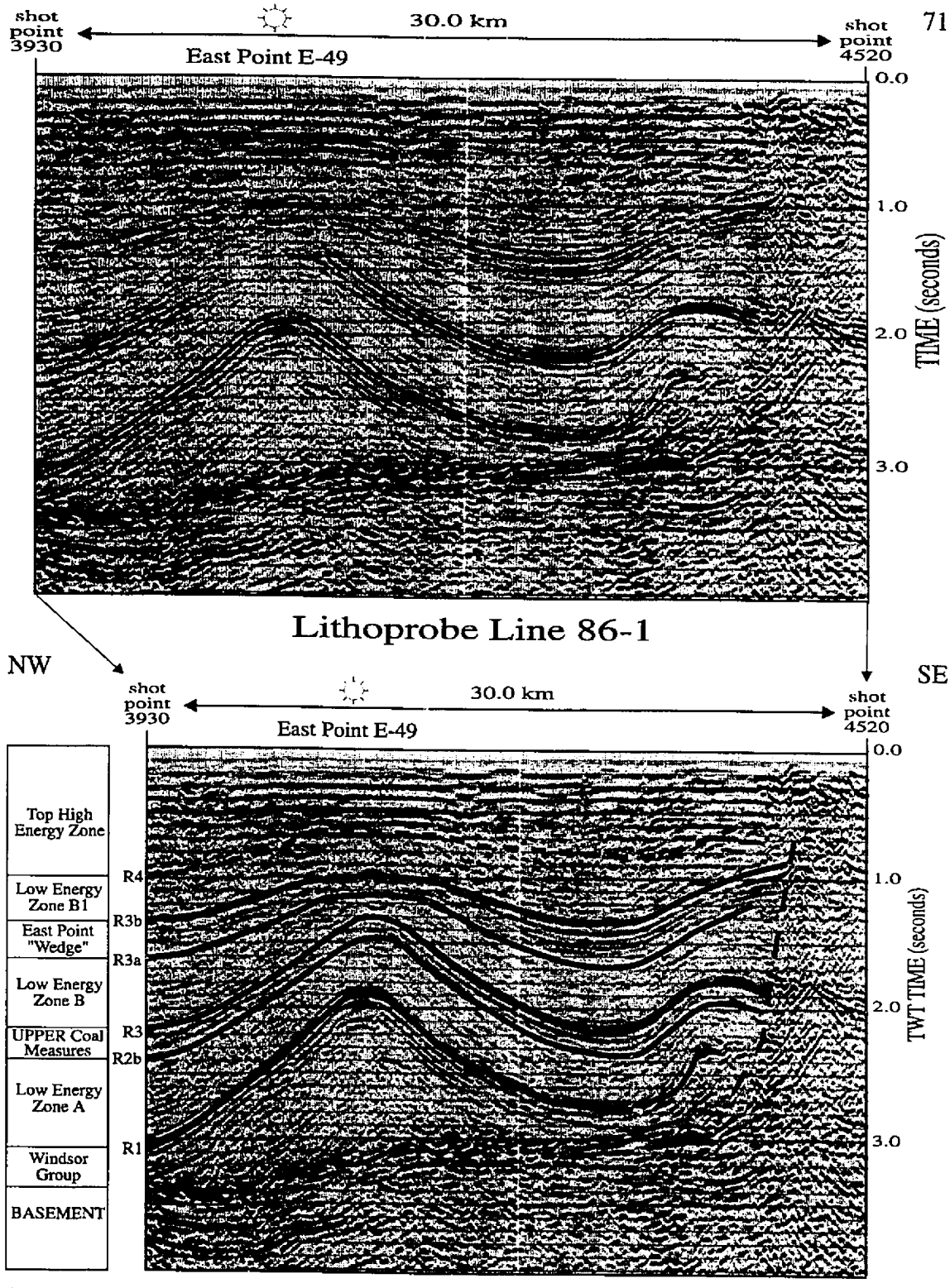



Figure 2.18 (Top) A portion of Line 86-1 (Fig. 2.14) through the East Point E-49 well site. (Bottom) Seismo-stratigraphic packages (East Point Wedge and LEZ B1) and seismic boundaries (R3a and R3b) identified above the East Point salt structure.

boundary R4 is interpreted to erosionally truncate two sub-sequence boundaries (R3a, R3b) and the two seismic sub-sequences (East Point Wedge and Low energy zone B1) in the south-southwestern quadrant of the CMB (left sideFig. 2.14) based on the apparent convergence of the sub-sequence boundaries with the subparallel R4 boundary. In most cases, primary boundaries R4 and R3 constitute the top and bottom surfaces of the LEZ B (Fig. 2.14) seismic sequence; however, near the central portion of the basin, sub-sequence boundary R3a constrains the top (Fig. 2.14).

**2.3.2.3 Facies Analysis of Primary Seismic Sequences**

The Horton/Fountain Lake Group seismo-stratigraphic unit lies at the base of the CMB seismic stratigraphic column and is bounded by the basement-sedimentary rock interface and the basal Windsor Group reflector. This seismic unit consists of continuous to discontinuous reflectors that have low to medium amplitudes. The reflections are commonly parallel to slightly subparallel and are undeformed unless associated with faulted areas (Durling and Marillier, 1993b). The succession commonly exhibits a seismic signal similar to the overlying Windsor Group seismo-stratigraphic unit and locally contains a volcanic succession near the top of the section which tends to be high in amplitude (Durling and Marillier, 1993b).

A succession identified with the Windsor Group overlies the Horton/Fountain Lake Group sequence, and is bounded by the basal Windsor Group and primary R1 boundaries. This seismo-stratigraphic package has highly continuous reflectors with medium to high amplitudes (Fig. 2.12). Reflectors commonly display parallel to subparallel configurations, however, the Windsor Group reflections become chaotic where they are associated with salt tectonism (bottom right side of Figs. 2.14, 2.15).

The first of four low-energy seismic sequences in the post-Windsor Group CMB fill overlies the R1 sequence boundary (Fig. 2.12). LEZ A has a dominantly reflector-free character, although some parallel to subparallel reflectors are present which show extremely variable continuity and very low amplitudes. When present, the reflectors suggest potential baselap relationships with the primary R1 boundary.

The CMB Coal Measures seismic sequence is defined by the R2 and R3 primary reflectors (Fig. 2.12). This stratigraphic package has been mapped over much of the Gulf of St. Lawrence by Grant and Moir (1992). The sequence has parallel to subparallel reflectors that display variable continuity. The reflectors exhibit baselapping relationships with the R2 boundary and prograding shingled clinoform configurations have been identified (Fig. 2.19).

LEZ B overlies the Coal Measures seismo-stratigraphic package (Fig. 2.12). This low-energy succession is dominantly reflection-free to chaotic in seismic character. Similar to underlying LEZ A, LEZ B locally has low amplitude, parallel to subparallel reflectors that are generally concordant.

The Top High Energy Zone seismic sequence is the stratigraphically youngest unit in the CMB seismo-stratigraphic column (Fig. 2.12). Bounded at the base by primary sequence boundary R4, this sequence has medium to high amplitude reflectors. Reflector configuration ranges from parallel to subparallel reflectors with some entirely chaotic zones. Some prograding clinoforms can be identified. This upper seismic unit is commonly masked by seismic multiples.

#### 2.3.2.4 Facies Analysis of Sub-Sequences

Three seismic sub-sequences have been identified between the primary sequence boundaries R2 and R3 and within the Coal Measures seismo-stratigraphic unit (Fig. 2.16). The LOWER Coal Measures seismo-stratigraphic succession is bounded at the bottom by R2 and at the top by R2a. Reflectors within the sequence commonly display uniform parallel to subparallel geometries. Prograding clinoforms are locally present in the sequence. As mentioned previously, biostratigraphic data indicate a Westphalian A to B age for this sequence.

LEZ A1 lies directly above sub-sequence boundary R2a (Fig. 2.16). This seismic sequence is characteristically reflection-free, however chaotic reflections to subparallel reflectors are locally present and show concordance with the underlying R2a boundary.

The UPPER Coal Measures seismo-stratigraphic sequence typically overlies LEZ

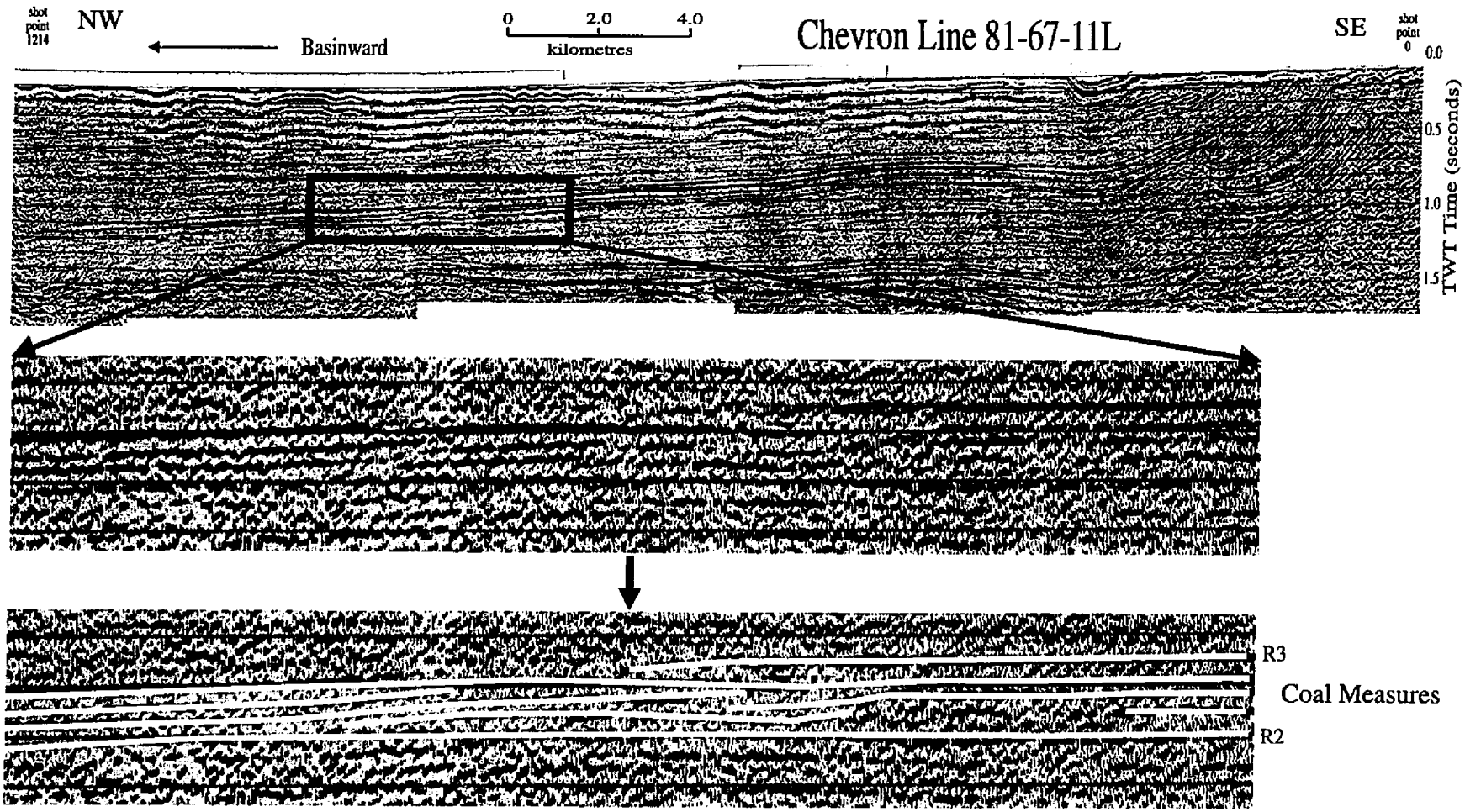



Figure 2.19 (Top) Uninterpreted Chevron seismic line 81-67-11L (line C, Fig. 2.11). (Middle) An enlarged section of the primary Coal Measure seismo-stratigraphic package. (Bottom) Enlarged section showing the interpreted prograding/shingled nature of the Coal Measures reflections basinward (NW). The Coal Measures seismo-stratigraphic unit is bounded by primary reflectors R2 and R3.

A1 with the R2b seismic sequence boundary separating the two sequences (Fig. 2.17), however, as mentioned above, the UPPER Coal Measures sequence directly overlies the primary LEZ A sequence in the vicinity of the East Point E-49 well (Fig 2.14, 2.16). Reflectors in the UPPER Coal Measures sequence are commonly parallel to subparallel in geometry and locally display baselapping relationships with the underlying sequence boundary. There is convincing evidence for prograding clinoforms within the unit (Fig. 2.17). Biostratigraphic data suggest a Westphalian C to D age for this seismo-stratigraphic unit.

The wedge of seismo-stratigraphic units in the south-central portion of the CMB contains the East Point Wedge, bounded on the top and bottom by the R3b and R3a sub-sequence boundaries, and the LEZ B1 seismic sub-sequence bounded by R3b and R4 on the bottom and top, respectively (Fig. 2.16). Reflectors within the East Point Wedge sequence appear to be uniformly parallel to subparallel near the basin axis but change laterally from subparallel reflectors to chaotic reflection geometries toward the basin flank (Fig. 2.14). Some prograding clinoforms have been identified within the sequence. The overlying LEZ B1 seismic sub-sequence is characterized by reflection-free and chaotic reflection zones. The sequence locally has some subparallel, low amplitude reflectors.

### 2.3.3 Seismo/Lithostratigraphic Relationships

The construction of synthetic seismograms, which assisted in the conversion of welldata depths to time, established strong correlations between the seismo-stratigraphy and lithostratigraphy (Fig. 2.20). The most obvious features of this correlation are the direct relationships between low and high seismic energy zones and the corresponding fine- and coarse-grained lithostratigraphic units. It was found that Low Energy Zones (A, B and B1 seismic sequences) are the stratigraphic equivalents of the dominantly fine-grained Mabou, Green Gables and Seacow stratigraphic successions. In the absence of a direct seismic tie, the association of low energy seismic sequences with finer grained lithostratigraphic sequences suggests that LEZ A1 (Fig. 2.17), situated between the

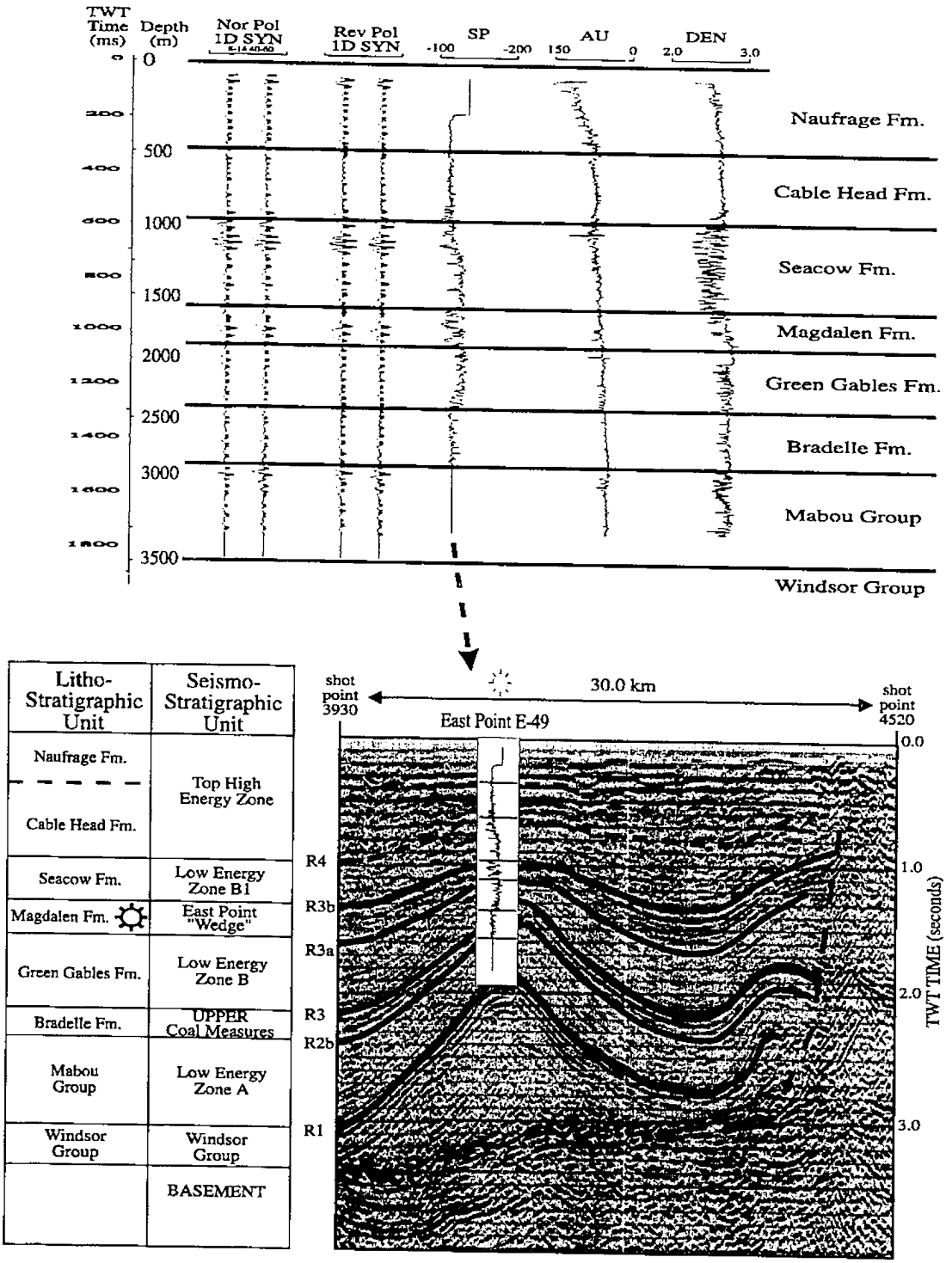



Figure 2.20 (Top) Typical synthetic seismogram produced from the convolution of sonic/density well logs and a Ricker seismic wavelet. (Bottom) A synthetic well tie from East Point E-49 (Fig. 2.3) to LITHOPROBE seismic line 86-1 (line D, Fig. 2.11) suggests a strong correlation between seismo-stratigraphic units and lithostratigraphic units (defined in the preceding text). The well log shown is the time-scaled Spontaneous Potential (SP) log taken from the above synthetic seismogram. The gas bearing sands discovered in East Point E-49 are indicated with the gas well symbol.

UPPER and LOWER Coal Measures sequences, would be the stratigraphic equivalent of the Bird Rock Formation.

The correlations between the well and seismic data further show stratigraphic equivalence between the Bradelle Formation and upper part of the primary Coal Measures seismic sequence (UPPER Coal Measures seismic sub-sequence), the Magdalen Formation and the East Point Wedge seismic sub-sequence, and the collective Cable Head/Naufrage formations with the primary Top High Energy Zone seismic sequence. The problem of differentiating the Cable Head and Naufrage formations associated with the upper energy zone seismic sequence, is believed to reflect inherent problems with seismic data close to the surface. In the absence of a direct well tie, the relationship between high energy seismic sequences and coarser grained lithostratigraphic units implies that the LOWER Coal Measures seismic sub-sequences (Fig. 2.16), which in the central CMB are identified collectively as the Coal Measures (Fig. 2.12), is approximately equivalent to the Brion Island Formation.

### 2.3.4 Central Maritimes Basin Stratigraphic Nomenclature

The cross-sections and seismic data used for this study show that the regional depocentre for the Maritimes Basin lies offshore in what has been defined as the Central Maritimes Basin. The seismic and well data together show that a large portion of the CMB fill is composed of thick, regionally extensive blankets of strata which, apart from salt flowage, are relatively undeformed (Figs. 2.14, 2.15). Thus, the offshore Central Maritimes Basin contains the most complete record of stratigraphic development in the Maritimes Basin.

The identification of regionally correlatable lithostratigraphic/biostratigraphic units, tied to regionally correlatable seismic sequences has led to the development of the stratigraphic framework presented here. Based on geologic criteria for subdividing the Maritimes Basin Carboniferous strata onshore (Ryan and Boehner, 1994) (Table 2.5, 2.6), the CMB contains Horton, Windsor, Mabou, Cumberland and Pictou Group equivalents (Fig. 2.6). Based on age, lithology and the obvious contact relationships with the

Table 2.5 General lithologic criteria for onshore group level classification in the Maritimes Basin (from Ryan and Boehner, 1994).

| | Age | Dominant Lithology |
|---|---|---|
| **PICTOU GROUP** | Westphalian D to Permian | Predominantly fine-grained redbeds with rare conglomerates and coals. |
| **CUMBERLAND GROUP** | Westphalian A to D | Predominantly grey sandstones, conglomerates and shales, coals are common. |
| **MABOU GROUP** | Late Visean to Late Namurian | Red and grey fine-grained clastics with minor lacustrine limestones |
| **WINDSOR GROUP** | Visean | Marine carbonates, fine-grained clastics and evaporites |
| **HORTON GROUP** | Tournaisian | Red and grey sandstones conglomerates and shales, minor lacustrine limestones volcanics |

Table 2.6 Lithologic criteria used for defining the Cumberland and Pictou Groups (modified from Ryan *et al.*, 1991).

| **Criteria** | **Cumberland Group** | **Pictou Group** |
|---|---|---|
| Coal Bearing | generally but not always | locally |
| Red lithofacies: | subordinate | dominant |
| Grey lithofacies: | dominant | subordinate |
| Conglomerate: | locally abundant | locally present |
| Fine lithofacies: | subordinate-subequal | subordinate-subequal |
| Lateral variation: | rapid, diverse | limited |
| Contacts: | conformable to disconformable with Mabou Group, unconformable with older Carboniferous and basement rocks; conformable to disconformable with Pictou strata (dominantly redbeds) | conformable to unconformable with the heterogeneous Cumberland Group and correlatives; unconformable with older Carboniferous strata and basement rocks |

underlying Windsor Group, the Mabou Group in the CMB is easily identified. Above the Mabou Group, eight distinct mappable lithologic units are identified which, applying the criteria outlined by Ryan *et al.* (1991) (Table 2.6) can be broadly assigned to the CMB Cumberland and CMB Pictou Groups (Fig. 2.6). The CMB Cumberland Group is composed of (in ascending order) the Brion Island, Bird Rock, Bradelle, Green Gables, Magdalen and Seacow formations (Fig. 2.6). The CMB Pictou Group is composed of the Cable Head and Naufrage Formations (Fig. 2.6).

The stratigraphic framework presented is based on the traditional system of nomenclature originally proposed by Bell (1944). Age is not a critical factor in the definition and recognition of the CMB offshore stratigraphic units. The stratigraphic units are defined below in accordance with the International Stratigraphic Guide (1979) and are mappable lithostratigraphic units at the group or formation levels. The following sections focus almost exclusively on the Late Carboniferous to Early Permian (Early Namurian to Early Permian) basin fill; the CMB Horton/Fountain Lake and Windsor Group offshore equivalents will be only briefly outlined.

### 2.3.4.1 Horton/Fountain Lake Groups in the CMB

Well data for the CMB Horton/Fountain Lake Group are scarce. Only five study wells (Table 2.1; wells #12, #13, #17, #18 and #28) penetrated any significant portion of the group, and investigations primarily have used the extensive offshore seismic database (Durling and Marillier, 1990, 1993b).

Most strata are found in isolated SW-NE trending, fault-bounded subbasins in the southern portion of the CMB (Durling and Marillier, 1993a; Marillier *et al.*, 1989). The subbasins commonly have a half-graben geometry and are typically overlain by the Windsor Group. Subbasin fills are typically 2 to 4 km thick but reach 8 km locally (Durling and Marillier, 1993a). In addition, 100-1000m sections of Horton/Fountain Lake Group are found in seismically defined thin veneer or sag basins, that locally overlie deformed basement rocks in the southern portion of the CMB (Durling and Marillier, 1993a).

Investigation of well data (well logs, well reports, and Canadian Stratigraphic Services Logs) from penetrated Horton Group strata indicate that, similar to the onshore, Horton Group in the offshore consists of an upper and lower coarser grained facies separated by a finer grained facies. The lower coarse-grained facies is predominantly an interbedded sandstone/siltstone facies with minor thin shales. The sandstone beds are 5 to 10 m thick and are locally massive. The predominately argillaceous sandstones are medium to coarse-grained, medium to well sorted, with subangular grains cemented with silica and calcite. The siltstones are grey to green to brown-red, argillaceous, micaceous with sandy stringers. The shales are red to brown to green, silty, micaceous and dolomitic. The middle finer grained unit is predominantly red and grey shales with interbedded sandstones. The sandstone beds, typically less than 5m thick, are fine- to medium-grained, red, siliceous to dolomitic, have subangular grains that are medium to well sorted and cemented with calcite. The upper coarse-grained unit is predominantly medium- to coarse-grained sandstones with minor interbeds of siltstone and shale. The sandstones occur as individual beds (5 to 15m thick) and are locally massive. Rare quartz pebbles can be found in this facies. The quartzo-feldspathic sandstones are brown to dark grey to green to red, subangular, well sorted, siliceous to calcareous, micaceous and slightly dolomitic. The siltstones tend to be red to grey and contain thin shale stringers. The shales are red to brown to grey, slightly dolomitic and waxy. Porosities are generally low (<10%) and permeabilities are typically low to fair.

### 2.3.4.2 Windsor Group in the CMB

Only 5 study wells (Table 2.1; wells #12, #13, #17, #18 and #28) fully penetrated a Windsor Group stratigraphic section. In most cases, the CMB wells were drilled over Windsor Group salt structures with the Upper Carboniferous sandstones being the primary exploration target. As a result, 5 study wells (Table 2.1; wells #10, #11, #16, #21 and #26) bottomed in the Windsor Group before drilling was terminated. The bulk of information regarding the CMB Windsor Group comes from seismic data and geologic

investigations based on the Magdalen Islands.

The majority of Windsor Group strata in the offshore area is restricted to the zone of evaporite tectonism (Fig. 2.3) where the group occurs as large salt diapirs, pillows and walls. In this area the group is composed of anhydrite, halite, fine-grained redbeds and shales. On the Magdalen Islands, the basal anhydrite is overlain by a thick (>1000m) halite succession, interbedded with minor impurities including potash (Howie, 1988). Bimodal volcanics are associated with the Windsor Group on the Magdalen Islands (Barr *et al.*, 1985). Outside the main evaporite tectonism zone, towards the flanks of the CMB, the group typically occurs as thinly bedded, slightly deformed salts, local diapirs, or thinly bedded deposits of predominantly fine-grained redbeds (Giles and Durling, 1993; Durling and Marillier, 1993a).

### 2.3.4.3 Mabou Group in the CMB

**Name:** Originally named by Belt (1964, 1965). CMB Mabou Group rocks have been previously assigned to the Canso (Soquip et al, 1975b), Canso-Riversdale (Soquip et al, 1975a) and Riversdale (Sarep Ltd, 1971) Groups. The Mabou Group in the Central Maritimes Basin is defined as the lithostratigraphic unit overlying the Windsor Group and underlying the Brion Island Formation.

**Well Reference Section:** Soquip *et al.* Tyrone No.1 from 3259 to 3949 m, 690 m thick, is here designated the primary CMB reference section (Fig. 2.21, Table 2.7). A secondary reference section occurs in Hudson's Bay-Fina Green Gables No.1 from 2418 to 2971 m, 553 m thick (Table 2.7).

**Lithology:** Typically consists of interbedded sandstones, siltstones, and shales with thin limestones and marlstones. The sandstones are light grey to buff, very fine- to fine-grained, subangular and well to medium sorted. The sandstones tend to increase in grain

# Tyrone No. 1

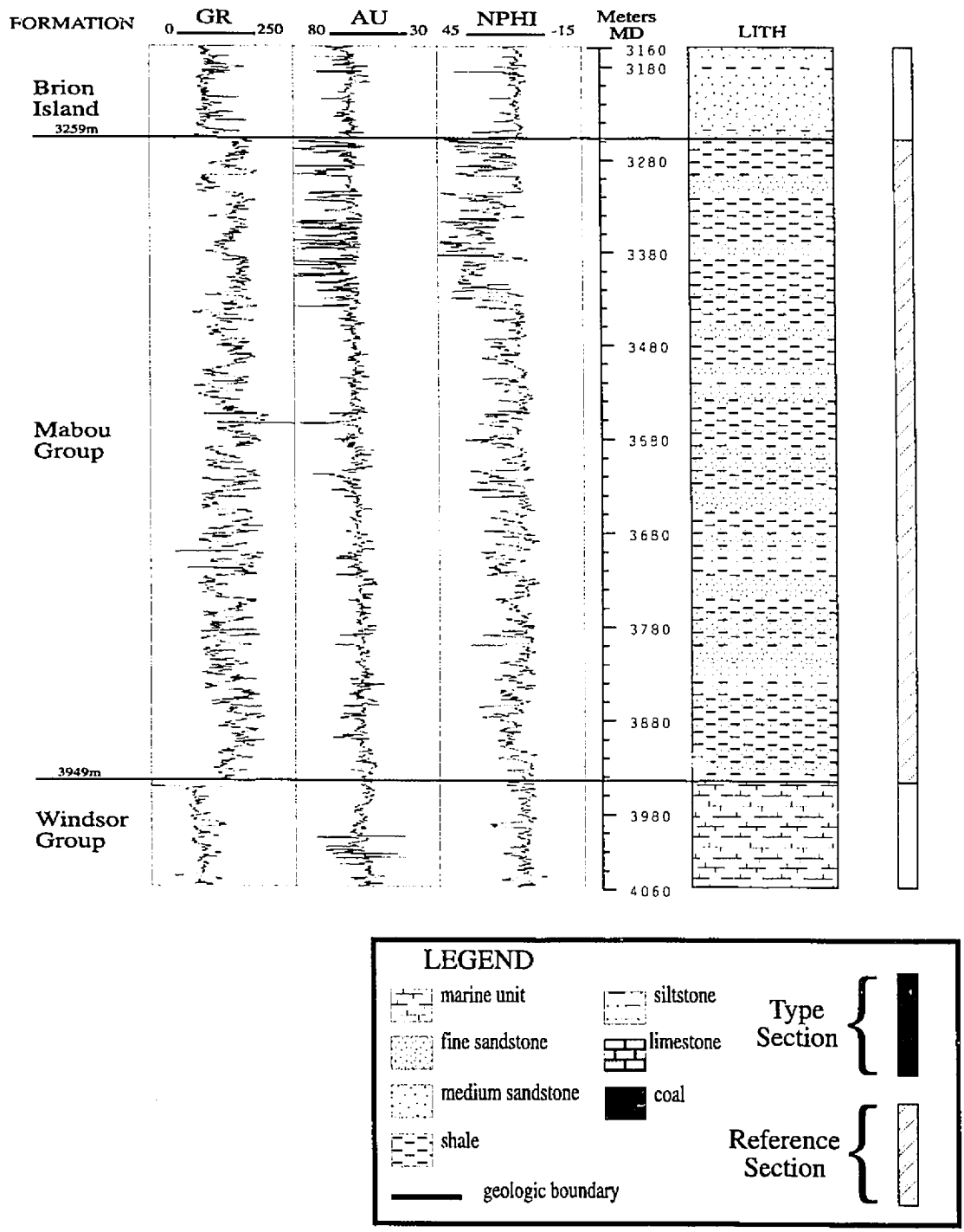



Figure 2.21 Gamma-ray/sonic/compensated neutron log and lithostratigraphy of the Tyrone No.1 well (see Fig 2.3 for location). Well reference section for the CMB Mabou Group. Legend applies to Figures 2.23 through 2.28.

Table 2.7 Well type sections and well reference sections defined in the following sections of text. All unit boundary depths are taken from original gamma-ray/sonic log depths.

| Litho-stratigraphic Unit | Type Section | Reference Section |
|---|---|---|
| **Naufrage Formation** | Soquip *et al.* Naufrage No.1<br>GL-1140 m | Irving-Chevron-Texaco Cable Head E-95<br>SF-1073 m |
| | | Soquip *et al.* Tyrone No.1<br>GL-1430 m |
| **Cablehead Formation** | Irving-Chevron-Texaco Cable Head E-95<br>1073-1597 m | Hudson's Bay-Fina Green Gables No.1<br>935-1515 m |
| | | Sarep H.Q. Brion Island No.1<br>405-802 m |
| **Seacow Formation** | Hudson's Bay-Fina East Point E-49<br>956-1581 m | Irving-Chevron-Texaco Cable Head E-95<br>1597-1891 m |
| **Magdalen Formation** | Hudson's Bay-Fina East Point E-49<br>1581-1878 m | Hudson's Bay *et al.* East Point E-47<br>1545-1869 m |
| **Green Gables Formation** | Hudson's Bay-Fina Green Gables No.1<br>1515-1744 m | Hudson's Bay-Fina East Point E-49<br>1878-2396 m |
| | | Sarep H.Q. Brion Island No.1<br>862-1133 m |
| **Bradelle Formation** | Shell-Soquip-Amoco Bradelle L-49<br>1498-1794 m | Sarep H.Q. Brion Island No.1<br>1133-1538 m |
| | | Hudson's Bay *et al.* Beaton Point F-70<br>1201-1734 m |
| **Bird Rock Formation** | Sarep H.Q. Brion Island No.1<br>1538-1737 m | Shell-Soquip-Amoco Bradelle L-49<br>1794-2105 m |
| **Brion Island Formation** | Sarep H.Q. Brion Island No.1<br>1737-2049 m | Shell-Soquip-Amoco Bradelle L-49<br>2105-2395 m |
| **Mabou Group** | | Soquip *et al.* Tyrone No.1<br>3259-3949 m |
| | | Hudson's Bay-Fina Green Gables No.1<br>2418-2971 m |

size and bed thickness upsection. The sandstones are cemented by silica and calcite. The shales are red to grey to green, silty, micaceous and redden upsection. The thin limestones are light brown, silty, slightly dolomitic and grade into marlstones. Thin stringers and traces of coal increase in abundance towards the top of the section. The unit has an overall sandstone/shale ratio of 1.13. Porosity values range between 7% and 10% and cuttings reports indicate permeability is typically very low.

**Boundaries:** The upper and lower contacts are abrupt and easily identified using well logs and samples. In the CMB the lower contact between the Mabou Group and the underlying evaporite dominated Windsor Group is conformable to disconformable. On well logs it is clearly marked by a sharp decrease in gamma-ray response and an increase in acoustic velocity. The Mabou Group locally onlaps older Carboniferous strata and unconformably overlies basement. The upper contact is marked by the Namurian-Westphalian event at the contact with the overlying Brion Island Formation, and is defined as the base of the first major sand-dominated sequence of the overlying Brion Island Formation. Locally, the Mabou Group in the CMB is unconformably overlain by the Bradelle Formation, in which case the upper contact is identified at the base of the first sand-dominated sequence of the overlying Bradelle Formation. In such situations, the contact between the Mabou Group and the Bradelle Formation represents the converging of the Namurian-Westphalian and Mid-Westphalian events.

**Distribution:** Seismic and well data indicate that the Mabou Group is found throughout the offshore area with the best development (thickest and highest sandstone/shale ratios) occurring towards the depocentre of the Maritimes Basin. The Mabou Group becomes thinner towards the basin flanks and eventually onlaps older Carboniferous, Devonian and Precambrian rocks. The Mabou locally thins over some prominent structures (Figs 2.14, 2.18).

**CMB Seismo-Stratigraphic Equivalents:** The LEZ A seismic sequence is stratigraphically equivalent to the Mabou Group in the CMB. The upper and lower contacts of the Mabou group are defined by the primary seismic sequence boundaries R2 and R1, respectively. In the instance that the Namurian-Westphalian and Mid-Westphalian events merge, the top of the Mabou Group is defined by seismic sub-sequence boundary R2b.

**Depositional Environment:** The dominantly serrated, with subordinant cylindrical-funnel shaped, log signatures suggest a fluvial floodplain with minor braided river and deltaic sand development (Cant, 1992). The seismic facies suggests a concordant interbedded shale/sand succession deposited under relatively uniform rates of deposition that potentially may have exhibited prograding characteristics (Vail *et al.*, 1977). Together, the depositional environment for the Mabou Group in the CMB is interpreted to be an extensive alluvial floodplain that locally showed signs of progradation. This interpretation is generally consistent with previous onshore interpretations (Table 2.8).

**Age:** Namurian (Soquip *et al.*, 1975b), Late Visean to Early Namurian (Barss *et al.*, 1979) at the primary reference section. An evaluation of the biostratigraphic data for the Mabou Group in the CMB suggests Late Viséan-Early Namurian to Early Westphalian A.

**Onshore Equivalents:** Middleborough/Shepody, Pomquet/Hastings, and Searston formations. Hopewell and Canso groups (Figs. 2.22, 2.2).

### 2.3.4.4 CMB Cumberland Group

#### 2.3.4.4.1 Brion Island Formation

**Name:** From the Sarep H.Q. Brion Island No.1 well in the Central Maritimes Basin where the formation is well developed and the type section is located. The Brion Island

Table 2.8 Summary of previously interpreted paleoenvironments for Central Maritimes Basin stratigraphic onshore equivalents. See Figure 2.6 for an overview of offshore stratigraphic nomenclature and Figure 2.1 for subbasin/platform locations. The Magdalen and Seacow formations are locally developed in the offshore area. N/P = Not present; N/D = Not Defined; (BST = Backstepping systems tract; FST = Forestepping systems tract; discussed in Chapter 3)

| Offshore Stratigraphy | New Brunswick | Nova Scotia (Cumberland Subbasin) | Nova Scotia (Western Cape Breton Island) | Nova Scotia (Sydney Subbasin) | Newfoundland (Bay St. George Subbasin) |
|---|---|---|---|---|---|
| **Naufrage Fm. (BST 4)** | **Pictou Grp. Megacycles 2 & 3**: Alluvial floodplain transitional to a bed-load dominated fluvial system (braided)(LeGallais, 1983). | **Tatamagouche/Cape John Fm.**: Anastomosing fluvial systems with shallow lacustrine environments (Ryan and Boehner, 1994). | N/D | N/D | N/P |
| **Cable Head Fm. (FST 4)** | **Tormentine Fm./Pictou Grp. (II-1-A to II-1-C)**: High bed and suspended load fluvial system with braided pattern (LeGallais, 1983). | **Balfron/Tatamagouche Fm.**: Transitional from braided to meandering fluvial systems with minor vegetation in the interchannel areas (Calder, 1984). | **Broad Cove Fm.**: Alluvial sandstones and mudstones (van de Poll et al., 1995). | **"Unnamed Redbeds"**: Distal alluvial plain with a low water table (Rust et al., 1987). | N/P |
| **Seacow Fm. (BST 3)** | | | | | |
| **Magdalen Fm. (FST 3)** | | | | | |
| **Green Gables Fm. (BST 2)** | **Pictou Grp. (U. Succession I-2)**: Floodplain sedimentation with isolated channel and crevasse splay deposits (LeGallais, 1983). | N/D | **uppper Inverness Fm.**: muddy with coals and calcretes, alluvialplain? (Norman, 1935) | **Sydney Mines Fm.**: Poorly drained, alluvial plain with minor meandering fluvial deposition. Peat development, marine intercalations (Gibling and Bird, 1994). | N/P |
| **Bradelle Fm. (FST 2)** | **Richibucto Fm./Pictou Grp. (L. Succession 1)**: Bed and suspended load braided fluvial system , high sedimentation (LeGallais, 1983). | **Ragged Reef/Malagash Fms.**: Sandy braided systems with minor shallow lacustrine deposits and minor peat development (Ryan and Boehner, 1994). | **lower Inverness Fm.**: Braidplain deposits with shallow lacustrine and overbank fines on a heavily vegetated, poorly drained, floodplain (Gibling et al., 1994). | **South Bar Fm.**: Braidplain deposits with local and regional peat development (Rust and Gibling, 1990). | N/P |
| **Bird Rock Fm. (FST1)** | **Salisbury Fm.**: shale prone, siltstones, a few coals, alluvialplain? (Gussow, 1953) | **Joggins Fm.**: Delta plain with channel and overbank deposition. Fluvial sand developed in an anastomosing system (Duff and Walton, 1973; Rust et al., 1984). | **Upper Port Hood Fm.**: Meandering fluvial system with subaerial floodplain deposition, heavily vegetated interchannel areas (Gersib and McCabe, 1981). | N/P | **U. Barachois Grp.**: Alluvial to upper delta plain, poorly drained, heavily vegetated with isolated channels (Hyde et al., 1991). |
| **Brion Island Fm. (FST 1)** | **Boss Point Fm.**: Prograding braidplain envrionment with subordinate lacustrine and interchannel deposits (Browne and Plint, 1994). | **Boss Point Fm.**: Prograding braidplain envrionment with subordinate lacustrine and interchannel deposits (Browne and Plint, 1994). | **Lower Port Hood Fm.**: Braided fluvial deposition with interchannel lacustrine and overbank fines (Waterfield, 1986). | N/P | **L. Barachois Grp.**: Bedload dominated meandering systems with vegetated floodplain/interchannnel areas (Knight, 1983). |
| **Mabou Group** | **Hopewell Grp.**: Alluvial fan to plain setting with minor shallow lacustrine development, becomes more fluvial upsection (van de Poll et al., 1995). | **Middleborough/Shepody Fm.**: Upward coarsening from arid floodplain to humid meandering-braided river systems (Ryan and Boehner, 1994). | **Pomquet/Hastings Fms.**: Semi-arid lacustrine transitional to humid fluvial regimes (Allen, 1995). | **Point Edward/Cape Dauphin Fms.**: Lacustrine with fluvial influences. (Gibling, 1995; Gibling et al . 1987). | **Searston Fm.**: Semi-arid floodplain transitional to humid fluvial deposits (Knight, 1983). |

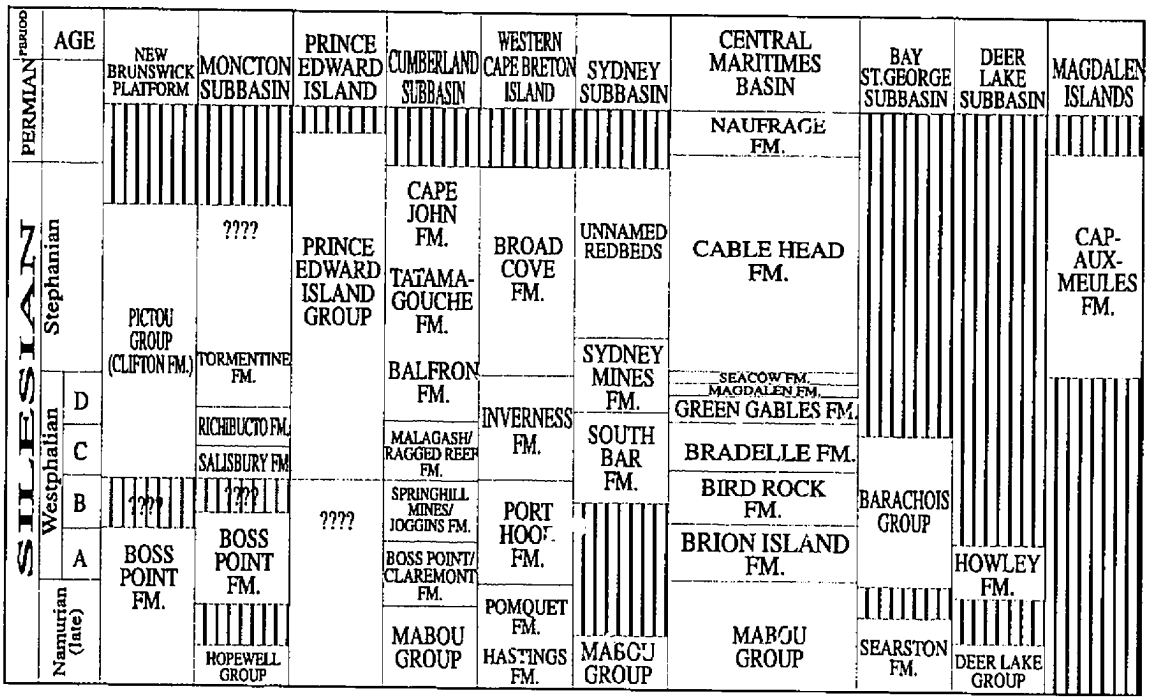



Figure 2.22 Summary chronostratigraphic chart for subbasins, platforms and basins of the Maritimes Basin. See Figure 2.1 for locations. Age and formational data from Ryan et al. (1991) -- Cumberland Subbasin; Johnson (1995b)/van de Poll (1995) -- Moncton Subbasin; Gibling et al. (1992b) -- Prince Edward Island, Magdalen Islands, New Brunswick Platform and Sydney, Bay St. George and Deer lake Subbasins; Gibling (1995) -- Western Cape Breton Island.

Formation is defined as the sandstone-dominated lithostratigraphic unit overlying the Mabou Group and underlying the Bird Rock Formation. Rocks of this formation have been previously assigned to all or parts of the Canso (Petro-Canada *et al.*, 1984), Riversdale (Sarep Ltd, 1971) or Pictou (Soquip *et al.*, 1975b) Groups.

**Well Type Section:** Sarep H.Q. Brion Island No.1 from 1737 to 2049 m, 312 m thick, is here designated the type section (Fig. 2.23, Table 2.7)

**Well Reference Section:** Shell-Soquip-Amoco Bradelle L-49 from 2105 to 2395, 290 m thick (Fig. 2.24, Table 2.7).

**Lithology:** Typically a sandstone dominated succession with grain sizes and bed thicknesses that tend to increase upwards. Sandstone units at the base are generally 10 to 20 m thick whereas the upper part of the formation is typically very thickly bedded sandstones 60 to 80 m thick. A corresponding trend in well log signatures is displayed by basal serrated-cylindrical patterns changing to blocky patterns near the top. The sandstones are light grey to light green to light red, medium- to coarse-grained, subangular and poor to medium sorted. Subangular quartz pebbles tend to be found near the base of the section, however they are locally common throughout the section. Cements are dominantly silica. The unit is generally quartz-rich and the overall feldspar content of the unit decreases upsection. Shales in the unit tend to be grey-green-red, silty, micaceous and "grey" upwards. Thin stringers and traces of coal can be found towards the top of the section. The unit has an average sandstone/shale ratio of 2.75. Porosity values average 7 to 10% and cutting reports indicate permeability is low to fair.

**Boundaries:** The lower boundary is marked by a regionally extensive conformable to unconformable surface of Late Namurian C to Early Westphalian A age at the contact with the Mabou Group (Namurian-Westphalian event). The lower contact is recognized by a change from the finely interbedded clastics of the Mabou Group to the thick

# Brion Island No. 1

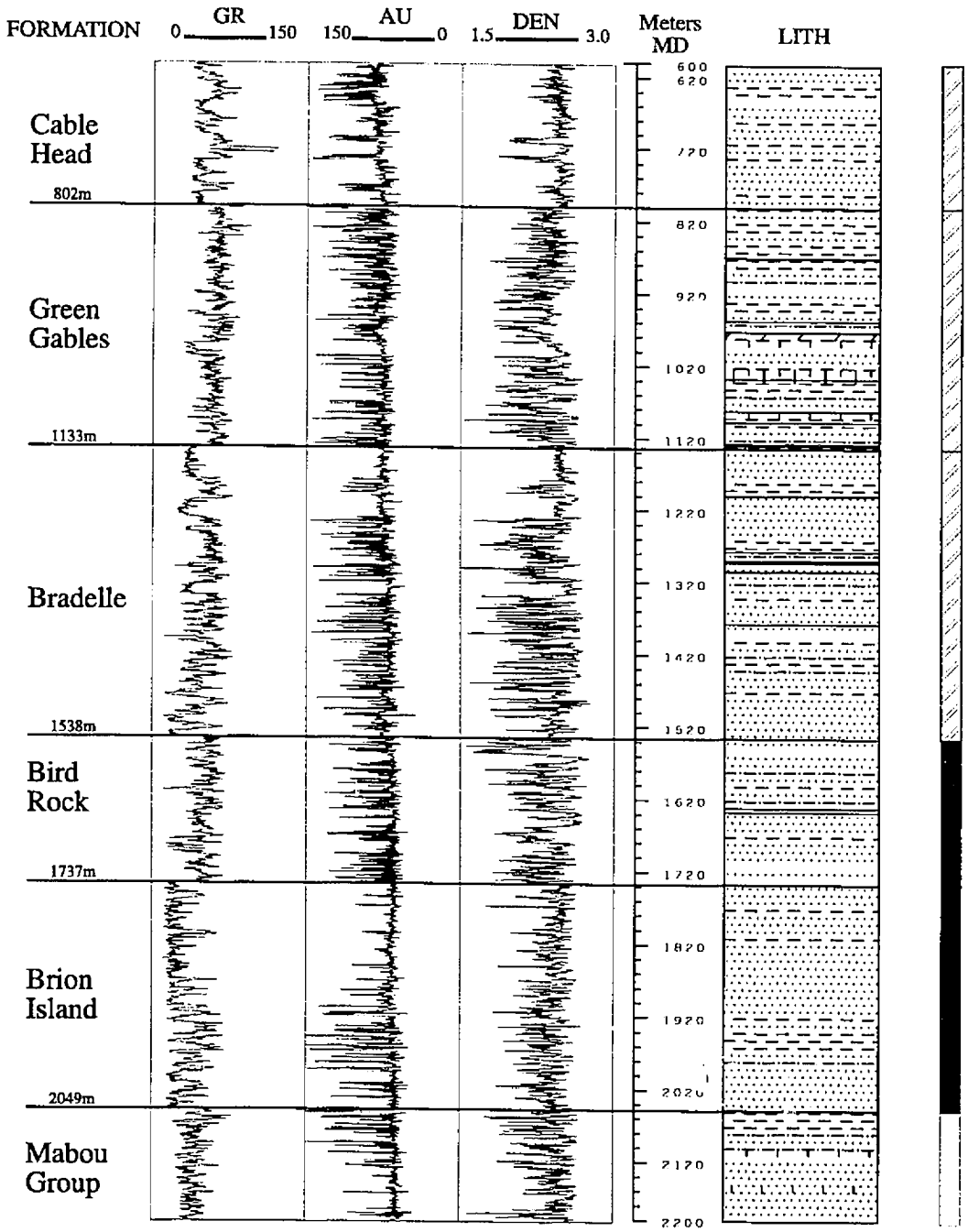



Figure 2.23 Gamma-ray/sonic/density log and lithostratigraphy of the Brion Island No.1 well (see Fig. 2.3 for location). Well type section for the Brion Island and Bird Rock formations. Well reference section for the Bradelle and Green Gables Formations. A portion of the Cable Head Formation reference section in the Brion Island No.1 well is shown near the top. Legend as in Figure 2.21.

# Bradelle L-49

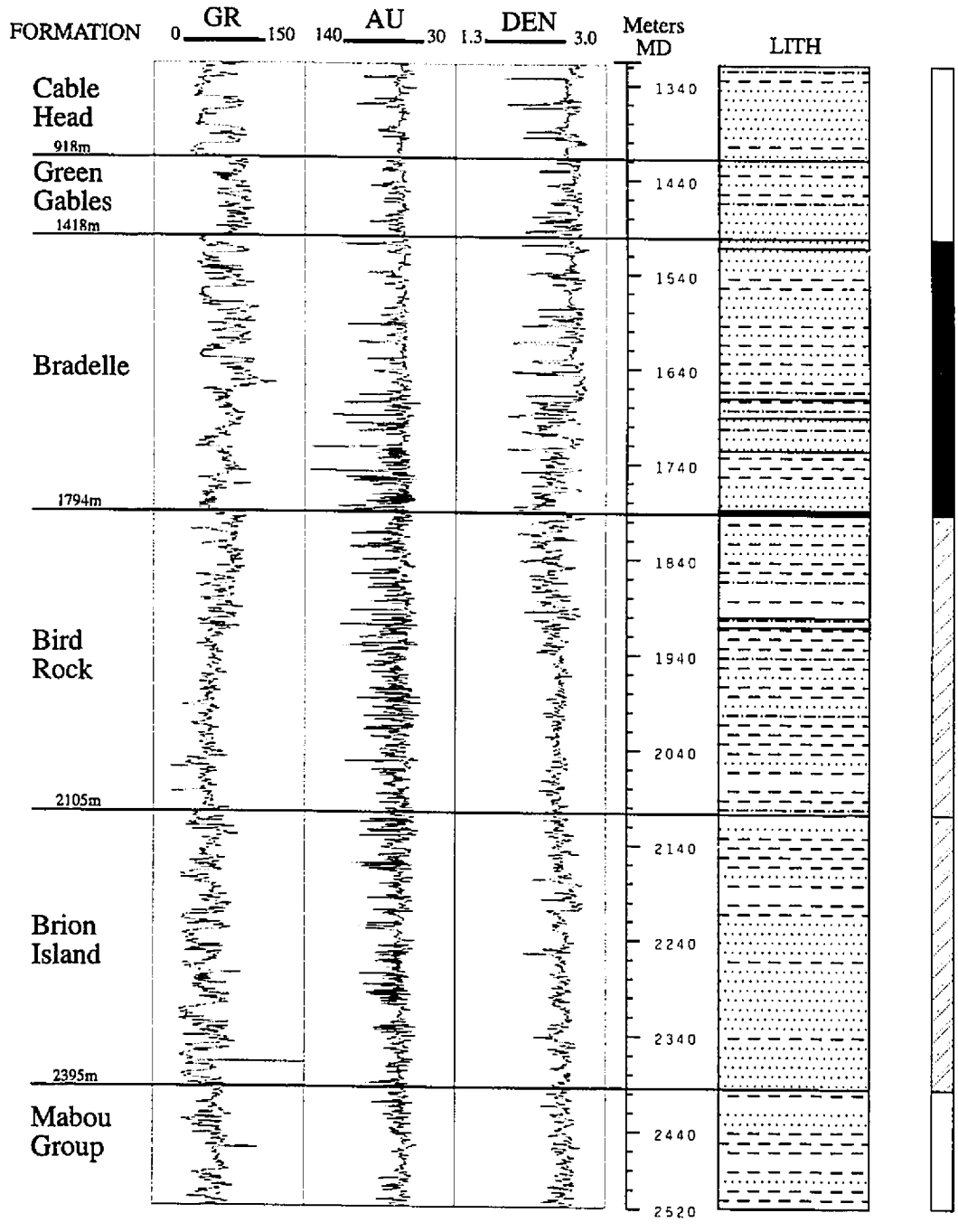



Figure 2.24 Gamma-ray/sonic/density log and lithostratigraphy of the Bradelle L-49 well (see Fig. 2.3 for location). Well type section for the Bradelle Formation. Well reference section for the Brion Island and Bird Rock formations. Legend as in Figure

medium- to coarse-grained sandstone beds of the lower Brion Island Formation, and is marked by an abrupt change in log character. An easily identified, conformable upper contact is picked on well logs at the abrupt contact between the massive upper sandstones of the Brion Island Formation and the shale dominated beds of the overlying Bird Rock Formation. The upper contact is locally marked by a regional event of Late Westphalian B to Early Westphalian C (Mid-Westphalian) age at the contact with the overlying Bradelle Formation. Although more difficult to define, the boundary in these instances is picked using well logs and cutting descriptions at the contact between the blocky quartz rich sandstones of the upper Brion Island Formation and thinner basal sandstones of the overlying Bradelle Formation.

**Distribution:** The original distribution of the Brion Island Formation is unclear because the overlying Mid-Westphalian event has locally removed part or all of the formation. The Brion Island Formation is present in most wells around the basin flanks but wells closer to the central portion of the CMB (Cable Head E-95, Beaton Point F-70 and Naufrage No.1) did not penetrate deep enough to reach the formation. Seismic data indicate that the formation is present over a large area of the CMB. Well and seismic data indicate that the formation is absent over the East Point salt structure (East Point E-49) and in the Sydney subbasin (North Sydney P-05, North Sydney F-24 and Birch Grove No.1).

**CMB Seismo-stratigraphic Equivalents:** The Brion Island Formation is equivalent to the LOWER Coal Measures seismic sub-sequence and, where LEZ A cannot be recognized, to the lower part of the CMB Coal Measures seismo-stratigraphic unit. The lower boundary of the Brion Island Formation is associated with seismic sequence boundary R2, which is commonly recognized on seismic profiles by the distinct change in acoustic impedance contrasts between the homogenous Mabou Group and the coarser grained heterogeneous Brion Island Formation. The Brion Island Formation is bounded by sub-sequence boundary R2a at the top.

**Depositional Environment:** The dominantly cylindrical log signatures, with minor funnel shapes suggests a braided fluvial environment with some deltaic units (Cant, 1992). The typically massive nature of the sandstones and increased evidence of coal development at the top of the section suggests that the depositional system evolved into a more stable, or mature, environment (Melvin, 1993). The seismic facies analysis of the basal Coal Measures and the LOWER Coal Measures seismic facies suggests that the Brion Island Formation was deposited in a high energy environment. The visible prograding clinoforms suggest progradation of the system basinward. Combining the two interpretations suggests that the Brion Island Formation was deposited in a prograding braidplain fluvial system. This interpretation is generally consistent with previous onshore interpretations (Table 2.8).

**Age:** Westphalian A at the type section (Sarep Ltd. 1971; INRS-Petrole, 1973). An evaluation of the biostratigraphic data from all penetrated sections suggests Early Westphalian A to Early Westphalian B.

**Onshore Equivalents include all or part of:** Enrage, Claremont, Boss Point, Lower Port Hood and Howley Formations; Lower Barachois Group (upper Searston Formation-upper coal bearing sequence)(Figs. 2.22, 2.2).

#### 2.3.4.4.2 Bird Rock Formation

**Name:** From a small island northeast of Brion Island in the Gulf of St. Lawrence. The Bird Rock Formation is defined as the predominantly shale and siltstone interval overlying the Brion Island Formation and underlying the Bradelle Formation. Rocks of this formation have previously been assigned to all or parts of the Canso (Petro-Canada *et al.*, 1984), Riversdale (Sarep Ltd, 1971), Cumberland (COGLA, 1990) and Pictou (Shell Canada Resources Ltd, 1973) Groups.

**Well Type Section:** Sarep H.Q. Brion Island No.1 from 1538 to 1737 m, 199 m thick, is here designated as the type section (Fig. 2.23, Table 2.7)

**Well Reference Section:** Shell-Soquip-Amoco Bradelle L-49 from 1794 to 2105 m, 311 m thick (Fig. 2.24, Table 2.7).

**Lithology:** Predominantly consists of shales that are grey-green-dark brown/red, micaceous, waxy and silty. The formation has corresponding high gamma-ray responses and the curves tend to be highly serrated. The shale beds contain thin siltstone stringers and grey upwards. The thin sandstones are very fine- to fine-grained, subangular, silty, silica cemented, argillaceous and medium to well sorted. Sandstone beds range from less than a metre up to approximately 10m thick, typically less than 4m. The sands become more dolomitic towards the top of the section. Thin coal stringers (<1m) and traces are found at the top and bottom of the section. Thin (<1m), white to light brown, argillaceous, silty limestones are found near the base of the formation. The Bird Rock Formation has an average sandstone/shale ratio of 0.50.

**Boundaries:** The Bird Rock Formation is clearly distinguished from the overlying Bradelle Formation and the underlying Brion Island Formation by a relatively high gamma-ray signature. The characteristics of the conformable lower contact with the Brion Island Formation were defined in the previous section. The upper contact with the Bradelle Formation is marked by the Mid-Westphalian event and is clearly identified by an abrupt decrease in gamma-ray response. The upper contact is defined as the base of the first thick sandstone-dominated succession overlying the Bird Rock Formation.

**Distribution:** As with the Brion Island Formation, the original distribution of the Bird Rock Formation is unclear because of erosion associated with the Mid-Westphalian event, which has locally removed the entire Bird Rock Formation. The formation appears to be present around the basin flanks with thicker deposits found north-northwest of the

Magdalen Islands. On the south-southeastern flanks, the formation occurs as thin, isolated, erosional remnants. Further towards the depocentre, the presence of the Bird Rock Formation is untested as CMB wells did not penetrate to sufficient depth. As with the Brion Island Formation, the Bird Rock Formation is absent over the East Point salt structure (East Point E-49) and in the Sydney subbasin (North Sydney P-05, North Sydney F-24 and Birch Grove No.1).

**CMB Seismo-Stratigraphic Equivalents:** The Low Energy Zone A1 seismic sub-sequence is stratigraphically equivalent to the Bird Rock Formation. Although not identifiable on many study lines due to limited seismic resolution, the Bird Rock Formation would be found within the primary CMB Coal Measures seismic sequence. The top and bottom of the Bird Rock Formation are defined by sub-sequence boundaries R2b and R2a, respectively.

**Depositional Environment:** The high gamma-ray, serrated log signatures of the Bird Rock Formation suggest deposition on a fluvial floodplain that had abundant fine-grained sediment along with conditions suitable for minor peat development (Cant, 1992). Seismic facies analysis of LEZ A1 suggests a uniform, interbedded sandstone/shale succession deposited under relatively uniform sedimentation rates on a stable basin-plain setting (Vail *et al.*, 1977). Together, the two data sets suggest that the Bird Rock Formation was deposited on a stable fluvial floodplain under low energy conditions which is generally consistent with previous onshore interpretations (Table 2.8)

**Age:** The type section was dated as Late Westphalian A (Sarep Ltd., 1971), Westphalian A to Westphalian C (INRS-Petrole, 1973). The reference section was dated as Westphalian B - Early Westphalian C (Dolby, 1994) and Late Westphalian B - Early Westphalian C (Barss et al, 1979). An evaluation of the biostratigraphic data compiled for the Bird Rock Formation suggests Early Westphalian B to Late Westphalian B - Early Westphalian C.

**Onshore Equivalents include all or part of:** Upper Port Hood (Colindale Member of Giles et al, 1996), Parrsboro, Emery Brook, Joggins, Salisbury, and Upper Howley Formations; Upper Barachois Group (upper coal bearing sequence) (Figs. 2.22, 2.2).

#### 2.3.4.4.3 Bradelle Formation

**Name:** From the Shell-Soquip-Amoco Bradelle L-49 well in the Central Maritimes Basin. The Bradelle Formation is defined as the first sand-dominated succession immediately underlying the Green Gables Formation and overlying the Bird Rock Formation. Rocks of this formation have previously been assigned to all or parts of the Canso (Soquip *et al.*, 1975b), Lower Riversdale (Murphy Oil Company Ltd., 1968), Upper Riversdale (Hudsons Bay Oil and Gas Ltd., 1980b), Cumberland (COGLA, 1990), and Pictou (COGLA, 1990) Groups. Parts of the formation have been assigned informally to the Pictou Massive Sandstone (Chevron Canada Resources, 1983).

**Well Type Section:** Shell-Soquip-Amoco Bradelle L-49 from 1498 to 1794 m, 296 m thick, is designated the type section (Fig. 2.24, Table 2.7).

**Well Reference Sections:** Sarep H.Q. Brion Island No.1 from 1133 to 1538 m , 405 m thick (Fig. 2.23, Table 2.7) and Hudson's Bay *et al.* Beaton Point F-70 from 1201 to 1734 m, 533 m thick (Table 2.7).

**Lithology:** Well logs and ditch cuttings from the type section indicate that the formation is predominantly composed of sandstones with minor shales and coals. The sandstones are light green to light brown, fine- to medium-grained, subangular, siliceous, and moderately sorted. Quartz pebbles are locally found near the base of the section, however they are not as abundant as in the Brion Island Formation. Sandstone bed thickness and grain size tends to increase towards the top of the section. Beds on average are 5 to 10 m thick near the bottom of the section and 15 to 20 m thick at the top. Kaolinite and

feldspar content increases upsection as does the shale content. Well history reports indicate traces of glauconite in the ditch cuttings. The shales are dark green to grey to red, silty, micaceous and redden upwards. Beds (<1.5m), thin stringers, and traces of coal increase towards the top of the section. The average sandstone/shale ratio is 2.93. The porosity of the sandstones averages 6 to 10% and cuttings descriptions indicated permeability is typically low to fair.

**Boundaries:** The upper and lower contacts are always sharp and clearly marked by gamma-ray and sonic breaks. The upper contact with the Green Gables Formation is placed at the top of the uppermost sand-dominated succession of the Bradelle Formation. The contact is abrupt and easily identified by log character. Locally, the Bradelle Formation unconformably overlies the Brion Island Formation or the Mabou Group, these boundary conditions have been described previously.

**Distribution:** The Bradelle Formation is a remarkably consistent and laterally extensive stratigraphic unit. It is found in 26 out of 28 study wells (absent in Northumberland Strait F-25, which spudded in Brion Island Formation, and East Point E-47, which only penetrated into overlying Green Gables Formation). The best developed sections (thickest and highest sandstone/shale ratios) of the Bradelle Formation are located in the south-southeastern portion of the CMB, in an area bounded by the northeastern point of P.E.I., western coast of Cape Breton Island and the Magdalen Islands.

**CMB Seismo-Stratigraphic Equivalents:** The Bradelle Formation is equivalent to the top portion of the primary Coal Measures seismo-stratigraphic unit (the UPPER Coal Measures seismic sub-sequence, where identifiable). The formation is bounded by sub-sequence boundary R2b and primary sequence boundary R3 at the bottom and top, respectively.

**Depositional Environment:** The dominantly cylindrical log signatures, with an

increasing number of funnel-shaped signatures upsection, suggests a braided fluvial environment that may have developed deltaic units as the system evolved (Cant, 1992). The development of thicker, more massive, sandstone bodies and the increased number of coals near the top of the section suggests the depositional system evolved into a more stable, or mature, environment (Melvin, 1993). Seismic facies analysis suggests that the Bradelle Formation was deposited in a high energy environment. The identification of prograding clinoforms suggests the progradation of the depositional surface basinward (Vail *et al.*, 1977). The interpretation of both data sets implies that the Bradelle Formation was deposited in a braided fluvial system that was prograding basinward. This interpretation is generally consistent with previous onshore interpretations (Table 2.8).

**Age:** Late Westphalian B/Early Westphalian C to Late Westphalian C/Early Westphalian D (Barss *et al.*, 1979), Westphalian C to Westphalian D (INRS-Petrole, 1975b) and Westphalian B to Mid - Late Westphalian C (Dolby, 1994) at the type section. From an evaluation of the biostratigraphic data compiled for the Bradelle Formation, interpreted to be Late Westphalian B/Early Westphalian C to Early Westphalian D.

**Onshore Equivalents include all or part of:** Ragged Reef/Malagash, lower Inverness, South Bar and Richibucto Formations; Lower Succession (I-1) of Pictou Group Megacycle I (LeGallais, 1983) (Figs. 2.22, 2.2).

#### 2.3.4.4.4 Green Gables Formation

**Name:** From the Hudson's Bay-Fina Green Gables No.1 well where the formation is best developed in the Central Maritimes Basin and where its type section is located. The Green Gables Formation is defined as the first shale-dominated sequence overlying the Bradelle Formation and overlain typically by the Cable Head Formation but locally by the Magdalen Formation. Rocks of the Green Gables Formation previously have been correlated with all or parts of the Upper Riversdale (Hudsons Bay Oil and Gas Ltd.,

1980b), Upper Cumberland (COGLA, 1990) or Pictou (Sarep Ltd, 1971) Groups.

**Well Type Section:** Hudson's Bay-Fina Green Gables No.1 from 1515 to 1744 m, 229 m thick, is designated as the type section (Fig. 2.25, Table 2.7).

**Well Reference Section:** Hudson's Bay-Fina East Point E-49 from 1878 to 2396 m, 518 m thick and Sarep H.Q. Brion Island No.1 from 802 to 1133 m, 331 m thick (Figs. 2.26 and 2.23, Table 2.7).

**Lithology:** Predominantly grey to red, micaceous, silty shales. The shales are interbedded with minor sandstones and coal beds. The unit has a corresponding well log signature that tends to be serrated with high gamma-ray responses and low spikes on the density log. Limestones are locally found at the base of the section. The shales are waxy, slightly dolomitic and contain stringers of siltstone, coal and limestone. The overall quantity of shale increases upsection as does the ratio of red to grey shale. The sandstones occur as thin beds that are typically less than 5m thick but can locally exceed 10m. They are light brown to grey to light red, very fine- to fine-grained, subangular, argillaceous, medium to well sorted, and are cemented by calcite and silica. The thin coal beds (<1.5m), stringers, and traces are generally found at the base of the section. The thin beds (<1.0m) and stringers of limestone are brown, argillaceous and silty. The formation has an average sandstone/shale ratio of 0.41.

**Boundaries:** The gamma-ray and sonic breaks at the upper and lower boundaries of the shale-dominated Green Gables Formation are clearly distinguished on petrophysical logs from the sand-dominated sequences of the overlying Cable Head Formation and underlying Bradelle Formation. The lower contact, as mentioned in the last section, is easily picked by logs or samples above the topmost sand-dominated succession of the Bradelle Formation. The upper contact with the overlying Cable Head Formation is marked by the regional Westphalian-Stephanian event, and is easily identified by well log

# Green Gables No. 1

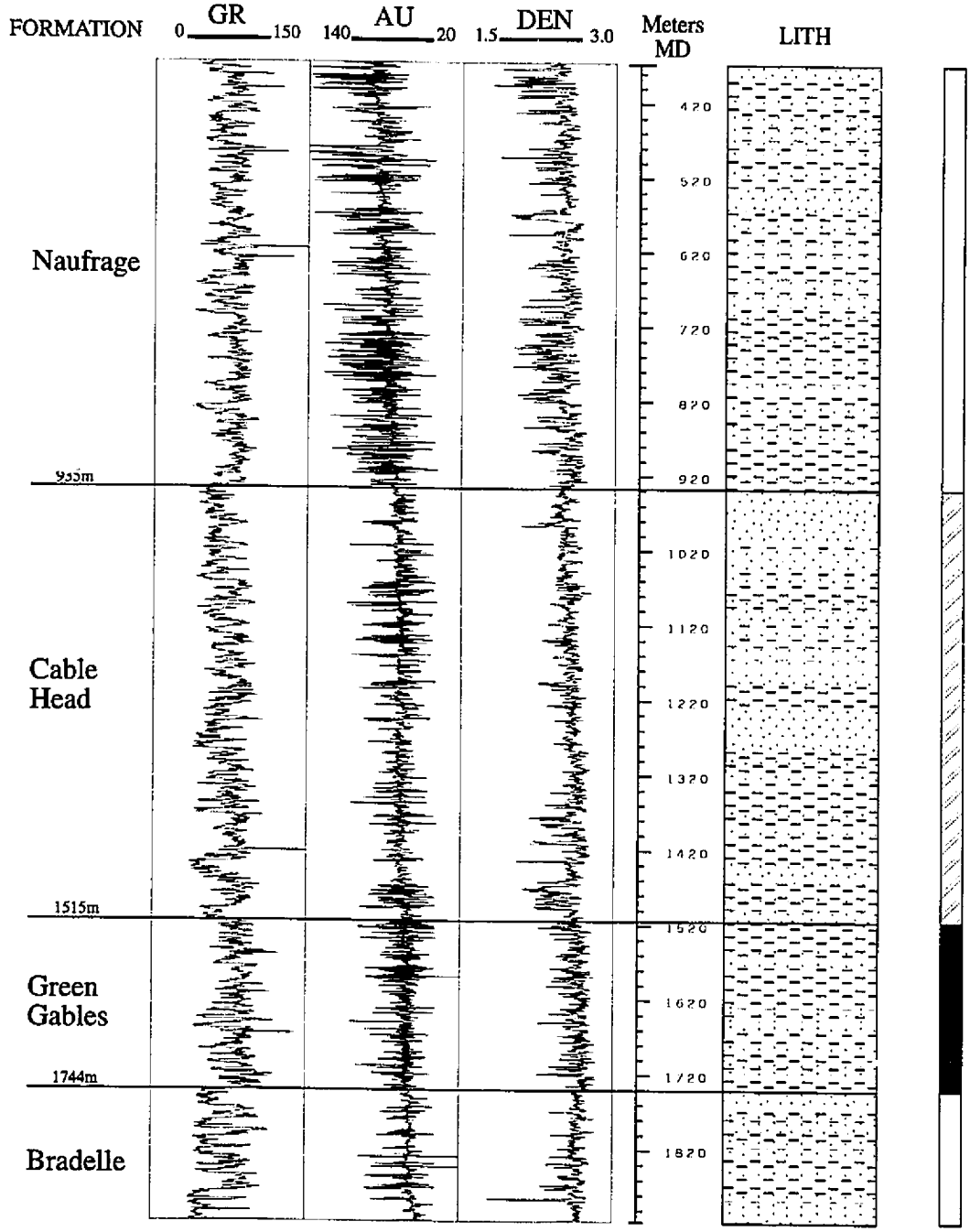



Figure 2.25 Gamma-ray/sonic/density log and lithostratigraphy of the Green Gables No.1 well (see Fig. 2.3 for location). Well type section for the Green Gables Formation. Well reference section for the Cable Head Formation. Legend as in Figure 2.21.

# East Point E-49

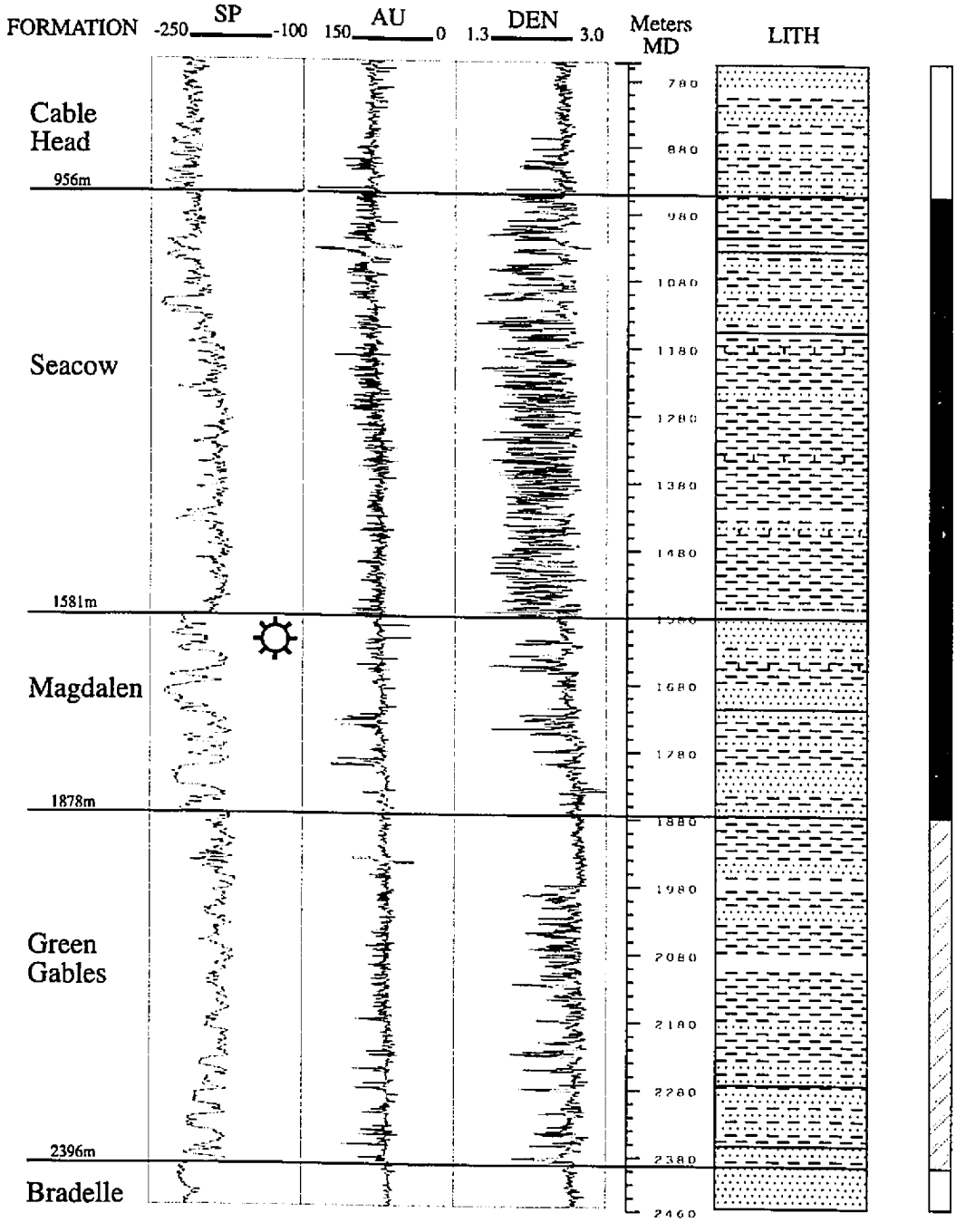



Figure 2.26 Spontaneous potential/sonic/density log and lithostratigraphy of the East Point E-49 well (see Fig. 2.3 for location). Well type section for the Magdalen and Seacow formations. Well reference section for the Green Gables Formation. Legend as in Figure 2.21.

signatures and by an abrupt lithological change to the sand-dominated redbed succession of the Cable Head Formation. In the south-southeastern portion of the CMB, in an area approximately bordered by the Magdalen Islands, western Cape Breton and northeastern P.E.I., the Magdalen Formation conformably to disconformably overlies the Green Gables Formation. In this general area, the contact is easily distinguishable by the change in well log character and abrupt increase in sand content; the boundary is chosen at the base of the first sand-dominated sequence of the Magdalen Formation. Where the overlying Magdalen Formation "shales" out towards the basin flanks, the boundary becomes more difficult to identify and is tentatively placed at the base of the first major fining upwards trend above the shale-rich Green Gables Formation.

**Distribution:** The distribution appears to be similar to that of the Bradelle Formation. A total of 27 out of 28 study wells penetrated the formation (Northumberland Strait F-25 spudded in the older Brion Island Formation).

**CMB Seismo-Stratigraphic Equivalents:** The Green Gables Formation is the lithostratigraphic equivalent of the Low Energy Zone B seismo-stratigraphic unit. The lower boundary is a regionally mappable seismic sequence boundary referred to as R3 (Fig. 2.11) or the "Top of the Coal Measures Facies" (Grant and Moir, 1992). The upper boundary is typically defined by primary seismic sequence boundary R4, however, locally in the southern portion of the CMB, the upper contact of the formation is defined by seismic sub-sequence boundary R3a.

**Depositional Environment:** The dominantly serrated, with minor cylindrical, log signatures suggests deposition on a fluvial floodplain with local channel-sand bodies, probably of braided style (Cant, 1992). The environment was favourable for the development of peats. The seismic facies analysis of the low energy zone B seismic unit suggests relatively uniform depositional rates on a stable basin plain setting (Vail *et al.*, 1977). An interpreted fluvial floodplain environment is generally consistent with

previous onshore interpretations (Table 2.8).

**Age:** Westphalian ? to Westphalian D (Barss *et al.*, 1979), and Westphalian D to Stephanian (INRS-Petrole, 1975b) at the type section; Westphalian C to Stephanian (Sarep Ltd., 1971) and Westphalian D to Stephanian (INRS-Petrole, 1975b) at the Brion Island No.1 reference section. Early to Late Westphalian D is interpreted based on an evaluation of all the biostratigraphic data compiled for the Green Gables Formation.

**Onshore Equivalents include all or part of:** Upper Succession (I-2) of Pictou Group Megacycle I (LeGallais, 1983); upper Inverness and Sydney Mines Formations (Figs. 2.22, 2.2).

#### 2.3.4.4.5 Magdalen Formation

**Name:** From the Magdalen Islands in the Gulf of St. Lawrence, the Magdalen Formation type section is best developed within the Central Maritimes Basin. In the south-southeastern portion of the CMB, the Magdalen Formation is defined as the first major sand-dominated succession overlying the Green Gables Formation and underlying the Seacow Formation. Magdalen Formation rocks have previously been correlated with all or parts of the Upper Riversdale (Hudsons Bay Oil and Gas Ltd., 1980a, 1980b, 1970) or Pictou (Chevron Canada Resources, 1983) Groups. The formation has also been informally referred to as the "Gas Sands" (COGLA, 1990).

**Well Type Section:** Hudson's Bay-Fina East Point E-49 from 1581 to 1878 m, 297 m thick, is designated the type section (Fig. 2.26, Table 2.7).

**Well Reference Section:** Hudson's Bay *et al.* East Point E-47 from 1545 to 1869 m, 324m thick (Table 2.7).

**Lithology:** The formation is predominantly sandstone in the central portion of the CMB but becomes shalier towards the basin flanks. The unit contains minor coal and limestone beds. The sandstones are light green to grey to pink, fine- to medium-grained, subangular, siliceous, argillaceous, and medium to well sorted. The unit locally contains quartz pebbles. Feldspar content is up to 40% near the base of the unit then decreases upwards. Calcite cementation increases upsection. Shales are green to grey to red, silty, micaceous, dolomitic and contain stringers of coal and siltstone. The shales redden upwards. Thin beds (<1m) and stringers of coal are found throughout the section. Limestones tend to be thin beds (<1.5m ) and stringers, light brown, argillaceous and silty. They are found generally at the base and middle of the section. The average sandstone/shale ratio of the Magdalen Formation is 1.10. Porosity values are between 7 to 9 % and cuttings reports indicate permeability is typically low to fair.

**Boundaries:** In the central portion of the CMB the conformable contact with the overlying shales of the Seacow Formation is placed above the last major sandstone succession of the Magdalen Formation. This contact is easily distinguished by the well logs and cuttings samples. As the Magdalen Formation becomes shalier towards the basin flanks, the upper contact becomes increasingly difficult to identify and is tentatively placed at the top of the first significant fining upwards-coarsening upwards cycle (the Magdalen Formation) above the Green Gables Formation. The lower contact with the underlying Green Gables Formation has been discussed previously.

**Distribution:** The original distribution of the Magdalen Formation is unclear due to removal of section during the Stephanian-Westphalian event. The formation is presently restricted to the southeastern portions of the Maritimes Basin, broadly bordered by the Magdalen Islands, western Cape Breton and northeastern P.E.I.. The Magdalen Formation is at its thickest and has the highest sandstone/shale ratios close to the basin axis and depocentre. The sandstone/shale ratios decrease toward the flanks. The formation is erosionally truncated to the south-southwest, towards the New Brunswick platform and

northeastern P.E.I., by the overlying Cable Head Formation and thins towards Cape Breton Island.

**CMB Seismo-Stratigraphic Equivalents:** In the central portion of the CMB, the East Point Wedge seismic sub-sequence is equivalent to the Magdalen Formation which is defined by seismic sub-sequence boundaries R3b and R3a, respectively.

**Depositional Environment:** The Magdalen Formation displays a dominantly cylindrical-funnel shaped log signature that suggests a braided fluvial environment that may have developed some deltaic units (Cant, 1992) and was favourable for the development of peats. Toward the basin flanks, the formation is characterized by serrated log signatures suggesting deposition on a floodplain (Cant, 1992). Together the two interpretations suggest the Magdalen Formation was deposited on a broad braidplain with larger channels concentrated in the central portion of the CMB. The seismic facies analysis suggests that the Magdalen Formation was deposited under higher energy conditions towards the depocentre. The presence of locally developed prograding clinoforms suggests that the higher energy environment was potentially prograding towards the depocentre (Vail *et al.*, 1977). The lower energy environments towards the basin flanks suggest relatively uniform deposition in a stable basin plain setting (Vail *et al.*, 1977).

**Age:** Westphalian (INRS-Petrole, 1975c), Stephanian (Barss *et al.*, 1979) at the type section and Stephanian B-D (Dolby, 1994) at the reference section. Late Westphalian D is interpreted from an evaluation of available biostratigraphic data for the Magdalen Formation.

**Onshore Equivalents:** As mentioned above, the seismic and well data indicate the formation either is eroded to the south-southwest or "shales" towards the southeast-east-northeast becoming essentially indistinguishable from the underlying shale-prone Green

Gables Formation. No onshore equivalents are interpreted.

### 2.3.4.4.6 Seacow Formation

**Name:** From the prominent coastal inlet on the Magdalen Islands in the Gulf of St. Lawrence. The Seacow Formation is defined as the lithostratigraphic unit overlain by the Cable Head Formation and underlain by the Magdalen Formation. The Seacow Formation has been previously correlated with all or parts of the Cumberland (Hudsons Bay Oil and Gas Ltd., 1970) and Pictou (Chevron Canada Resources, 1983) Groups.

**Well Type Section:** Hudson's Bay-Fina East Point E-49 from 956 to 1581 m, 625 m thick, is here designated the type section (Fig. 2.26, Table 2.7).

**Well Reference Section:** Irving-Chevron-Texaco Cable Head E-95 from 1597 to 1891 m, 294 m thick (Fig. 2.27, Table 2.7).

**Lithology:** A slightly coarsening upwards unit predominantly composed of shales with interbedded sandstones and thin limestones. Thin beds (<0.5m), stringers, and traces of coal are found locally at the base of the section. The corresponding well log profile displays a serrated character which typically displays a slight decrease in gamma-ray or spontaneous potential response towards the top of the section. The shales are red to green to grey, silty, calcareous, micaceous and contain siltstone, coal, and limestone stringers. The sandstones are light grey to light pink, fine- to medium-grained, subangular, silty, calcite cemented, argillaceous, and medium to well sorted. Thin beds (<1m) and stringers of limestone are grey to light brown, argillaceous, fossiliferous, and found at the base of the section. The Seacow Formation has an average sandstone/shale ratio of 0.66.

**Boundaries:** The upper and lower contacts in the south-southeastern portion of the CMB, broadly in an area bordered by the Magdalen Islands, western Cape Breton and

# Cable Head E-95

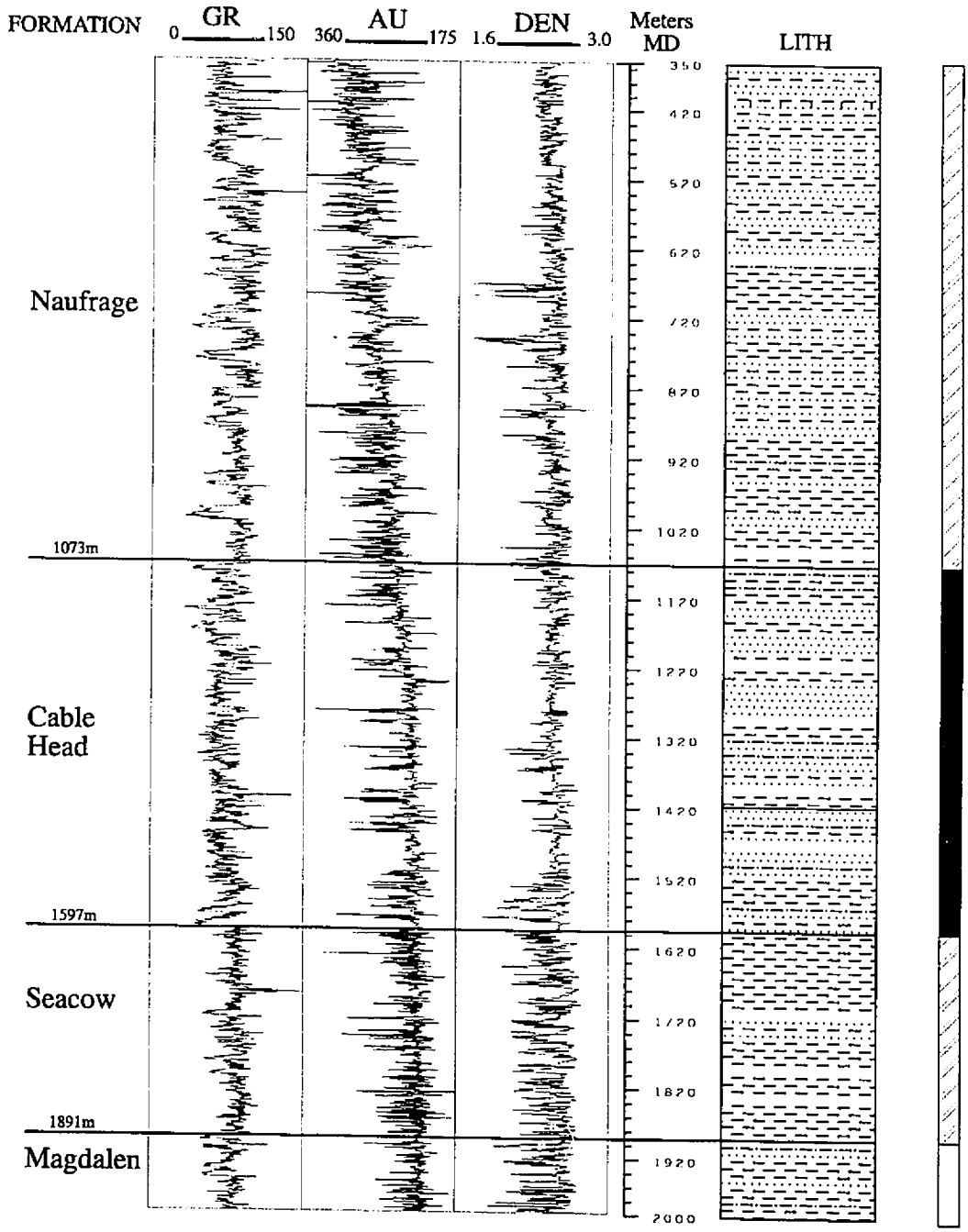



Figure 2.27 Gamm-ray/sonic/density log and lithostratigraphy of the Cable Head E-95 well (see Fig. 2.3 for location). Well type section for the Cable Head Formation. Well reference section for the Seacow and Naufrage formations. Legend as in Figure 2.21.

northeastern P.E.I., are sharp and easily identified from well logs. The lower conformable contact with the underlying Magdalen Formation was discussed previously. The top of the Seacow Formation is marked by the regional Westphalian-Stephanian event. Lithologically it is defined as the base of the first thick red-sandstone dominated sequence above the Seacow Formation and is easily picked on logs.

**Distribution:** The distribution of the Seacow Formation appears to be broadly the same as the Magdalen Formation.

**CMB Seismo-Stratigraphic Equivalents:** The Seacow Formation is stratigraphically equivalent to the Low Energy Zone B1 seismic sub-sequence. The lower and upper contacts of the Seacow Formation correspond to the seismic sub-sequence boundary R3b and primary sequence boundary R4, respectively.

**Depositional Environment:** The high gamma-ray responses with a dominantly serrated log signature suggest deposition on a fluvial floodplain (Cant, 1992). The formation locally has cylindrical-funnel shaped signatures within the section suggesting some braided fluvial to deltaic bodies. The low energy zone B1 seismic unit facies analysis suggests relatively uniform deposition on a stable basin platform (Vail *et al.*, 1977). Both data sets suggest that the Seacow Formation was deposited on a broad fluvial floodplain with local channel-sand bodies, probably of braided style.

**Age:** Lacking biostratigraphic data for the type section and Westphalian D to Stephanian (Hacquebard, 1986) at the reference section. An evaluation of all biostratigraphic data for the Seacow Formation indicates Late Westphalian D to Early Stephanian.

**Onshore Equivalents:** As with the Magdalen Formation, the seismic and well data indicate the formation either is eroded to the south-southwest and to the southeast-east-northeast becomes indistinguishable from the Green Gables Formation. No specific

onshore equivalents are interpreted.

### 2.3.4.5 CMB Pictou Group

#### 2.3.4.5.1 Cable Head Formation

**Name:** From the Irving-Chevron-Texaco Cable Head E-95 well where the formation is best developed in the Central Maritimes Basin and where its type section is located. The Cable Head Formation is defined as the sandstone-dominated lithostratigraphic unit typically overlying the Green Gables Formation but locally overlying the Magdalen or Seacow formations. Cable Head Formation rocks have previously been correlated with all or parts of the Cumberland (Hudsons Bay Oil and Gas Ltd., 1980a) or Pictou (Chevron Canada Resources, 1983) Groups. The formation has been informally assigned to the "Permian" (Sarep Ltd., 1971).

**Well Type Section:** Irving-Chevron-Texaco Cable Head E-95 from 1073 to 1597 m, 524 m thick, is here designated the type section (Fig. 2.27, Table 2.7).

**Well Reference Section:** Hudson's Bay-Fina Green Gables No.1 from 935 to 1515 m, 580 m thick (Fig. 2.25, Table 2.7) and Sarep H.Q. Brion Island No.1 from 405 to 802 m, 397 m thick (Table 2.7)

**Lithology:** The formation is predominantly composed of sandstones with interbedded shales and traces of coal. The sandstones are dark red to red to light brown, fine- to medium-grained, subangular grading to subrounded upwards, medium sorted changing to well sorted upwards, and argillaceous. The sands typically coarsen upwards and there are local rusty brown quartz pebbles at the top of the section. Cuttings reports indicate that feldspar seems to be absent from this unit but there is an increase upwards in glauconite and kaolinite. The entire unit is dominantly calcite cemented. The shales are dark red to red grey, silty, micaceous, mottled and redden upwards. They contain abundant plant

fragments and have thin siltstone and limestone stringers. Thin beds, stringers and traces of coal are found throughout the section. The unit has an average sandstone/shale ratio of 2.25. Porosity values are 5 to 8 % and well history reports indicate traces of fracture porosity. The cuttings reports indicate that permeability is generally very low to low.

**Boundaries:** The upper and lower contacts are sharp and distinguishable with well logs and samples. The lower contact, mentioned previously, is marked by the regional Westphalian-Stephanian, conformable to disconformable surface which separates the Cable Head Formation from the underlying Green Gables, Magdalen and Seacow formations. The upper contact with the Naufrage Formation is conformable and defined at the top of the highest sandstone dominated succession of the formation. The contact is easily identified with gamma-ray logs and samples.

**Distribution:** The Cable Head Formation is a laterally extensive lithostratigraphic unit that blankets the complete CMB. It is best developed (thickest section and highest sandstone/shale ratios) in the south-southeastern portion of the CMB in an area broadly bordered by the Magdalen Islands, western Cape Breton and northeastern P.E.I.. The formation thins towards the basin flanks where it eventually onlaps older basin fill strata as well as the basement.

**CMB Seismo-Stratigraphic Equivalents:** The Cable Head Formation and overlying Naufrage formation collectively are equivalent to the Top High Energy Zone seismic sequence. Primary seismic sequence boundary R4 is equivalent to the base of the Cable Head Formation.

**Depositional Environment:** The dominantly cylindrical, with minor funnel shaped, log signatures suggests a braided fluvial environment that may have developed some deltaic bodies (Cant, 1992). The typically massive nature of the sandstones towards the top of the sections suggests the depositional system evolved into a more stable, or mature,

environment (Melvin, 1993). The seismic facies analysis of the top high energy zone seismic facies suggests that the Cable Head Formation was deposited in a high energy environment. The recognition of locally prograding clinoforms suggests that the high energy environment may have been prograding towards the basin depocentre (Vail *et al.*, 1977). Combining the two interpretations suggests that the Cable Head Formation was deposited in a prograding braidplain fluvial system. This interpretation is generally consistent with previous onshore interpretations (Table 2.8).

**Age:** Stephanian (Hacquebard, 1986) at the type section and Stephanian (INRS-Petrole, 1975c; Barss *et al.*, 1979) at the reference section. Early Stephanian to Early Permian is interpreted from an evaluation of the biostratigraphic data for the Cable Head Formation.

**Onshore Equivalents include all or part of:** Balfron/Tatamagouche, Broad Cove and Tormentine Formations; "Unnamed Redbeds" (Sydney subbasin); Lower Succession (II-1-A to II-1-C) of Pictou Group Megacycle II (LeGallais, 1983) (Figs. 2.22, 2.2).

#### 2.3.4.5.2 Naufrage Formation

**Name:** From the Soquip *et al.* Naufrage No. 1 well where the type section is located. The Naufrage Formation is defined as the coarsening upwards lithostratigraphic unit that conformably overlies the Cable Head Formation. Naufrage Formation rocks have previously been correlated with all or parts of the Cumberland (Hudsons Bay Oil and Gas Ltd., 1980a) and Pictou (Hudsons Bay Oil and Gas Ltd., 1980b) Groups. The formation has informally been referred to as the "Permian" (Chevron Canada Resources, 1983) and "Red Bed" (Soquip *et al.*, 1975a, 1975b) units.

**Well Type Section:** Soquip *et al.* Naufrage No.1 from ground level to 1140 m, 1135 m thick, is here designated the type section (Fig. 2.28, Table 2.7).

# Naufrage No. 1

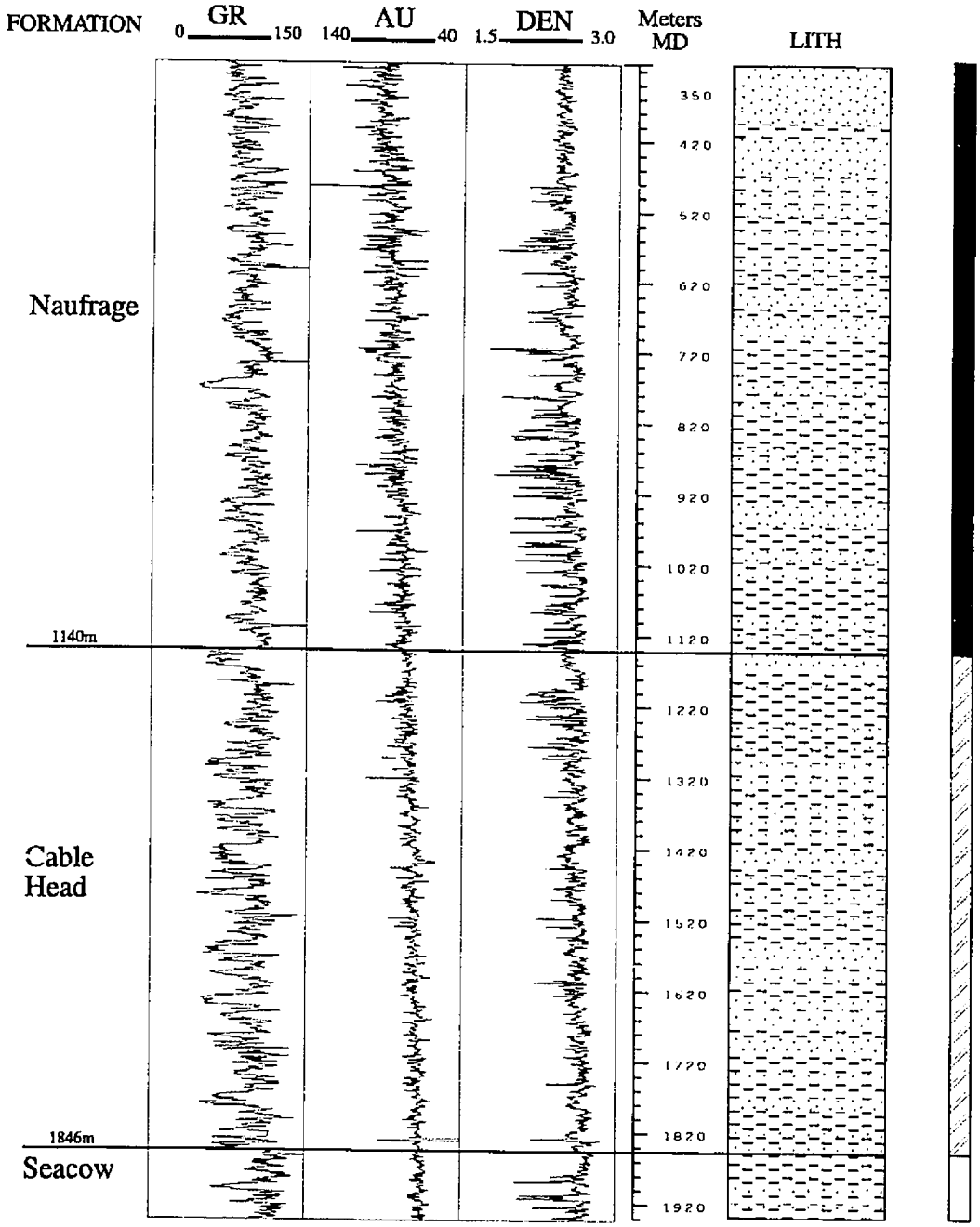



Figure 2.28 Gamma-ray/sonic/density log and lithostratigraphy of the Naufrage No.1 well (see Fig. 2.3 for location). Well type section for the Naugrage Formation and reference section for the Cable Head Formation. Legend as in Figure 2.21.

**Well Reference Sections:** Irving-Chevron-Texaco Cable Head E-95 from sea bottom to 1073 m, 990 m thick (Fig. 2.27, Table 2.7) and Soquip *et al.* Tyrone No.1 from ground level to 1430 m, 1426 m thick (Table 2.7).

**Lithology:** The formation is predominantly composed of sandstones with interbedded shales and some limestones. The unit coarsens upwards, being shale-dominated at the base and sandstone-dominated at the top. The sandstones are red brown to light green, fine- to medium-grained, subangular grading upwards to subrounded, medium sorted changing upwards to well sorted, and contain some quartz pebbles. The sandstones tend to increase in grain size and bed thickness upsection. Sandstones at the base occur as individual units, generally less than 10m thick and become massive towards the top of the section. Cuttings reports indicate an increase in chert, glauconite, and kaolinite upwards. The sandstones are cemented with calcite. The shales are red brown to light brown, silty, micaceous, and contain both limestone and siltstone stringers. The limestones are red, argillaceous, dolomitic, silty, and found at the base and middle of the section. The formation has an average sandstone/shale ratio of 0.90. Porosity values are 5 to 8% and cuttings reports indicate permeability is very low.

**Boundaries:** The Naufrage Formation conformably overlies the Cable Head Formation. The lower contact with the Cable Head Formation has been discussed previously. The upper contact of the Naufrage Formation, the uppermost stratigraphic unit in the CMB, is marked by the regional Permian unconformity which has removed an indeterminate quantity of upper Naufrage Formation strata.

**Distribution:** The presence of the Permian unconformity masks the original details of Naufrage Formation distribution. Well and seismic data imply that the formation is presently widely distributed throughout the entire Central Maritimes Basin and forms isolated erosional remnants onland. The best developed (thickest) sections are located in the P.E.I. and Magdalen Islands areas.

**CMB Seismo-Stratigraphic Equivalents:** The Naufrage Formation and underlying Cable Head Formation are collectively equivalent to the Top High Energy Zone seismo-stratigraphic unit. Detailed seismic resolution of this unit is masked by seismic multiples and surface noise.

**Depositional Environment:** The Naufrage Formation is dominated by serrated log signatures near the base, suggesting deposition on a fluvial floodplain. The upper portions of the formation have more cylindrical and blocky signatures suggesting a change to a higher energy environment, probably a fluvial braidplain environment (Cant, 1992). The typically massive nature of the sandstones towards the top of the sections suggests the depositional system evolved into a more stable, or mature, environment (Melvin, 1993). The seismic facies analysis is inconclusive due to seismic multiples and surface noise. An alluvial floodplain to braided fluvial environment is generally consistent with prior interpretations of equivalent strata (Table 2.8).

**Age:** Stephanian to Early Permian (Dolby, G., 1994, pers. comm.), Westphalian D to Stephanian to Lower Permian (Soquip *et al.*, 1975a) at the type section and Stephanian to Permian (Barss *et al.*, 1979) at the reference section (Soquip *et al.*, 1975b). An evaluation of the biostratigraphic data for the Naufrage Formation suggests Early Permian to Late Early Permian.

**Onshore equivalents include all or part of:** Tatamagouche/Cape John and Cap-aux-Meules Formations; Prince Edward Island Group; Upper Northumberland Strait Supergroup (van de Poll, 1989); Upper Succession of Pictou Group Megacycle II and Megacycle III (LeGallais, 1983) (Figs. 2.22, 2.2).

### 2.3.5 CMB Paleodepositional Environments: Protozoan Analysis

Combining the protozoan data set with the CMB stratigraphic framework, indicates that there is an overall increase in the proportion of agglutinated foraminifera

from near the base of the Bird Rock Formation up to the base of the Cable Head Formation (Fig. 2.29), suggesting that, in addition to the depositional environments proposed in the above sections, this succession of strata may have been deposited in restricted-marine conditions.

Data for the schematic sea level curve are derived from the original 65 CMB samples as well as previously documented occurrences of marine influenced agglutinated foraminifera onshore. Similar assemblages of marine influenced foraminifera in the upper Cumberland Group onshore have been identified by Archer *et al.* (1995) in the Joggins Formation (Bird Rock Formation onshore equivalent), R. Naylor (1995, pers. comm.) in the Malagash Formation (Bradelle Formation onshore equivalent) and by Gibling and Bird (1994) in the Sydney Mines Formation (Green Gables Formation onshore equivalent).

A closer examination of the section, from bottom to top, reveals that the proportion of foraminifera increase upwards to a relative maximum at the top of the Bradelle Formation. The numbers of foraminifera then decrease slightly in the Green Gables Formation, then increase, to a maximum, near the top of the Magdalen Formation. The data then suggest a slight decrease in proportions from the base of the Cable Head Formation upwards. Relative foraminifera maxima seem to coincide with the upper contacts of the Bradelle and Magdalen Formations, units which are relatively coarse-grained.

The ratio of foraminifera to thecamoebians is a semi-quantitative indicator of marine influence (Wightman *et al.*, 1994a). These ratios, along with the geologic boundaries associated with described CMB stratigraphy, imply that there was a relative rise in sea level from approximately Early Westphalian B to Late Westphalian C/Early Westphalian D (Fig. 2.29). A subsequent decrease in relative sea level followed during the Middle Westphalian D. This was followed by another sea level rise, from Late Westphalian D to possibly Early Stephanian time, after which sea level seems to have dropped (Fig. 2.29).

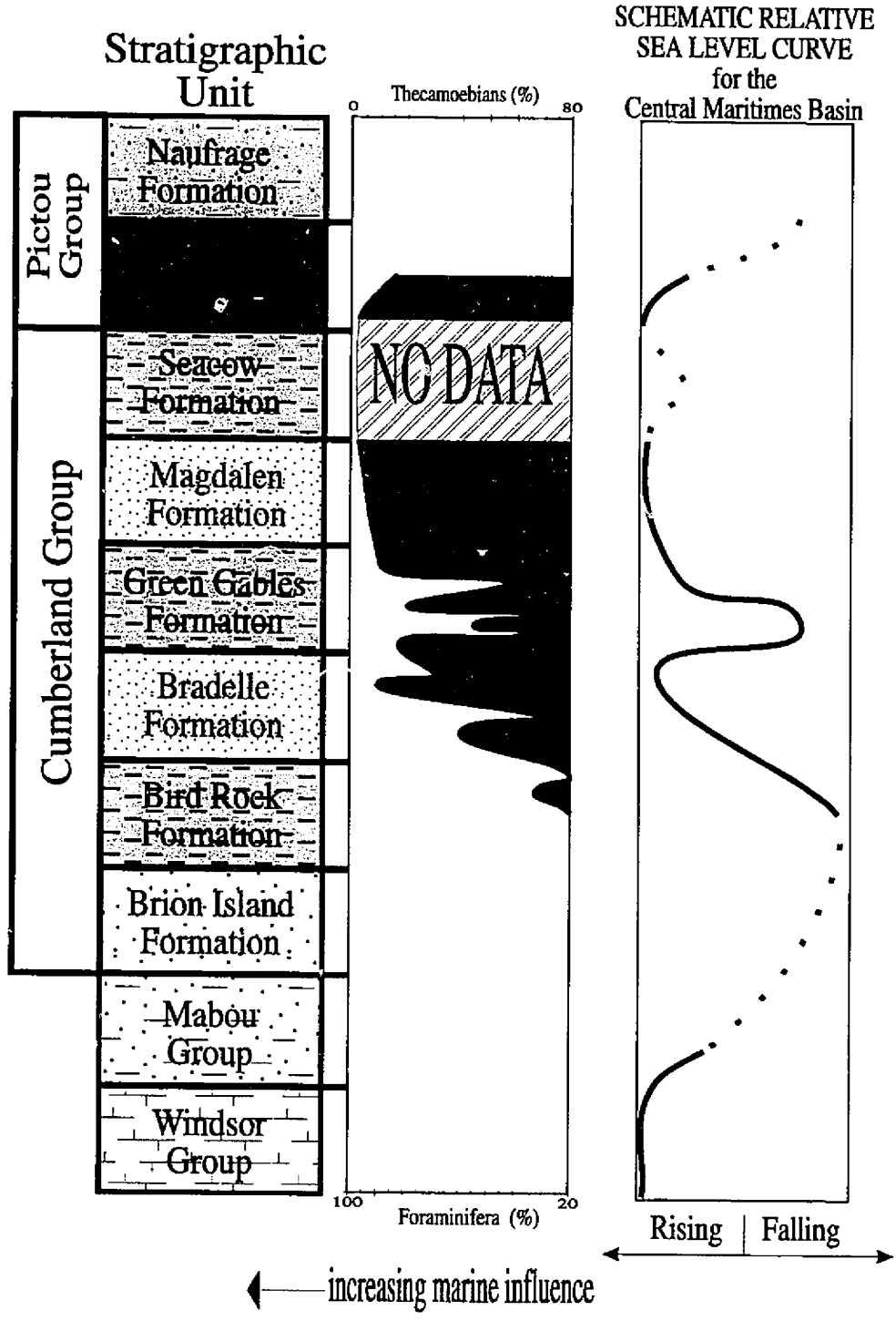



Figure 2.29 Stratigraphic column (left) and general quantitative distribution of agglutinated foraminifera over the CMB stratigraphic column. Data from wells #7, #15, #16 and #17: see Table 2.1 for well names and Figure 2.3 for locations. (Right) Schematic relative CMB sea level curve based on an integration of CMB protozoan analysis results and onshore interpretations by Archer et al. (1995), R. Naylor (1995, pers. comm.) and Gibling and Bird (1994).

## 2.4 Discussion

### 2.4.1 Stratigraphic Uncertainties

Subsurface stratigraphic correlation is an interpretative process, the accuracy of which depends on the amount, availability and quality of subsurface data. For this project, biostratigraphic, lithologic and seismic data sets were used collectively to develop the stratigraphic framework proposed. Use of a single data set would have resulted in differing stratigraphic interpretations as discussed below.

Using one, or all, of the biostratigraphic data sets would have led to interpretations that linked units of apparently similar age despite changes in lithologic characteristics or apparent lithologic boundaries. This would have led to the correlation of genetically unrelated sandstone and shale successions suggesting unlikely facies changes or faulting. Further, as shown on the bio/lithostratigraphic cross-sections (Enclosures 1-6), the CMB biostratigraphic data typically do not exhibit the resolution needed to pick consistent geologic boundaries; time-lines could be placed only at the 100s of metres scale, an order of magnitude larger than the resolution currently being utilized in most modern, high frequency, sequence stratigraphic studies (Church and Gawthorpe, 1994).

Using only the lithologic data collected from well logs and chip samples would have resulted in the correlation of major stratigraphic units across geologic time lines, implying strongly diachronous boundaries. Although on smaller scales (tens of metres) this may be acceptable (Slatt, 1992), on the scale of this basin analysis project a strict adherence to lithostratigraphy would have resulted in correlation of major stratigraphic units that were not stratigraphically equivalent.

Finally, correlation utilizing only the seismic data would have resulted in the complete identification of a CMB seismo-stratigraphic column with mappable seismic sequence boundaries and seismic sequences, however, chronostratigraphic significance of the surfaces and sequences or the lithologic characteristics of the seismic sequences would have remained unresolved.

The integration of each data set into the stratigraphic analysis contributed to a

better overall understanding of the proposed CMB stratigraphic framework. Utilization of the biostratigraphy led to the identification of time gaps or events. The resolution of the data, however, was not sufficient to precisely identify a specific stratigraphic horizon for the event or to resolve whether the gaps were due to erosional events, depositional hiatuses or faulting. The lithologic information helped identify potential bounding surfaces as abrupt breaks in lithology at the bases of mappable lithostratigraphic units. The final integration with the seismic data established that, apart from post-depositional salt flowage, the CMB fill is relatively undeformed, suggesting that the events displayed by the fill were not caused by localized faulting. Synthetic seismograms assisted the correlation of biostratigraphic events and lithostratigraphic units with major seismic sequence boundaries and seismic sequences, implying that the CMB fill consists of regionally mappable, large-scale stratigraphic units which are bounded by regionally identifiable surfaces with chronostratigraphic significance. Analysis of the seismic sequence boundaries resulted in the recognition of reflector terminations/truncations and baselapping relationships that contributed to a better understanding of the nature of the Namurian-Westphalian, Mid-Westphalian and Stephanian-Westphalian events discussed below.

### 2.4.2 Regional Boundaries

Regionally significant discontinuities are identified by locating biostratigraphic discontinuities (Visher, 1984), by identifying abrupt lithologic breaks or changes in the depositional record (Lindsay and Korsch, 1989), and by recognizing reflector terminations, baselapping relationships or discontinuities on seismic records (Vail *et al.*, 1977). Three regionally extensive events referred to as the Namurian-Westphalian, Mid-Westphalian and the Westphalian-Stephanian events have been identified in the CMB fill.

#### 2.4.2.1 Namurian-Westphalian Event

The biostratigraphic break near the Namurian-Westphalian boundary could have been the result of erosion, depositional hiatus or faulting (i.e., Slatt, 1992). The

accompanying abrupt change in lithology from the interbedded fine- to medium-grained sandstones, siltstones and shales of the Mabou Group to the medium- to coarse-grained, locally conglomeratic, sandstones of the Brion Island Formation confirms the presence of a major bounding surface at the top of the CMB Mabou Group. The correlative R2 seismic boundary is conformable to unconformable, locally truncates underlying reflectors and shows evidence of baselapping relationships on older CMB strata and deformed basement rocks.

An apparent clay mineralogical anomaly was identified at the top of the Mabou Group (Figs. 2.30, 2.31). Recognition of the anomaly is somewhat debatable due to the widely spaced sample locations and the lack of detailed documentation regarding data analysis. Nevertheless, the anomaly is marked by a noticeable absence, or significant decrease, in kaolinite proportion near the top of the Mabou Group (Namurian-Westphalian event) on the bulk clay mineralogy (2-16$\mu$ and <2$\mu$) profiles (Fig. 2.30). The reduction is present over a 200 to 300 m interval, above which the proportion of kaolinite typically increases and stays fairly stable. There is an accompanying abrupt increase in the even/odd ratios of chlorite peak ratios (002/001 and 004/003) (Fig. 2.31), which remain elevated for a short interval then decrease gradually towards the top of the wells. The increase in chlorite peak ratios was first identified by INRS-Petrole (1975a) and the anomaly was informally referred to as the "chlorite break marker".

The causes of the kaolinite and chlorite anomalies were not investigated by INRS-Petrole (1975a, 1975c). However, the company reports concluded that there was no trace of clay diagenesis due to burial and no improvement of illite crystallinity with depth, and that the anomalies were due to changes in the type and origin of detrital constituents (INRS-Petrole, 1975a, 1975c; Soquip, 1987). Further interpretations are speculative as the original X-ray diffraction data are not available.

Detrital kaolinite is formed typically in humid environments as a result of the weathering of kaolinite-rich or feldspathic rocks (Weaver, 1989). The disappearance or significant decrease in kaolinite from the stratigraphic column just above the Namurian-

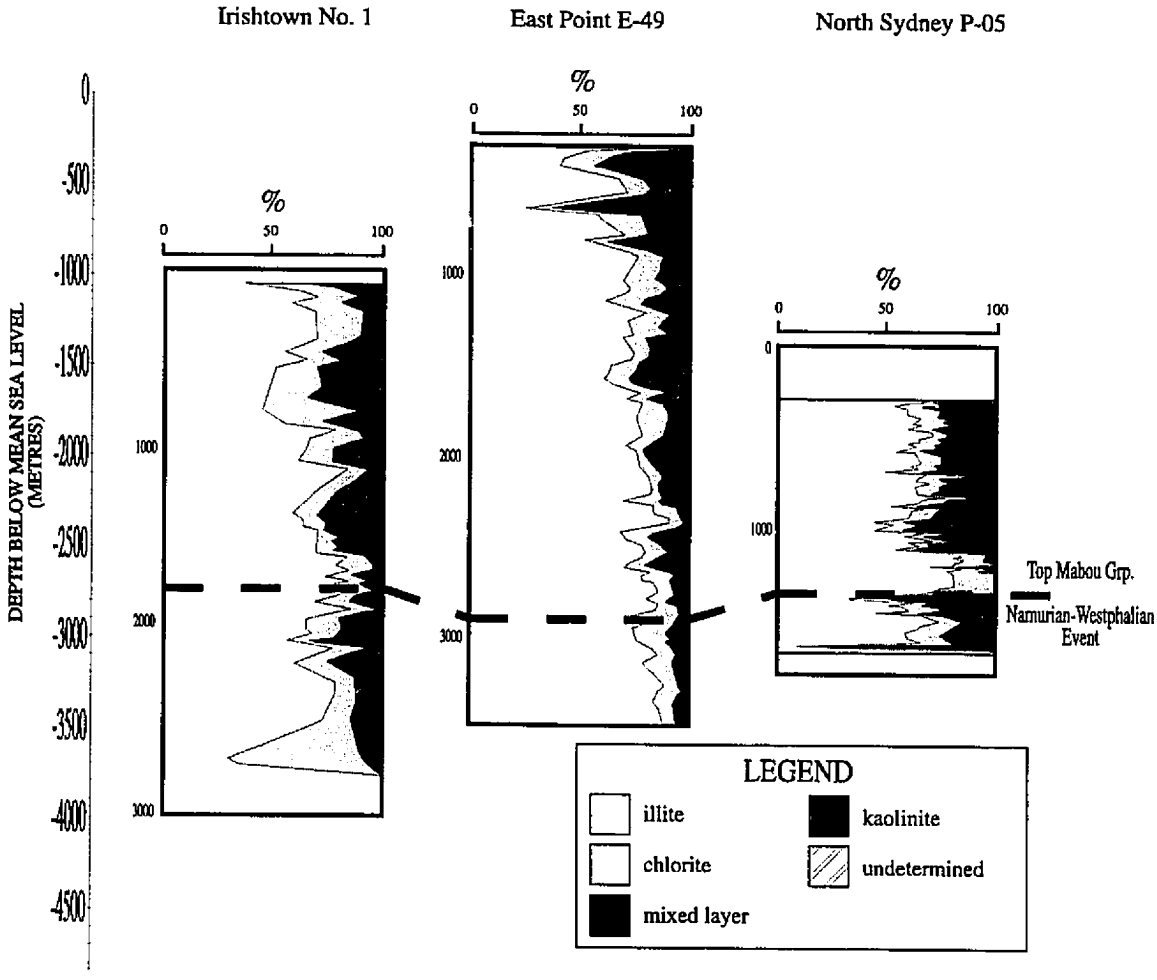



Figure 2.30 Semi-quantitative vertical distribution of bulk clay mineralogy (<2$\mu$ fraction) for three wells in the CMB (see Fig. 2.3 for well locations)(modified from INRS-Petrole, 1975a, 1975b). An absence, or significant decrease in kaolinite occurs in close proximity to the top of the Mabou Group (Namurian-Westphalian event). Trends in data are similar for (2-16$\mu$) bulk clay mineralogy fraction.

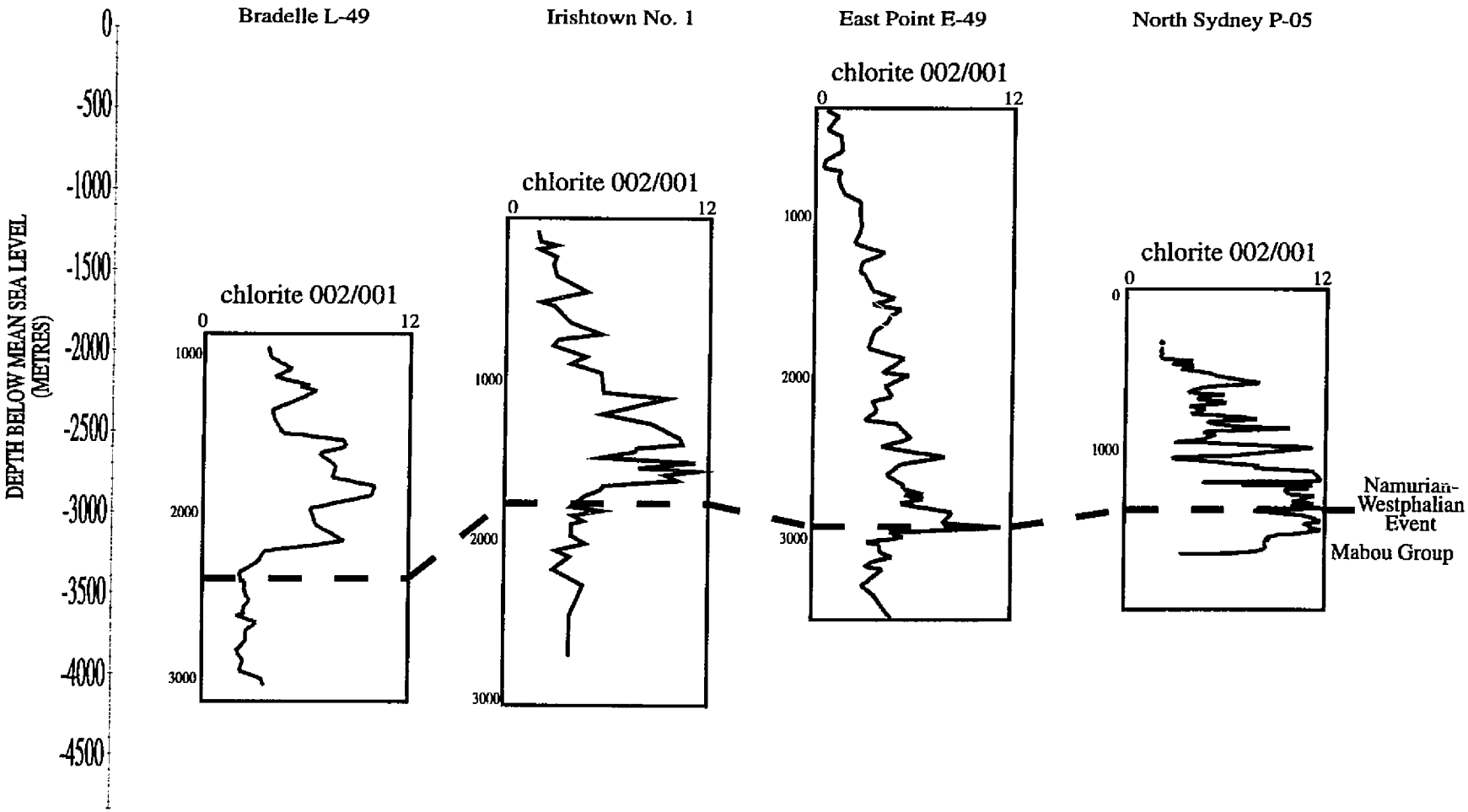



Figure 2.31 Semi-quantitative vertical plots of changing chlorite 002/001 peak ratios (<2μ fraction) for four wells in the CMB (see Figure 2.3 for well locations) (modified from INRS-Petrole, 1975a, 1975b. 1975c). An abrupt increase in the ratio occurs in close proximity to the top of the Mabou Group (Namurian-Westphalian event). Trends in data are similiar for the 2-16μ clay fraction and the chlorite 004/003 peak rations.

Westphalian event (top of Mabou Group) suggests that the formation and transportation of kaolinite from the original source was terminated or that a new source was exposed that could not provide kaolinite, or diluted other kaolinite sources. Paleogeographic reconstructions for the Namurian and Westphalian indicate that the Maritimes Basin was in close proximity to the paleoequator (Scotese and McKerrow, 1990), so it is unlikely that the weathering process at the original source area was terminated. It is more likely that detrital kaolinite variation was due to a geographical change in detrital source areas (cf., Huertas *et al.*, 1995).

If detritus was being transported from a newly exposed source after the Namurian-Westphalian event, the subsequent increase in the kaolinite fraction could reflect the readjustment of the depositional system (cf., Debrabant *et al.*, 1993). Lag times, or periods of decreased kaolinite yield, of up to 10 million years have been reported between pulses of kaolinite-rich sediments in the Amazonian Lowlands (Irion *et al.*, 1995). These pulses are attributed to the time needed for a new bedrock source to weather, produce kaolinite-rich soils, and supply the kaolinite to the basin (Irion *et al.*, 1995).

The detrital chlorite identified in the INRS-Petrole (1975a, 1975b, 1975c) samples is interpreted to be derived primarily from the erosion of mica-rich granites and chlorite-bearing metamorphic and volcanic rocks (Weaver, 1989). A stable supply of chlorite to the system is evident from Fig. 2.30, which displays no apparent change in proportion of chlorite through the stratigraphic column. However, Figure 2.31 shows an abrupt increase in the 002/001 (004/003) even/odd peak area ratios of the $<2\mu$ ($2\text{-}16\mu$) fractions of chlorite. High even/odd peak ratios indicate that detrital chlorites are iron-rich rather than magnesium-rich chlorites (Brindley, 1961). The abrupt compositional change in detrital chlorite could suggest a switch to a newly exposed source area for the Maritimes Basin, further supporting the suggested cause of the kaolinite anomaly.

The Namurian-Westphalian event has been identified, commonly in the form of an unconformity, by several authors working around the periphery of the CMB. In

southern New Brunswick, Gussow (1953) identified an unconformable contact between the Enrage and Shepody Formations (Table 2.8, Figs. 2.22, 2.2). St. Peter (1993, 1996) identified an unconformity (his $\mathbf{V_2}$) between the overlying Cumberland and underlying Hopewell Groups in the Moncton subbasin (Table 2.8, Figs. 2.22, 2.2). In southwestern Nova Scotia, Bell (1926) recognized an unconformable contact between the Millsville (Lower Cumberland) and River John Series. The most recent stratigraphic interpretation in the Cumberland subbasin by Ryan and Boehner (1994) indicates that the Cumberland Group conformably to disconformably overlies the Mabou Group and unconformably overlies older Carboniferous rocks and basement.

On the southern edge of the CMB, a Namurian-Westphalian event was identified as a Riversdalian lacuna represented by an unconformable to conformable surface between the overlying New Glasgow and the underlying Lismore Formations (Fralick and Schenk, 1981). In the same general area, Chandler *et al.* (1995) have mapped the Upper Mabou Group eroded and unconformably overlain by Claremont and New Glasgow Formations. On the western coast of Cape Breton Island, an unconformity typically separates the Mabou Group from the overlying Port Hood Formation (Crawford, 1995) (Table 2.8, Figs. 2.22, 2.2).

In the Cabot Strait, between Cape Breton Island and Newfoundland, an unconformable surface (NWU = Namurian Westphalian Unconformity, Fig. 2.2) has been recognized between Cumberland and Mabou Group equivalent rocks (Langdon and Hall, 1994). In the Deer Lake subbasin (Fig. 2.1) the Namurian-Westphalian event can be identified by an unconformable contact between the underlying Deer Lake Group and the overlying Howley Formation (Hyde *et al.*, 1988) (Table 2.8, Figs. 2.22, 2.2).

Soquip (1987) mapped a regional unconformity above the Canso-Riversdale stratigraphic succession in the Gulf of St. Lawrence which was correlated with the chlorite break marker identified in the previously mentioned wells. This regional unconformity was mapped over an area in excess of 50 000 km$^2$ and is presumed to be stratigraphically equivalent to the Namurian-Westphalian event more fully documented

here.

### 2.4.2.2 Mid-Westphalian Event

Biostratigraphic data from 6 wells (Fig. 2.8) in the CMB indicate that a potential time gap exists near the Westphalian B - C boundary (Mid-Westphalian), which suggests the removal, non-deposition or faulting of portions of Early to Middle Westphalian B and Westphalian A strata. This event is in close proximity to the base of the Bradelle Formation where there is an abrupt contact between the overlying sandstone-dominated succession and the underlying shale-dominated Bird Rock Formation. In four cases (wells #1, #2, # 7 and #27; Enclosure 2) the Bradelle Formation lies directly on the interbedded sandstones and shales of the Mabou Group. This implies the merging of the Mid-Westphalian and the Namurian-Westphalian events.

Integrating the bio/lithostratigraphic information with the seismic data using synthetic seismograms allowed the correlation of the Mid-Westphalian event with the seismic sub-sequence boundary R2b, which displays strong downlapping relationships with the underlying seismo-stratigraphic unit in its type section. On the LITHOPROBE 86-1 seismic line (Fig. 2.14) the interpreted R2b seismic sub-sequence boundary cuts down into the primary sequence boundary R2 near the East Point salt structure.

Previous authors have identified disconformable surfaces suggesting an onshore Mid-Westphalian event at numerous outcrop locations around the Gulf of St. Lawrence. In New Brunswick, Gussow (1953) identified a disconformity at the contact between the Richibucto Formation and the Scoudouc Formation (Table 2.8). S. Johnson (1995, pers. comm.) has indicated that the Richibucto Formation on the New Brunswick coast, unconformably overlies the Boss Point Formation (Table 2.8, Fig. 2.22). In the Cumberland subbasin the Malagash/Boss Point Formation boundary is an angular unconformity (Table 2.8, Fig. 2.22) (Ryan and Boehner, 1994; Webb, 1963). On western Cape Breton Island, the Inverness Formation is inferred to lie unconformably on the older Port Hood Formation (Giles *et al.*, 1996) (Table 2.8, Fig. 2.22), although the contact is not observed in outcrop.

The special case where the Mid-Westphalian event and the Namurian-Westphalian event merge has been documented by several authors. Gibling *et al.* (1987) show an angular unconformity between the Westphalian C strata of the South Bar Formation and the underlying Mabou Group in the Sydney subbasin (Table 2.8, Figs. 2.22, 2.2). On the west coast of Cape Breton Island, Giles (1996) mapped the Inverness Formation unconformably overlying all older Carboniferous strata as well as basement (Table 2.8, Fig. 2.22).

### 2.4.2.3 Westphalian-Stephanian Event

Biostratigraphic data for CMB wells suggests the occurrence of a time gap, or event, at the Stephanian-Westphalian boundary. Only one well exhibits this event, however, in close proximity to this event is the abrupt lithologic contact between the red sandstone-dominated Cable Head Formation and the grey-red shale-dominated Green Gables Formation. In the south-southeastern portion of the CMB the sharp lithologic break is between the Cable Head Formation and the underlying shale-prone Seacow Formation. The seismic data suggest the correlation of the event, or basal Cable Head Formation, with the primary seismic reflector R4 which truncates reflectors and scours into the underlying strata.

A Stephanian-Westphalian event has been identified, commonly in the form of an unconformity, at numerous locations onshore. In the Cumberland subbasin, Bell (1926) mapped the contact between the Pictou Group and the underlying Joggins Formation as an unconformity, and more recently it has been mapped as the disconformable contact between the Malagash and Balfron Formations (Ryan *et al.*, 1991; Ryan and Boehner, 1994) (Table 2.8, Fig. 2.22). In the Merigomish area, Fralick and Schenk (1981) indicated that the Pictou and Cumberland Groups are separated by a significant lacuna.

In New Brunswick, Gussow (1953) indicated that the distinctive colour difference between the redbed-dominated Pictou Group and the underlying greybed-dominated Cumberland Group suggests a disconformity. St. Peter (1993) recognized a significant

unconformity ($V_3$) separating the Pictou Group from the underlying Cumberland Group in the Moncton subbasin. In the Cabot Strait area, Langdon and Hall (1994) have identified an unconformity (Barachois Unconformity) which is Westphalian to lower Stephanian in age and locally merges with their Namurian-Westphalian unconformity (NWU) (Fig. 2.2). The key contacts between the upper Inverness and Broad Cove formations on the western coast of Cape Breton and between the Sydney Mines Formation and the "unnamed redbeds" in the Sydney subbasin are not observed in outcrop (Table 2.8, Fig. 2.22).

### 2.4.3 CMB Stratigraphy: Basin-Scale Cyclicity

#### 2.4.3.1 Mabou Group in the CMB

The relatively fine-grained Mabou Group in the CMB was completely penetrated by 15 study wells (see Enclosures 1-13) of which the thickest complete section (690m) is found in the Tyrone No.1. well (Fig. 2.3). The thickness of the group increases towards the zone of evaporite tectonism, where it can exceed 1500m (Soquip, 1987). The seismic data indicate that the Mabou Group in the offshore is a uniform, regionally mappable unit bounded by the primary seismic sequence boundaries R1 and R2, which are correlatable with the top and bottom of the Windsor Group and Brion Island Formation, respectively. Towards the flanks of the CMB, the group onlaps all older Carboniferous rocks and pre-Carboniferous basement.

A biostratigraphic synthesis of all the study data suggest that the age of the CMB Mabou Group is Late Viséan-Early Namurian to Early Westphalian A. The well logs and ditch cutting samples indicate that the group is typically composed of thinly interbedded fine- to medium-grained red-grey sandstones, siltstones and shales with minor limestones and marlstones. Seismic and lithostratigraphic data suggest that the CMB Mabou Group was deposited on a relatively stable broad alluvial plain, an interpretation that is generally consistent with onshore interpretations (Crawford, 1995).

### 2.4.3.2 CMB Cumberland Group

The CMB Cumberland Group consists of six regionally mappable formations which were introduced and named in the preceding sections. The formations can be broadly grouped into three packages, each consisting of a basal coarse-grained succession overlain by a finer grained succession. The cyclic succession is bounded by the Namurian-Westphalian and Westphalian-Stephanian events and locally by the Mid-Westphalian event.

The three coarser grained formations (Brion Island, Bradelle and Magdalen formations), where fully developed, predominantly consist of sandstones with average sandstone/shale ratios over 2.0. The basal contacts of these formations are typically marked by conformable to unconformable surfaces. The nature of the Magdalen basal contact is uncertain as biostratigraphic and lithostratigraphic data are sparse. Locally, however, seismic sequence boundary R3, which coincides with the base of the Magdalen Formation in the central portion of the CMB, may be erosional. The upper contacts of all three coarse-grained formations are conformable with the overlying finer grained formations.

The relatively coarse-grained formations generally coarsen upwards, display high sand/shale ratios, show increased coal occurrences towards the top and have multi-storied channel fill with minor funnel log signatures that tend to amalgamate towards the top of the succession. On seismic profiles, the successions display evidence of prograding clinoforms. These characteristics suggest that the coarse-grained formations were deposited in fluvial systems that were prograding basinward.

The three finer grained units are (in ascending order) the Bird Rock Formation, Green Gables Formation and the Seacow Formation. Their lower contacts are conformable and their upper contacts are marked by conformable to unconformable surfaces correlatable with seismic sequence boundaries. The upper contact of the Green Gables Formation, where overlain by the Magdalen Formation may be erosional but this remains unresolved.

The fine-grained successions typically have low sandstone/shale ratios, coals and

thin limestones which tend to be more abundant near the bottom of the section, serrated log signatures and seismic facies characteristic of low energy stable environments. These characteristics suggests that the finer grained formations were deposited in floodplain environments.

Overall, the maximum penetrated section of CMB Cumberland Group is found in Brion Island No.1 (Fig. 2.3) where 1246m of section unconformably overlies the CMB Mabou Group. The East Point E-49 well (Fig. 2.3) penetrated a thicker partially complete section of CMB Cumberland Group (1966m), however, at this location, both the Brion Island and Bird Rock formations have been removed by the Mid-Westphalian event. The maximum thickness of CMB Cumberland Group observed on the study seismic lines was in excess of 4000m. It is suspected that the group reaches a maximum thickness within the zone of salt tectonism, near the depocentre. An evaluation of the biostratigraphic data implies that the age of the CMB Cumberland Group is Early Westphalian A to Late Westphalian D - Early Stephanian.

#### 2.4.3.3 CMB Pictou Group

The CMB Pictou Group is composed of a basal coarse-grained succession overlain by a finer grained succession. The fining upwards nature of the CMB Pictou Group coincides with the two predominantly redbed lithostratigraphic units of the Cable Head and Naufrage formations. Similar to the CMB Cumberland Group coarse-grained successions, the Cable Head Formation generally coarsens upwards, has high sand/shale ratios, shows traces of coal and displays multi-storied channel fill and minor funnel shaped log signatures that tend to amalgamate towards the top of the section. Seismic data show some prograding clinoforms, all of which suggest that the Cable Head Formation was deposited in a braided fluvial system that was prograding basinward. The overlying Naufrage Formation indicates a gradual change from a stable fluvial floodplain environment, as suggested by the serrated log signatures and predominantly fine-grained lithologies, to a high energy braided fluvial environment, as suggested by the massive, blocky log signatures and abundance of sandstone.

The CMB Pictou Group lies conformably to disconformably and locally unconformably over the CMB Cumberland Group and its base is marked by the Stephanian-Westphalian event. The top of the CMB Pictou Group has been eroded beneath a younger unconformity, and current estimates by Hendricks *et al.* (1993) for the Deer Lake area suggest that between 3 to 6 km of strata have been removed since the Triassic.

Overall, maximum penetrated thickness of CMB Pictou Group is 2159m in the Tyrone No.1 well (Fig. 2.3), below the capping unconformity. The thickest section of CMB Pictou Group identified on the study seismic lines is estimated to exceed 3500m near the zone of salt tectonics. The group thickens towards the depocentre so it is presumed that the thickest section of CMB Pictou Group is located within the zone of salt tectonism. A synthesis of all biostratigraphy for the CMB Pictou Group suggest an age of Late Westphalian D - Early Stephanian to Early Permian.

## 2.5 Concluding Statement

This chapter presented a detailed stratigraphic framework for the Central Maritimes Basin. Using an integrated approach which incorporated biostratigraphic, lithostratigraphic and seismic data, it was demonstrated that underlying the southern Gulf of St. Lawrence is a thick (>10km) succession of Carboniferous strata that is broadly equivalent at the group level with the strata that crop out onshore. Focused specifically on the Upper Carboniferous strata, the post-Windsor Group basin fill consists of a thick, essentially undeformed, Early Namurian to Early Permian strata that can be subdivided into three major lithostratigraphic units separated by regionally extensive, chronostratigraphically significant surfaces.

The lowermost Mabou Group conformably to unconformably overlies the Windsor Group and is capped by the regionally extensive Namurian-Westphalian surface. Conformably to unconformably overlying the CMB Mabou Group is the CMB Cumberland Group, which can be further subdivided into six formations consisting of (in ascending order) the Brion Island, Bird Rock, Bradelle, Green Gables, Magdalen

and Seacow Formations. The regionally extensive Mid-Westphalian event lies within this group at the base of the Bradelle Formation. Another potentially major bounding surface lies at the base of the Magdalen Formation, one of two units which are only found in the offshore area (the other being the Seacow Formation).

The CMB Cumberland Group is capped by the regionally extensive Stephanian-Westphalian event. The CMB Pictou Group conformably to unconformably overlies the CMB Cumberland Group and can be subdivided into the lower Cable Head and upper Naufrage Formations. The entire package of strata is capped by a younger (Permo-Quaternary) unconformity.

# CHAPTER 3 - CENTRAL MARITIMES BASIN SEQUENCE ANALYSIS

## 3.1 General Statement

Over the past decade, sequence stratigraphy has become a popular tool to assist interpretations of basin fill. Modern sequence stratigraphic concepts, which were first developed by Vail *et al.* (1977) at the Exxon Corporation, have been applied to basin fills in many different tectonic settings {i.e., foreland (Weimer, 1992), intracratonic (Lindsay and Korsh, 1989), passive margin (Baum and Vail, 1988)}, resulting in almost all cases, an improved understanding of relative time-stratigraphy and depositional history.

Considering the diversity of applications of sequence stratigraphy to the ancient rock record, it follows that such concepts should be applicable to Late Carboniferous strata in the Maritimes Basin. However, relatively few studies have been published that present the Maritimes Basin fill in a sequence stratigraphic context (i.e., Rehill *et al.*, 1995; Gibling and Bird, 1994). The goal of the CMB sequence analysis is to develop a relatively simple, nonmarine sequence stratigraphic model which honours the seismic and well data and which provides a basic framework for further and more comprehensive sequence analysis.

This chapter gives a brief overview of prevailing sequence stratigraphic techniques being applied to the geologic rock record, followed by the application of a sequence stratigraphic model to the CMB fill. The chapter concludes with a brief discussion of the sequence stratigraphic model as it compares to prevailing methods of sequence analysis, followed by a short summary.

### 3.1.1 Review of Sequence Stratigraphic Techniques

The sequence is the fundamental element of modern sequence stratigraphy and is defined in Table 3.1 as a stratigraphic unit bounded by unconformities or their correlative conformities that contains no apparent internal unconformities. The importance of this definition is that the boundaries of the sequence tend not to be lithological in nature but

Table 3.1 Definition of key sequence stratigraphic terms as used in this study (modified from Legarreta *et al.*, 1993; Schumm, 1993; Mitchum and Van Wagoner, 1991; Jervey, 1988; Posamentier *et al.*, 1988; Van Wagoner *et al.*, 1988; Vail *et al.*, 1977).

| |
|---|
| **Sequence Stratigraphy**<br>- the study of rock relationships within a chronostratigraphic framework wherein the succession of rocks is cyclic and is composed of genetically related strata. |
| **Stratigraphic Baselevel**<br>- effectively sea level in most cases but in nonmarine settings it is analogous to relative lacustrine and groundwater levels. |
| **Stratigraphic baselevel cycle**<br>- one complete cycle of stratigraphic baselevel change from relative fall to relative rise. |
| **Accommodation** - the space made available for potential sediments to accumulate where, in order for sediments to be preserved there must be space available below stratigraphic baselevel (the level above which erosion will occur). |
| **Sequence**<br>- a relatively conformable succession of genetically related strata bounded at its top and bottom by unconformities or their correlative conformities. A sequence contains no apparent internal unconformities and is interpreted to be the depositional response to one stratigraphic baselevel cycle. |
| **Systems Tract**<br>- a linkage of contemporaneous depositional systems (Brown and Fisher, 1977). Each is defined on the basis of bounding surface type, position within a sequence, and internal parasequence stacking patterns and is independent of time, scale and environment of deposition. Each systems tract is interpreted to be associated with a specific phase of one complete stratigraphic baselevel cycle. |
| **Sequence Set**<br>- a set of sequences organized in a distinctive aggradational, retrogradational or progradational stacking pattern. |
| **Composite Sequence**<br>- a stratal package bounded by unconformities but internally composed of genetically related high-frequency sequences in which the individual sequences stack into lowstand, transgressive and highstand sequence sets. Sequence sets are analogous to systems tracts in sequences. |
| **Parasequence**<br>- a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces. |
| **Parasequence Sets**<br>- successions of genetically related parasequences with distinctive stacking patterns (progradational, retrogradational, aggradational) |
| **Transgressive surface (TS)**<br>- the first significant marine (nonmarine) flooding surface across the shelf (alluvial-coastal plain) within the sequence. It separates younger from older stata across which there is an abrupt increase in relative water depth. |
| **Maximum Flooding Surface (MFS)** *Condensed Section*<br>- the surface on which the prograding clinoforms in the highstand systems tract downlap. It is marked by a change from retrogradation to aggradation stacking patterns and a facies consisting of thin marine beds of hemipelagic or pelagic sediments deposited during very slow sedimentation rates. |
| **Type-1 unconformity**<br>- an unconformity characterized by fluvial incision, sedimentary bypass of the shelf and an abrupt basinward shift in facies. |
| **Type-2 unconformity**<br>- an unconformity characterized by subaerial exposure, a downward shift of coastal onlap, and a vertical change in parasequence stacking pattern from progradational to aggradational. A Type-2 unconformity is not associated with fluvial incision. |

are in fact stratigraphic breaks in the rock record that are chronostratigraphically significant. The breaks record changes in the depositional regime that are intimately linked to basin development and depositional history. Its important to recognize that the concepts of modern sequence stratigraphy, detailing the development and subsequent definition of individual sequences, are both time and scale independent (Posamentier *et al.*, 1992).

As modern sequence stratigraphy has evolved one area of contention has been the delineation of the surfaces which bound the sequence. Conceptually sequence stratigraphy has developed primarily from investigations of rocks in the marine realm where many surfaces are inherently associated with variations in the eustatic cycle from levels of maximum regression to levels of maximum transgression (Galloway, 1989). The choice of surfaces between these two maxima is critical to any sequence stratigraphic interpretation. Alternatively, it has been suggested that the development of some sequence boundaries are primarily related to regional scale tectonic events (i.e., rifting) which further complicates the choice of sequence boundary location (Boyd *et al.*, 1993). Three prevailing methods of sequence stratigraphic interpretation have developed, each recognizing different bounding surfaces; depositional, genetic stratigraphic and T-R (transgressive-regressive).

Classic depositional sequence stratigraphy, commonly referred to as the Exxon model, evolved from the original work by Vail *et al.* (1977). Recent works by Jervey (1988) and Posamentier *et al.* (1988) proposed that the depositional sequence is bounded by a subaerial unconformity (and its correlative conformity) caused by a fall in relative sea level (Fig. 3.1, Table 3.1). The portion of the sequence boundary located on the basin margin is likely to be modified during transgression and as such would be identified as a ravinement surface (Helland-Hansen and Gjelberg, 1994; Walker, 1990). The complementary surface basinward of the subaerial unconformity would be the correlative conformity mentioned by Vail *et al.* (1977) which could theoretically extend far out into the basin through entirely unaffected strata. Above this sequence boundary, the Exxon model recognizes the transgressive and maximum flooding surfaces (Table 3.1) which

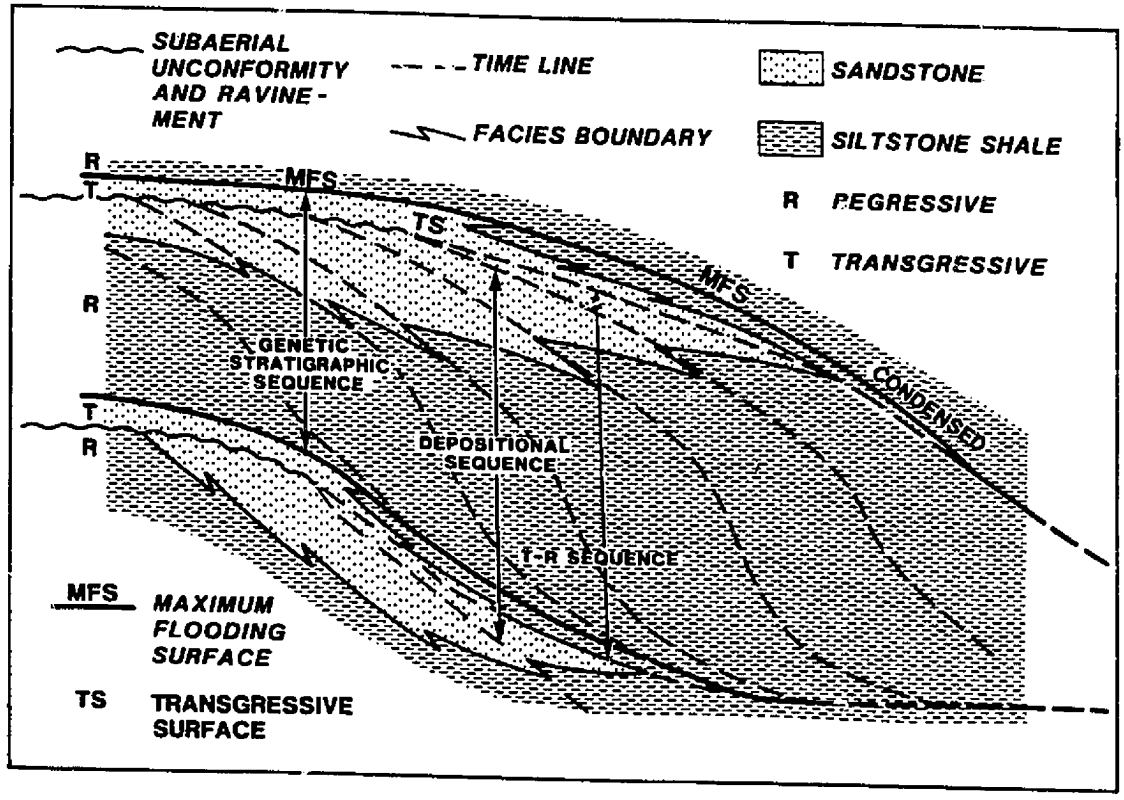



Figure 3.1 A schematic stratigraphic cross-section illustrating the principle bounding surfaces for depositional, genetic stratigraphic, and T-R sequence stratigraphy (from Embry, 1993).

bound the lowstand (LST), transgressive (TST) and highstand (HST) systems tracts, respectively (Van Wagoner *et al.*, 1988). Recently, the lowstand systems tract has been subdivided in to the forced regressive and lowstand wedge systems tracts (Helland-Hansen and Gjelberg, 1994). Further and more comprehensive reviews of the Exxon method of sequence stratigraphy can be found in Wilgus *et al.* (1988).

The original concepts of Vail *et al.*, 1977 are based fundamentally on third order sequences (0.5-3.0 Ma) which are resolvable using standard industry seismic data (Vail *et al.*, 1991). Recently, smaller, higher frequency sequences have been identified within the larger scale, lower frequency sequences (Burns *et al.*, 1996; Weber *et al.*, 1996; Mitchum and Van Wagoner, 1991). In an attempt to place these situations in a sequence stratigraphic context, Mitchum and Van Wagoner (1991) introduced the composite sequence (Table 3.1) which is composed of lowstand, highstand, and transgressive sequence sets. Sequence sets (Table 3.1) are analogous to systems tracts in sequences and are defined based on the internal stacking patterns of the sequences (Mitchum and Van Wagoner, 1991). Composite sequences will be discussed further in section 3.2.5.

In contrast to the depositional sequence, Galloway (1989) developed the genetic stratigraphic sequence which uses facies associations and depositional systems, deposited during periods of paleogeographic stability (Hamilton and Tadros, 1994) to define a depositional episode. This fundamental element of the genetic stratigraphic model, commonly referred to as the Galloway model, is defined and bounded by the surface of maximum transgression called the maximum flooding surface (MFS) (Fig. 3.1, Table 3.1) (Galloway, 1989). The MFS is hiatal in nature and is represented by either a submarine unconformity or a condensed section (Galloway, 1989). The surface typically marks the distinctive lithologic change from underlying transgressive strata to overlying regressive strata. The genetic stratigraphic model uses the transgressive surface (ravinement surface), the subaerial unconformity of Vail *et al.* (1977) and the maximum flooding surface to bound progradational, lowstand progradational and retrogradational systems tracts (Xue and Galloway, 1993).

T-R sequence analysis, previously referred to as T-R cycles (Johnson *et al.*, 1985), has been recently proposed by Embry (1993, 1995) as an alternative to the depositional and genetic stratigraphic sequence methods. The method utilizes traditional principles of transgression and regression in conjunction with chronostratigraphically significant surfaces to develop time-stratigraphic sequences. The transgressive surface, or surface of maximum regression, bounds the T-R sequence (Fig. 3.1). On the margin, the boundary surface is recognized as the ravinement surface used by Posamentier *et al.* (1988); basinward the surface is the transgressive surface separating underlying regressive deposits from the overlying transgressive deposits. The Embry model (1993) consists of a transgressive and regressive systems tract separated by the maximum flooding surface, all collectively bounded by two transgressive sequence boundaries (Fig. 3.1).

### 3.1.2 Nonmarine Sequence Stratigraphic Techniques

Sequence stratigraphy has traditionally focussed on strata in open- to marginal-marine settings, which strongly implied a primary eustatic control on the development of cyclic packages of strata. Only in the last few years has the focus turned to applying sequence stratigraphic concepts to strata in nonmarine, or continental settings (cf., Shanley and McCabe, 1994). As a result, non-marine sequence stratigraphy is in the early stages of development and so many questions regarding the development of nonmarine systems remain unresolved. Furthermore, the controls on nonmarine cyclic packages are also different as will be discussed in greater detail in the next chapter.

Unconformity bound sequences in nonmarine settings have been studied in the past (Sloss, 1988), however, their relationship to marine bounding surfaces is uncertain. Some workers (Shanley and McCabe, 1994; Posamentier and Vail, 1988) feel that the relationship is crucial to any understanding of the time-stratigraphic history of continental sedimentary basins, whereas others feel that eustasy plays an insignificant part in the development of nonmarine sequences (Legarreta *et al.*, 1993; Martinsen *et al.*, 1993) compared to the tectonic and climatic components.

Legarreta *et al.* (1993), as a result of investigations of nonmarine Mesozoic strata

in Argentina, proposed an innovative approach for nonmarine sequence stratigraphy (Fig. 3.2). They suggested that nonmarine strata are better interpreted in terms of the changing rates of supply and accommodation during successive lows in the stratigraphic baselevel cycle. In terms of net degradation and aggradation, Legarreta *et al.* (1993) defined a complete stratigraphic baselevel cycle as the time between successive degradational episodes. They proposed that the net degradational phase, associated with erosion and sediment bypass reflects situations above stratigraphic baselevel and the development of an erosional sequence boundary. Whereas the subsequent aggradational phase is associated first with sediment deposition in geomorphic lows eroded during degradation, followed by development of stratal packages building up depositional dip, both of which reflect a rising baselevel.

The sequence boundaries in their models are developed as a result of baselevel lowering and are typically identified at the bases of thick, bedload dominated multi-story sandstone bodies which they call the forestepping systems tract (FST) (Fig. 3.2). The FST lies conformably to unconformably on fine-grained alluvial deposits and is developed as a result of limited accommodation during baselevel fall. Above the forestepping systems tract, Legarreta *et al.* (1993) recognized a backstepping systems tract (BST) (Fig. 3.2) that develops as a result of increased accommodation associated with a rise in stratigraphic baselevel. The backstepping systems tract is a suspended- to bed-load dominated succession that displays increasingly finer grained sedimentation and isolated channel development towards the top of the systems tract. The uppermost systems tract in the model is the fine-grained, floodplain dominated, aggradational systems tract (AST) (Fig. 3.2). The AST develops during a period of limited to decelerating accommodation, similar to the highstand systems tract in a marine setting and is marked at the top by the next successive sequence boundary. The preservation of the AST depends largely on the degree of erosion associated with the next drop in relative stratigraphic baselevel.

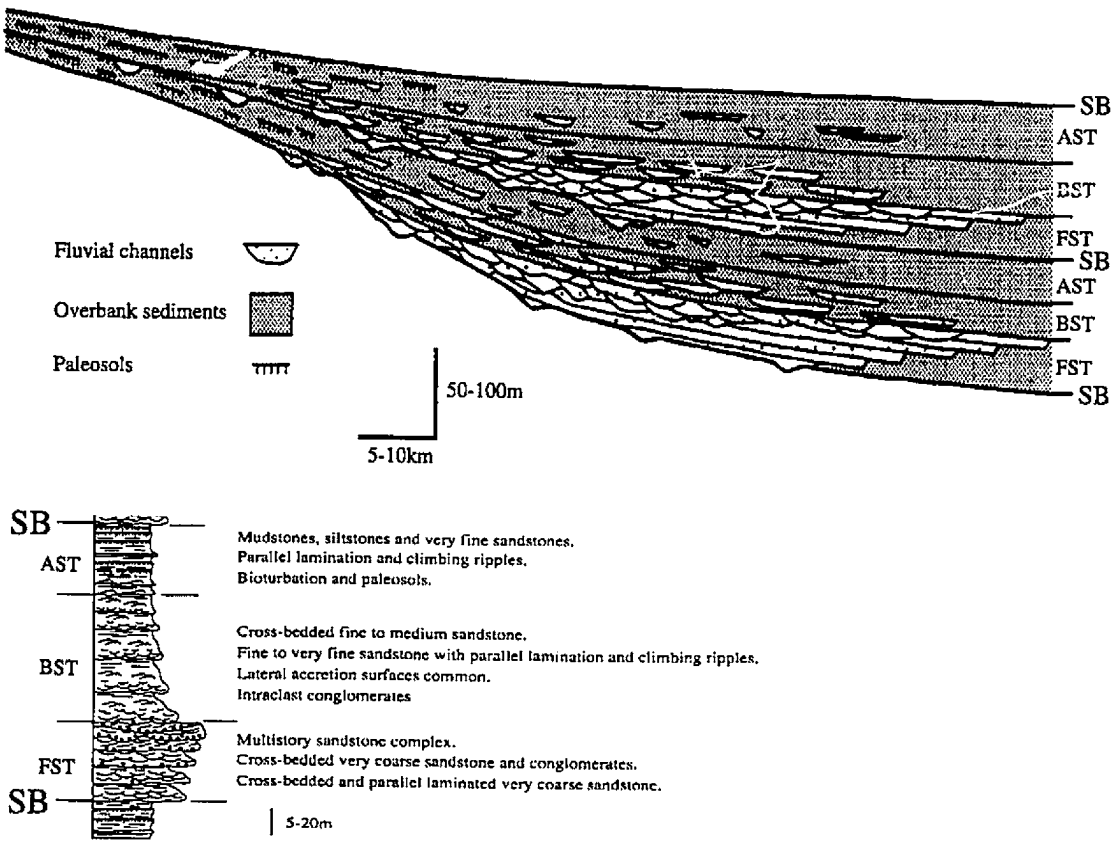



Figure 3.2 A conceptual stratigraphic cross-section and fluvial depositional cycle showing the application of nonmarine sequence stratigraphic concepts to Mesozoic strata in Argentina (from Legarreta et al., 1993). SB = Sequence boundary; FST = Forestepping systems tract; BST = Backstepping systems tract; AST = Aggradational systems tract.

### 3.1.3 Accommodation and Supply

Two concepts important to any sequence stratigraphic approach, marine or nonmarine, are accommodation and supply. It is the relative rates of change of these parameters which determine the overall geometry of the depositional system (Shanley and McCabe, 1994; Schlager, 1993). Changes in accommodation are relative to a surface above which there is erosion and below which there is deposition, suggesting that this surface is the stratigraphic baselevel (Van Wagoner *et al.*, 1988). Consequently, this implies that changes in baselevel determines accommodation space.

If the rates of change of accommodation are positive, the architecture of the depositional system will be influenced by processes responsible for sediment supply (Jervey, 1988). Shanley and McCabe (1994) proposed three general relationships between sediment supply and increasing accommodation; 1) if the rate of sediment supply > rate of accommodation increase, progradation occurs, 2) if the rate of sediment supply < rate of accommodation increase, retrogradation will occur, 3) If rate of sediment supply = rate of accommodation increase, aggradation will occur. On the other hand, if accommodation space is zero, sediment bypass and, probably, erosion will occur in the depositional system (Van Wagoner *et al.*, 1988).

## 3.2 CMB Sequence Analysis

There are few nonmarine sequence stratigraphic models that use terminologies that are not closely associated with the Exxon or Galloway models. The use of models which employ terms such as highstand, lowstand, or transgressive systems tracts, inherently are associated with open- to marginal-marine connotations. Even though, the protozoan analysis (Wightman *et al.*, 1994a; APPENDIX II) indicated brackish water influenced deposition for portions of the CMB fill, the analysis did not result in the delineation of any zones of marine incursion on the scale of a few metres. At the outcrop scale, the Exxon and Galloway models have been successfully applied to higher frequency sequences where the degree of marine influence can be precisely documented (Gibling and Bird, 1994). However, at the level of investigation used in this study, the

basin fill is considered predominantly nonmarine in character ruling out explicit use of the standard Exxon, Galloway or Embry models. A secondary consideration is the frontier nature of the offshore database for which a broad regional sequence stratigraphic approach, rather than a detailed high resolution approach, is warranted. As a result, application of sequence stratigraphic concepts to the Late Paleozoic fill in the Central Maritimes Basin requires a modification of the currently proposed techniques.

All three prevailing methods of sequence stratigraphic analysis were considered inappropriate for the CMB sequence analysis. However, conceptually, the basin-scale applicability of the T-R sequence analysis approach (Embry, 1995, 1993; Johnson *et al.*, 1985) was chosen as a primary framework for the CMB sequence analysis. The T-R method, however, applies to strata in an open- to marginal-marine regime (ie. transgressive vs. regressive), at odds with the CMB situation. This factor led to the merging of concepts from the T-R method with the work of Legarreta *et al.* (1993), incorporating the nonmarine terminology of Legarreta *et al.* (1993) with the two systems tracts of Embry (1993). The modification and combination of concepts from both these techniques resulted in what is introduced here as the F-B, or forestepping-backstepping, sequence analysis method (Fig. 3.3)

An F-B sequence as used in this study encompasses the predominantly nonmarine strata deposited between two successive drops in the relative stratigraphic baselevel. The two main components of the F-B sequence are the forestepping and backstepping systems tracts which could be, respectively, the nonmarine counterparts of the regressive and transgressive systems tract of Embry (1995, 1993). In contrast to Embry's T-R sequence, but in accord with the work by Legarreta *et al.* (1993), the surfaces under the forestepping systems tracts are taken as sequence boundaries. The transgressive surface (Table 3.1) is contained within the sequence at the base of the backstepping systems tract.

The traditional tri-partite sequence analysis, such as those proposed by Van Wagoner *et al.* (1988) and Legarreta *et al.* (1993), using highstand and aggradational systems tracts, respectively, was avoided in the CMB sequence analysis due to the large uncertainty associated with recognizing a maximum flooding surface (MFS) (Table 3.1).

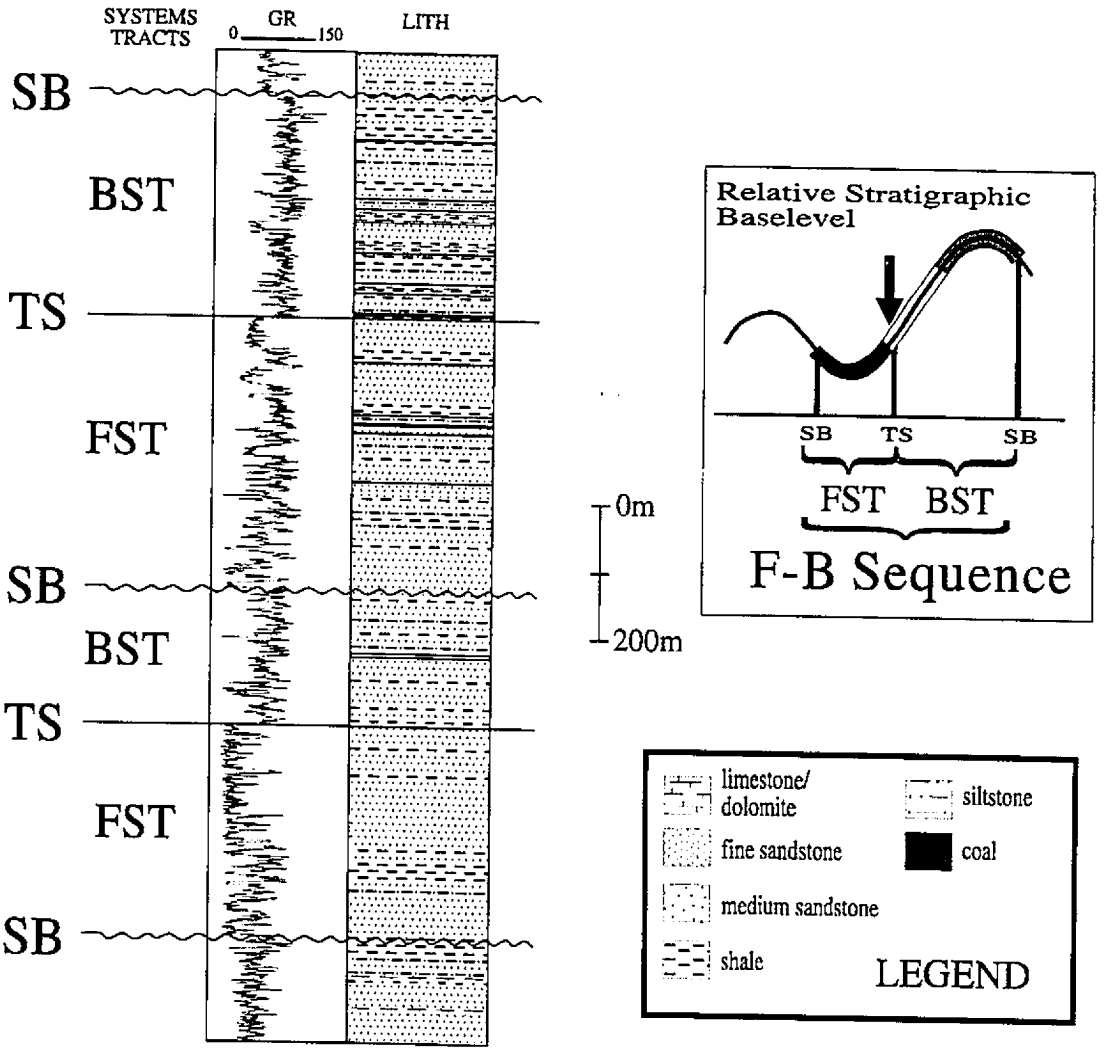



Figure 3.3 Two idealized Central Maritimes Basin fluvial Forestepping-Backstepping (F-B) Sequences with an associated stratigraphic baselevel curve which shows the relationship between baselevel changes and system tract development. Note the locations of the bounding unconformities, transgressive surfaces and forestepping-backstepping systems tracts which collectively make up the F-B sequences. The arrow on the baselevel curve indicates the preferred location for the development of coals and limestones. SB = Sequence boundary; TS = Transgressive surface; FST = Forestepping systems tract; BST = Backstepping systems tract.

Embry (1993) pointed out numerous reasons for not subdividing sequences using maximum flooding surfaces, hence the development of the two tier T-R sequence method. As well, recent nonmarine sequence stratigraphic models (e.g., Olsen *et al.*, 1995; Wright and Marriott, 1993) that do suggest a division between transgressive and highstand systems tract type deposits, do not present any specific criteria for recognizing a maximum flooding surface making the division meaningless. In any event, the observational criteria for maximum flooding surfaces in nonmarine regimes are questionable (Shanley and McCabe, 1994), even so, if criteria existed, considering the resolution of the CMB study dataset, a MFS would be difficult to identify. As a result, all strata above the transgressive surface is considered part of the backstepping systems tract.

### 3.2.1 Sequence Boundaries

The Vail *et al.* (1977) definition of a sequence requires that sequence boundaries are surfaces which are identified as unconformities or their correlative conformities. Potential indicators of a sequence boundary includes: abrupt breaks in the faunal record, sharp changes in wireline log signatures, abrupt lithologic contrasts, and reflector terminations or abrupt impedance contrasts on seismic reflection profiles (Lindsay and Korsh, 1989; Shanmugam, 1988; Vail *et al.*, 1977).

Although coincident with the lithostratigraphic formation boundaries described in Chapter 2, the most obvious choices for sequence boundary locations in the CMB are the tops or bottoms of the sand-dominated units (Fig. 3.3). Both surfaces represent distinctive changes between finer and coarser grained facies, however, only the basal surfaces of the coarse-grained units are typically marked by breaks in the biostratigraphic record. In addition, seismic data clearly indicate that the surfaces under the amalgamated coarse-grained facies are regionally identifiable, conformable to unconformable seismic sequence boundaries that correspond to the Namurian-Westphalian, Mid-Westphalian and the Westphalian-Stephanian events outlined in Chapter 2. All these events are chronostratigraphically significant, an important feature of sequence boundaries (Vail *et al.*, 1977). Of the two potential sequence boundary locations, only surfaces at the base of

the coarse-grained units meet all the above criteria and so they are chosen as the F-B sequence boundaries (Fig. 3.3).

### 3.2.2 Transgressive Surfaces

Applying F-B sequence analysis to the CMB fill requires the identification of transgressive surfaces (Table 3.1) between the forestepping and backstepping systems tracts. The most obvious location for a transgressive surface is at the abrupt facies change from underlying coarse-grained, multi-storied sandstone bodies to fine-grained material containing isolated sandstone bodies (Fig. 3.3). The placement of the transgressive surface at these locations is again coincident with the lithostratigraphic formation boundaries introduced in Chapter 2. Unlike, the identified sequence boundaries, no discernible biostratigraphic break occurs across the transgressive surfaces from forestepping to backstepping systems tracts and seismic evidence suggests that these boundaries are conformable.

### 3.2.3 Forestepping-Backstepping Sequences

The recognition of regionally extensive sequence boundaries and transgressive surfaces in the CMB resulted in the identification of four predominantly nonmarine forestepping-backstepping sequences, which on a systems tract level are directly comparable with the stratigraphic framework introduced in Chapter 2. In ascending order, the CMB forestepping-backstepping sequences are; the Brion Island - Bird Rock formations (Sequence 1), the Bradelle - Green Gables formations (Sequence 2), the Magdalen - Seacow formations (Sequence 3) and the Cable Head - Naufrage formations (Sequence 4) (Fig. 3.4). The sequences are developed throughout the region and were identified in the Central Maritimes Basin through the integration of seismic and well data (Figs. 3.5, 3.6) described in Chapter 2.

The forestepping systems tracts are typically bounded at the top and bottom by a transgressive surface (TS) and a conformable to unconformable sequence boundary (SB) respectively. The CMB backstepping systems tracts are usually bounded by a

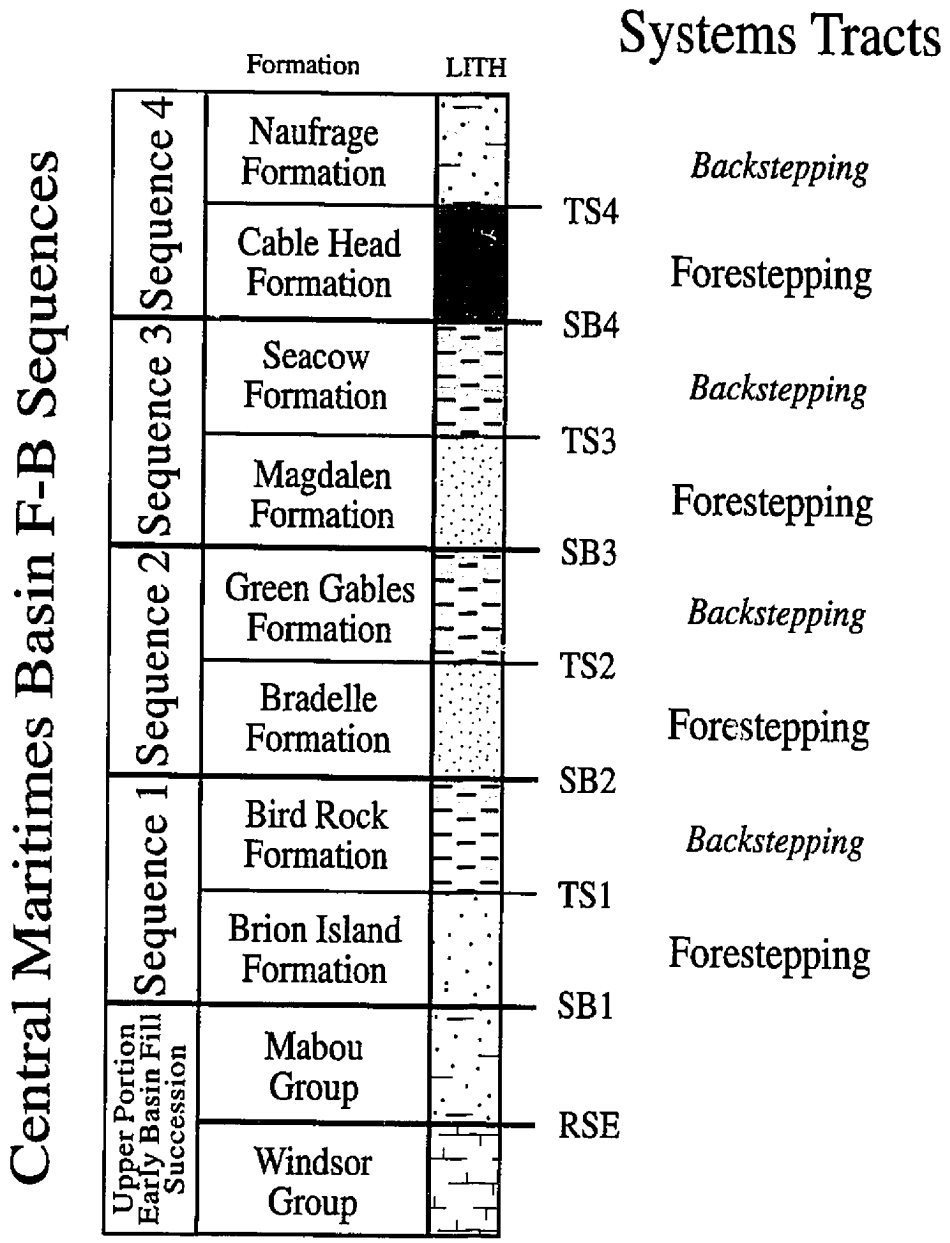



Figure 3.4 A schematic diagram showing the inter-relationship between the stratigraphic framework developed in Chapter 2 and the CMB F-B sequences and systems tracts identified by integrating the methods proposed by Embry (1993) and Legarreta et al. (1993). See Figure 2.9 for lithologic desciptions. No vertical depth of time scale is implied. SB = Sequence boundary; TS = Transgressive surface; RSE = Regressive surface of erosion.

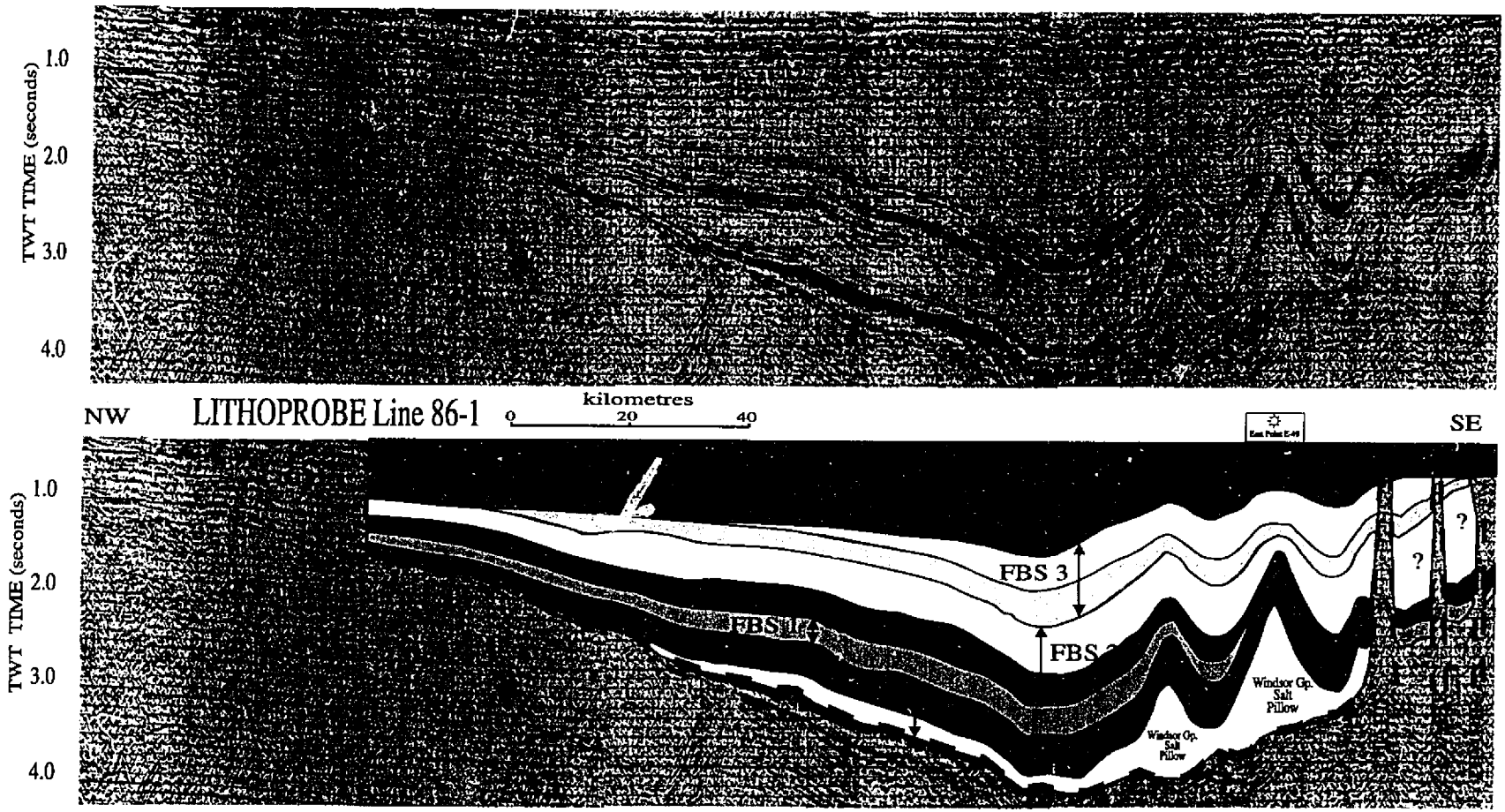
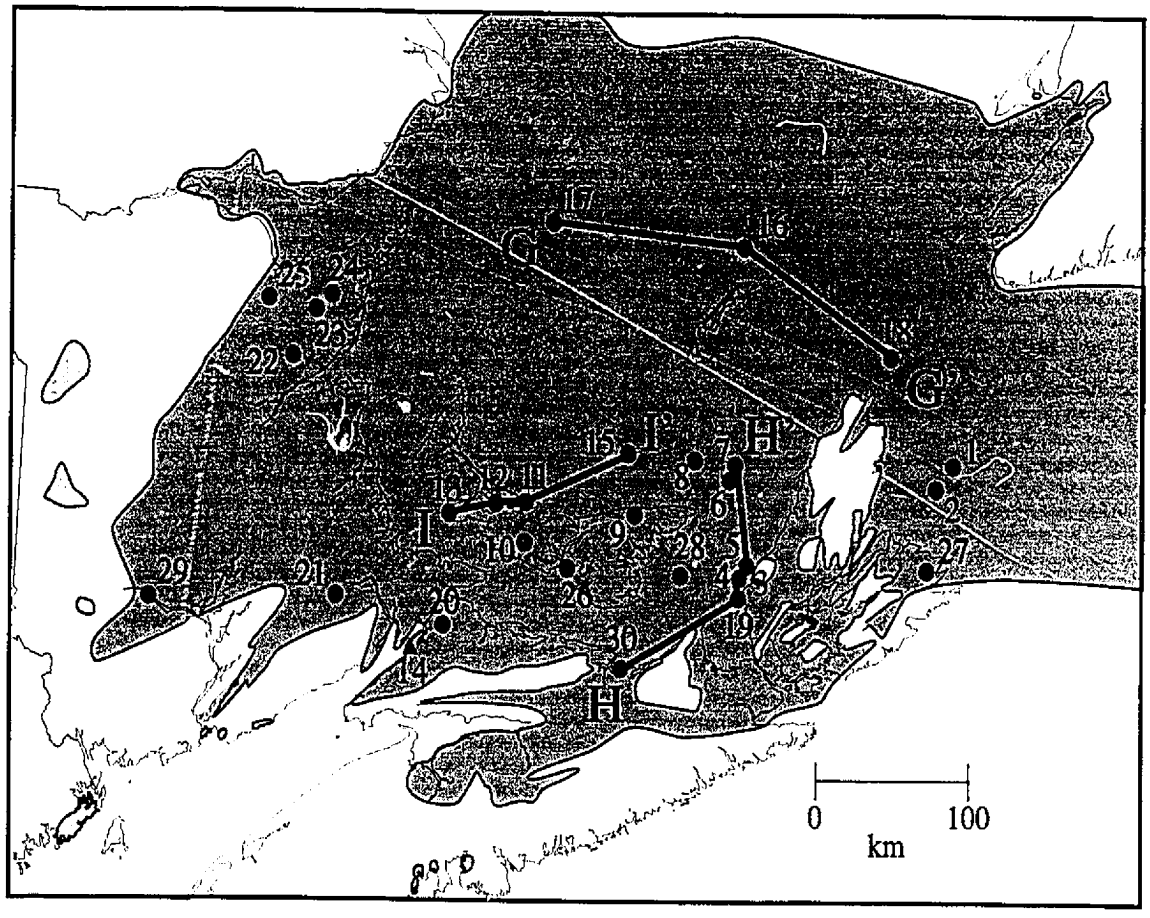



Figure 3.5 (Top) Uninterpreted LITHOPROBE line 86-1 (line D, Fig. 2.11) showing the undeformed nature of the CMB Late Carboniferous basin fill. (Bottom) Interpreted seismic record showing the identification of 4 regionally extensive F-B sequences which blanket the Central Maritimes Basin. The shaded units represent the forestepping systems tracts, the white units represent backstepping systems tracts. F-B Sequences 1 and 4 do contain both systems tracts, however the resolution of the seismic does not allow for individual identification. The lower dashed boundary is the interpreted base of the Windsor Group. Vertical scale near the basin axis is approximately 8-9 km. The seismic record appears to be "warped" as a result of the scanning and digitizing process. FBS = Forestepping-Backstepping Sequence; EBF = Early Basin Fill succession.




1. NORTH SYDNEY P-05
2. NORTH SYDNEY F-24
3. MABOU COASTAL SECTION
4. NSDME M-1
5. NSDME M-2A
6. EAST POINT E-47
7. EAST POINT E-49
8. BEATON POINT F-70
9. NAUFRAGE #1
10. TYRONE #1
11. GREEN GABLES #1
12. IRISHTOWN #1
13. WELLINGTON STATION #1
14. CUMBERLAND COASTAL SECTION
15. CABLE HEAD E-95
16. BRION ISLAND #1
17. BRADELLE L-49
18. ST. PAUL P-91
19. NSDME PH-3
20. HASTINGS #1
21. MIDDLESEX #1
22. BARTIBOG #1
23. ST. ISIDORE #1
24. ST. ISIDORE #2
25. BLANCHARD #1
26. HILLSBOROUGH #1
27. BIRCH GROVE #1
28. N. STRAIT F-25
29. FREDERICTON #2
30. NSDME P-58

Figure 3.6 Map showing the location of detailed geological cross-sections constructed for the sequence analysis portion of this study.

transgressive surface (TS) at the base and capped by a sequence boundary (SB) on the top. The following sections will first place the upper portion of the underlying early basin fill into a basic sequence stratigraphic context afterwhich F-B Sequences 1 to 4 will be discussed.

### 3.2.3.1 Early Basin Fill Succession

The upper portion of the early basin fill (EBF) succession, comprising the Windsor and the Mabou groups is broadly analogous to the original T-R sequence of Embry (1993). The Windsor Group, a recognized open-marine unit was deposited during a regionally extensive relative rise in stratigraphic baselevel, closely associated with a rise in eustatic sea level (Kelly, 1967). It has been recognized that the large scale, 2nd order (3-50 Ma duration) (Vail *et al.*, 1991), transgressive event that resulted in regional Windsor Group deposition is composed of numerous higher frequency sequences (Boehner, 1984; Giles, 1981) that may be correlatable to European sequences (Gibling, 1995). Overlying this major transgressive unit is the nonmarine Mabou Group which was deposited during a relative regression, or lowering of baselevel, associated with the withdrawal of the Windsor seas.

In the context of T-R sequence terminology, a transgressive surface clearly lies at the base of the Windsor Group, or transgressive systems tract, which according to the T-R model could be the sequence boundary. The surface between the Windsor Group and the Mabou Group (regressive systems tract) is a regionally extensive seismic sequence boundary (R1) and could be interpreted as the regressive surface of erosion (RSE) proposed by Embry (1995). The top of the Mabou Group is capped by the Namurian-Westphalian sequence boundary resulting in a complete transgressive-regressive sequence that was deposited from the Early Visean to Early Westphalian A, a period of approximately 28.2 million years (AGSO, 1996; Hess and Lippolt, 1986; Claoe-Long *et al.*, 1992).

### 3.2.3.2 F-B Sequence 1

Sequence 1 is bounded by the Namurian-Westphalian (SB1) and Mid-Westphalian (SB2) events (sequence boundaries) (Fig. 3.7), a period of approximately 3.6 million years (Hess and Lippolt, 1986). The forestepping systems tract unconformably to conformably overlies the broadly regressive Mabou Group (Fig. 3.7) implying a continual drop in baselevel from initial Mabou Group deposition to the transgressive surface of Sequence 1 (TS1).

The FST (Brion Island Fm.) in sequence 1 is generally coarser grained than other FST's in the CMB (Table 3.2). Well logs are predominantly cylindrical shaped, with minor funnel shaped log signatures (Fig. 3.7), suggesting a braided fluvial environment with minor deltaic influences. Lithologically, the FST consists of thick sandstone bodies which become more consolidated towards the top of the systems tract (Table 3.2). The typically massive nature of the sandstones and evidence of coal development at the top of the section suggests increased stability of the depositional system upsection (cf., Melvin, 1993). Seismic facies analysis of the Sequence 1 FST (Fig. 3.8) supports prograded reflector relationships. Such relationships imply that the forestepping systems tract was deposited in a bed-load dominated fluvial environment that prograded towards the basin depocentre (Table 3.2)

The backstepping systems tract (Bird Rock Formation) of Sequence 1 is bounded below by TS1 and above by the Mid-Westphalian (SB2) sequence boundary (Fig. 3.7). The protozoan analysis suggests an increase in restricted-marine influence above transgressive surface TS1 (Fig. 2.29). The log signatures and seismic facies analysis (Fig. 3.7, Table 3.2) of the BST implies deposition on a fluvial floodplain that had an abundant fine-grained sediment supply along with conditions suitable for peat development (Cant, 1992).

### 3.2.3.3 F-B Sequence 2

The Mid-Westphalian (SB2) and Westphalian-Stephanian (SB4) events bound Sequence 2 (Fig. 3.9). In the central portion of the Gulf of St. Lawrence the base of the

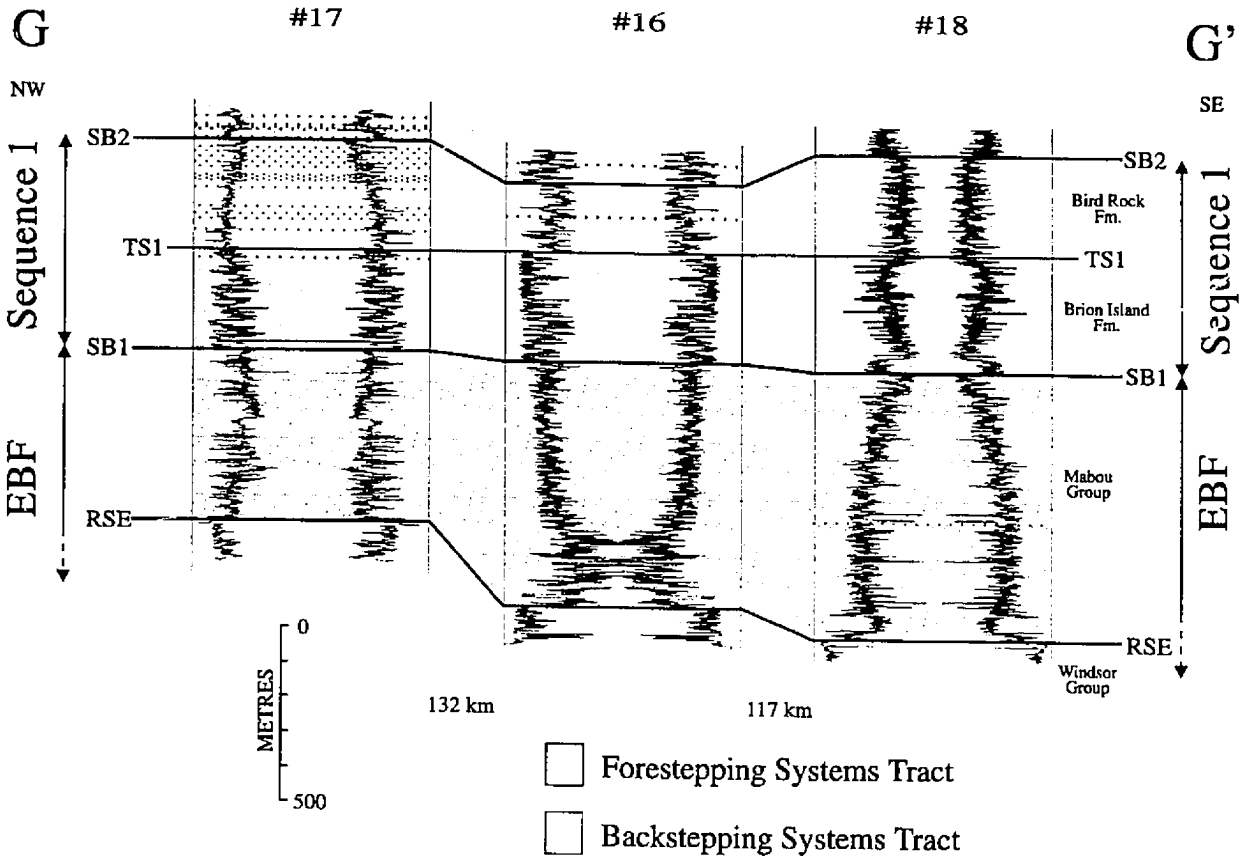



Figure 3.7 CMB stratigraphic cross-section G-G' (location and well names, Fig. 3.6) showing the detailed linking of upper portion of the early basin fill succession and F-B Sequence 1 using mirrored gamma-ray logs. The forestepping and backstepping systems tracts are shaded grey and white respectively. The TS1 transgressive surface is used as a datum and locations of probable coals are indicated by dotted lines across the well bore. Vertical scale is indicated and distance between wells is shown. EBF = Early Basin Fill Succession.

Table 3.2 Summary of interpreted palaeoenviroments for F-B sequences identified in the Central Maritimes Basin fill. Interpretations are based primarily on wireline and seismic signatures as minimal core is available in the area. Protozoan data suggest some degree of marine influence for several stratigraphic units (Fig. 2.29). See Figure 2.6 for an overview of stratigraphic nomenclature, Table 2.8 for onshore interpretations, and Figure 2.12 for seismic reflector overviews. ss/sh = sandstone/shale ratio; BST = Backstepping systems tract; FST = Forestepping systems tract.

| Unit Characteristics | Wireline Log Characteristics | Seismic Facies Characteristics | Interpreted Depositional Environment and Comments |
|---|---|---|---|
| **BST 4 (Naufrage Fm.)** ss/sh=0.9<br>Coarsening upwards redbed unit, shales near base changing to massive sandstones near top, thin beds and stringers of limestone. | Upwards coarsening/cleaning trend, serrated logs near the base becoming blockier towards the top, gamma displays cylindrical patterns at the top, sonic/density peaks decrease towards top. | Masked by multiples and noise. | Stable alluvial plain setting, fluvial floodplain evolving through time into a bed-load/suspended load fluvial system with minor interchannel deposits. |
| **FST 4 (Cable Head Fm.)** ss/sh=2.25<br>Red sandstones with interbedded shales and minor coals, sandstones coarsen and are massive upsection, multi-story bodies, fine-medium grained. | Predominantly cylindrical with subordinate funnel patterns with patterns becoming blockier towards the top, sonic and density logs are serrated with occasional peaks suggesting coal development. | Basal erosional surface (R4), prograding clinoforms, medium to high amplitude, parallel to subparallel reflectors. | Bed-load dominated braided fluvial system with minor interchannel deposits. Part of a complex prograding towards the depocentre. Very minor development of peat. |
| **BST 3 (Seacow Fm.)** ss/sh=0.66<br>Shales with interbedded fine-medium grained sandstones, thin coals and limestones, shales are grey to red, coals and limestones at base. | Predominantly serrated log patterns with a slight cleaning/coarsening upwards trend, the sonics and density suggest minor coals in the lower part of the section. | Reflection-free to chaotic, locally subparallel, low continuity and amplitude. | Stable alluvial plain setting, fluvial floodplain with vegetated areas. Isolated channel/crevasse splay deposition. |
| **FST 3 (Magdalen Fm.)** ss/sh=1.1<br>Basinward composed of fine-medium grained sandstones becoming shalier on the flanks, feldspathic, thin grey-red shales and coals. | variable log responses, serrated on flank, funnel-cylindrical towards the basin centre, peaks in sonic and density suggest minor coal development. | Sharp basal surface (R3a), prograding clinoforms, parallel to subparallel reflectors that "wedge" out to weakly stratified. | Bed-load to suspended-load fluvial system, braided fluvial environments with minor interchannel deposits. Part of a complex prograding towards the depocentre. Minor peat development. |
| **BST 2 (Green Gables Fm.)** ss/sh=0.41<br>Shales, minor sandstones, beds and stringers of coal, thin limestones, shales are grey to red and increase in abundance upsection. | Serrated log responses, high sonic and low density peaks suggest abundant coal development, minor cylindrical patterns, generally high gamma responses. | Reflection-free to chaotic, typically concordant, parallel to subparallel, low amplitude. | Stable alluvial plain setting, fluvial floodplain heavily vegetated. Environment suitable for major coal development. Isolated channel/ crevasse splay deposition. |
| **FST 2 (Bradelle Fm.)** ss/sh=2.93<br>Predominantly fine-medium gr. sandstones with minor shale and coal beds, sandstones become more massive upsection, multi-story sand bodies. | Predominantly cylindrical shaped with funnel patterns developing towards the top, overall cleaning trend upwards, blockier towards top, peaks in sonic and density suggest coal development near top. | Sharp basal surface (R2b), prograding clinoforms, parallel to subparallel reflectors, variable continuity and amplitude. | Bed-load dominated braided fluvial system with minor interchannel deposits. Part of a complex prograding towards the depocentre. Local peat development. |
| **BST 1 (Bird Rock Fm.)** ss/sh=0.5<br>Grey shales and siltstones, minor fine to v fine grained sandstones, coals and limestone/ dolomitic beds abundant towards bottom. | Serrated log shapes, high gamma responses, abundant sonic and density log peaks throughout, suggesting probable coal development. | Reflection-free to chaotic, locally subparallel, weakly concordant. | Stable alluvial plain setting, fluvial floodplain heavily vegetated locally. Isolated channel/crevasse splay deposition. |
| **FST 1 (Brion Island Fm.)** ss/sh =2.75<br>Predominantly sandstones, amalgamated towards the top, medium to coarse grained, minor grey shales, thin coals towards top, multi-story sand bodies. | Predominantly cylindrical patterns with minor funnel shapes, gamma becomes blockier towards the top, overall cleaning trend towards top, sonic/density peaks decrease towards top. | Erosive basal surface (R2), prograding clinoforms, parallel to subparallel reflectors, variable continuity and amplitude. | Bed-load dominated braided fluvial system with minor interchannel deposits. Part of a complex prograding towards the depocentre. Minor peat development. |
| **Mabou Group** ss/sh=1.13<br>Interbedded sandstones, siltstones, and shales with thin limestones and marlstones, isolated channels, v. fine to fine grained, red to grey. | Predominantly serrated gamma and sonics, subordinate cylindrical-funnel patterns, gamma shalier upwards, sonic/density spikes increase towards the top. | Reflection-free, locally parallel to subparallel reflectors, variable continuity, low amplitude, sharp bounding surfaces (R1/R2). | Fluvial-lacustrine floodplain with abundant interchannel deposits. |
| **Windsor Group**<br>Intebedded gypsum, anhydrite, halite, potash, limestone and redbed clastics. | Very low gamma responses, high sonic and low density responses, typically blocky patterns. | Well stratified to chaotic, salt structures. | Open marine to subaerial continental. |

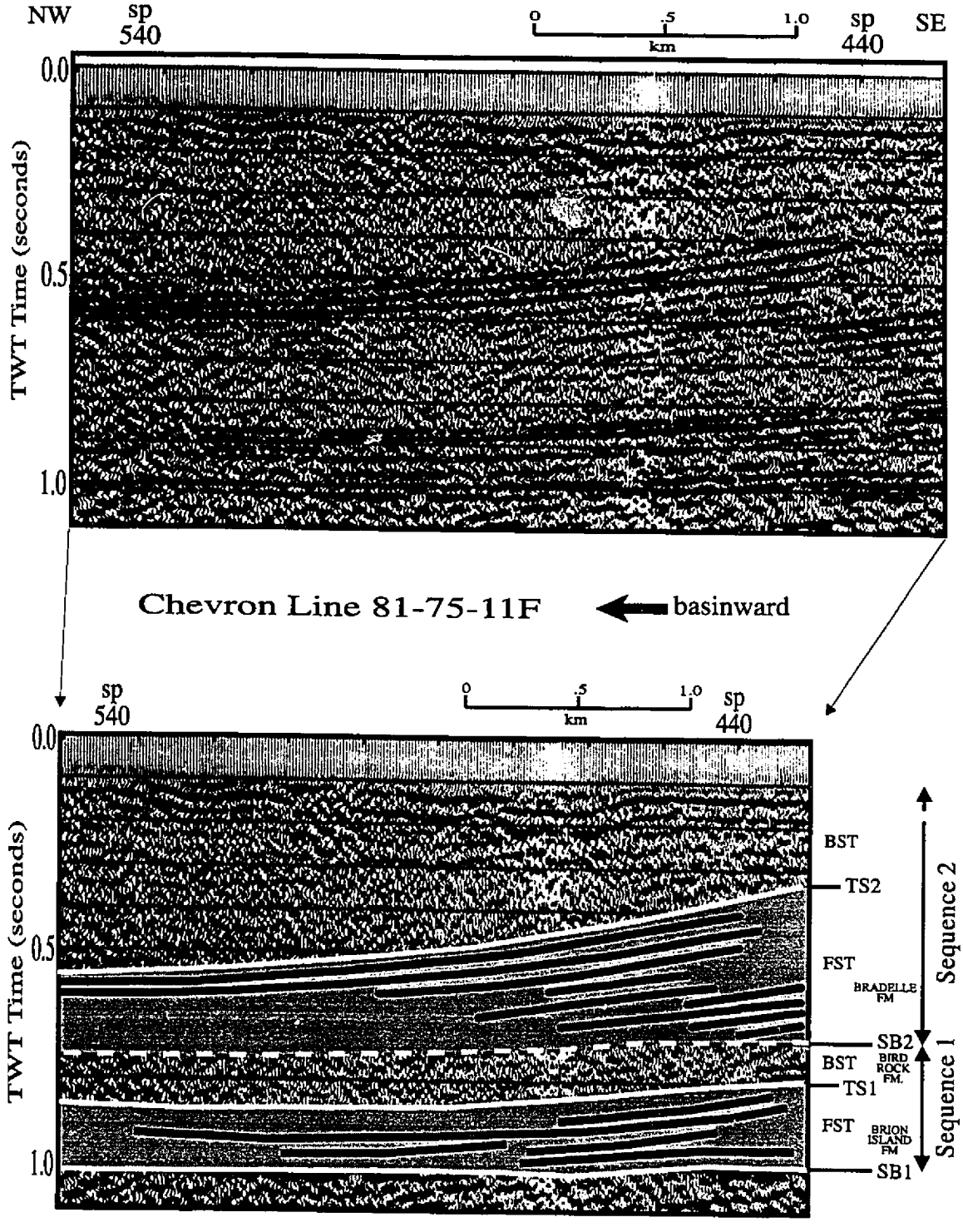



Figure 3.8 (Top) Uninterpreted Chevron seismic line 81-75-11F (line B; Fig. 2.11). (Bottom) Interpreted seismic record showing the identification of F-B sequences 1 and 2 with the associated forestepping systems tracts shaded grey. Both forestepping systems tracts show evidence of prograding/shingling reflectors (black) towards the basin centre (NW).

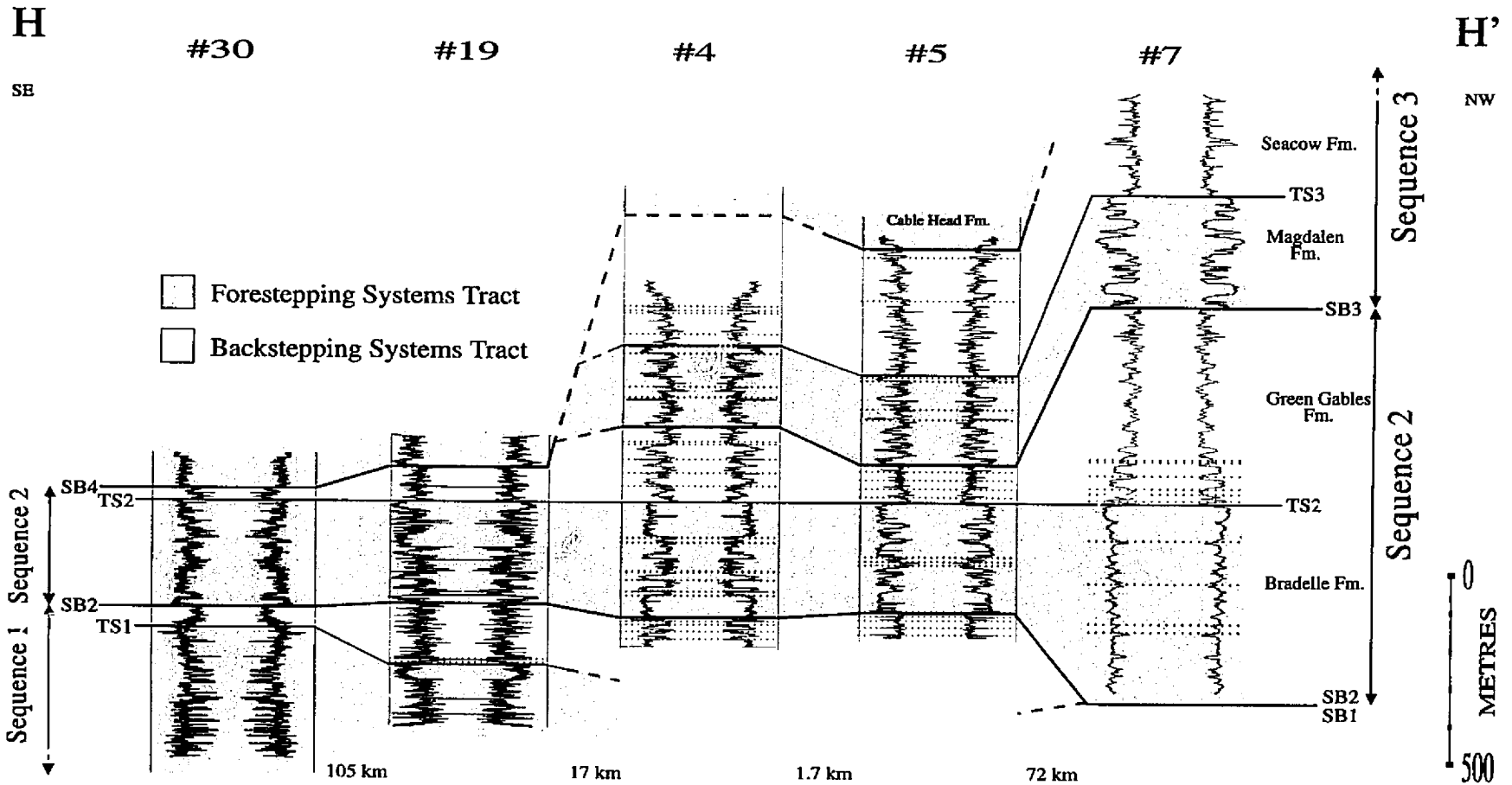



Figure 3.9 CMB stratigraphic cross-section H-H' (location and well names, Fig. 3.6) showing F-B Sequences 2 and 3 with forestepping and backstepping systems tracts shaded grey and white repectively. The cross-section uses mirrored gamma ray logs to show a basinward correlation (SE to NW) of forestepping backstepping systems tracts between 5 closely space CMB wells. The section uses the TS2 transgressive surface as datum and the locations of probable coals are indicated by dotted lines across the well bore. Vertical scale is indicated and distance between wells is shown.

Magdalen Formation, seismic sub-sequence boundary R3a, caps F-B Sequence 2 (Fig. 2.14). A synthesis of biostratigraphic data suggests that the complete sequence was deposited between Late Westphalian B - Early Westphalian C to Late Westphalian D, a period of approximately 4.2 million years (Hess and Lippolt, 1986).

The FST (Bradelle Fm.) has a high sandstone/shale ratio similar to the FST of underlying Sequence 1, but the log signature is slightly less blocky (Fig. 3.9, Table 3.2). Well log signatures are predominantly cylindrical shaped, with an increasing proportion of funnel shaped signatures upsection, suggesting a braided fluvial environment with increasing deltaic influences towards the top of the systems tract (Cant, 1992). The development of thicker, more amalgamated sandstone bodies and the increased number of coals near the top of the systems tract suggests increased stability of the depositional system upsection (cf., Melvin, 1993). The seismic facies analysis indicates that the FST consists of progradational seismic reflectors (Fig. 3.8) implying that the Sequence 2 FST was deposited on an inclined surface which prograded towards the basin depocentre (Table 3.2)

The BST (Green Gables Fm.) consists of interbedded fine-grained strata which in general displays more evidence of coal formation than any other sequence with the better developed coals found near the base of the BST. Similarly, thin carbonates typically occur in the basal part of the sequence. Well logs for the BST display a predominantly serrated shape, with minor cylindrical shaped log signatures that locally display fining-up patterns (Fig. 3.9, Table 3.2). The well logs and seismic data together imply that deposition of the Sequence 2 backstepping systems tract occurred in a broad fluvial floodplain environment that had conditions favourable for the development of substantial peat deposits (Table 3.2).

### 3.2.3.4 F-B Sequence 3

Sequence 3 is bounded at the base by sequence boundary SB3, which corresponds directly to seismic sub-sequence boundary R3a (Fig. 2.18), and at the top by the Westphalian-Stephanian event (SB4). The sequence coincides with the Magdalen and

Seacow formations (Fig. 3.9), which collectively were deposited from the Late Westphalian D to Early Stephanian, a period of approximately 1.3 Ma (Hess and Lippolt, 1986)

The FST (Magdalen Fm.) displays a distinct facies change from sand dominated deposits near the central portion of the gulf to shale dominated deposits toward the basin flanks. Corresponding well logs show predominantly cylindrical-funnel shaped log signatures near the depocentre (Fig. 3.9, well #7) which imply a braided fluvial environment with minor deltaic influences (Cant, 1992). Toward the basin flanks, the formation is characterized by serrated log signatures (Fig 3.9, wells #4, #5) suggesting deposition on a floodplain (Cant, 1992). Together the two interpretations suggest that the FST of Sequence 3 was deposited on a broad braidplain that progressively became higher in energy near the central portion of the CMB. Seismic facies analysis indicates the presence of some prograding reflector patterns, suggesting that the FST was deposited on an inclined surface that prograded towards the basin centre. Collectively, the well log, lithologic and seismic data (Table 3.2) suggest that the FST was deposited on a prograding braidplain system in the central portion of the basin and on a broad lower energy fluvial floodplain towards the basin flanks.

The Sequence 3 backstepping systems tract (Seacow Formation) is bounded at the base by transgressive surface TS3 and capped by sequence boundary SB4. The BST consists of interbedded sandstones and shales with a few minor coals. Well logs for the BST have high gamma-ray responses (Fig. 3.9) with predominantly serrated log signatures suggesting deposition on a fluvial floodplain (Cant, 1992). Locally, well logs indicate a slight coarsening upwards trend. Cylindrical-funnel shapes are scattered throughout the section suggesting some braided fluvial to deltaic influences. Both data sets (Table 3.2) suggest that the Sequence 3 BST was deposited on a broad fluvial floodplain.

#### 3.2.3.5 F-B Sequence 4

The uppermost CMB F-B sequence is bounded by the Westphalian-Stephanian

event (SB4) and the post-Permian unconformity. The complete sequence, as preserved, was deposited from the Early Stephanian to Late Early Permian, a period of approximately 16.5 Ma (Hess and Lippolt, 1986). This represents the estimated minimum time period, since it is not known how much section has been removed beneath the post-Permian unconformity.

The forestepping systems tract is coincident with the Cable Head Formation (Fig. 3.10) which is composed of a thick succession of fluvial redbeds with minor coal occurrences (Table 3.2). The thick sandstone bodies become increasingly consolidated towards the top of the systems tract (Fig. 3.10) suggesting improved stability of the depositional system upsection (cf., Melvin, 1993). FST well logs and seismic facies analysis (Table 3.2) suggest that the Sequence 4 FST was deposited in a prograding braided fluvial system.

The backstepping systems tract (Naufrage Fm.) in Sequence 4 is bounded by transgressive surface TS4 and the post-Permian unconformity. It is generally composed of a shale dominated succession which becomes coarser grained upwards (Fig. 3.10). BST well logs display predominantly serrated log signatures near the base suggesting deposition on a fluvial floodplain. The upper portions of the systems tract become more cylindrical shaped suggesting the presence of larger channel bodies. The log data on the upper section implies deposition in a channel and floodplain environment (Cant, 1992). The data for the sequence 4 BST (Table 3.2) implies an evolving depositional environment from a low energy fluvial floodplain to a higher energy fluvial environment which stabilized over time. Alternatively, it is speculated that the base of another F-B sequence (F-B Sequence 5?) is present in the upper portions of BST 4, with a sequence boundary located at the transition from finer grained to coarser grained deposits (Fig. 3.10). However, limited data for the upper interval of CMB fill prevents formal identification of a fifth F-B sequence at this time.

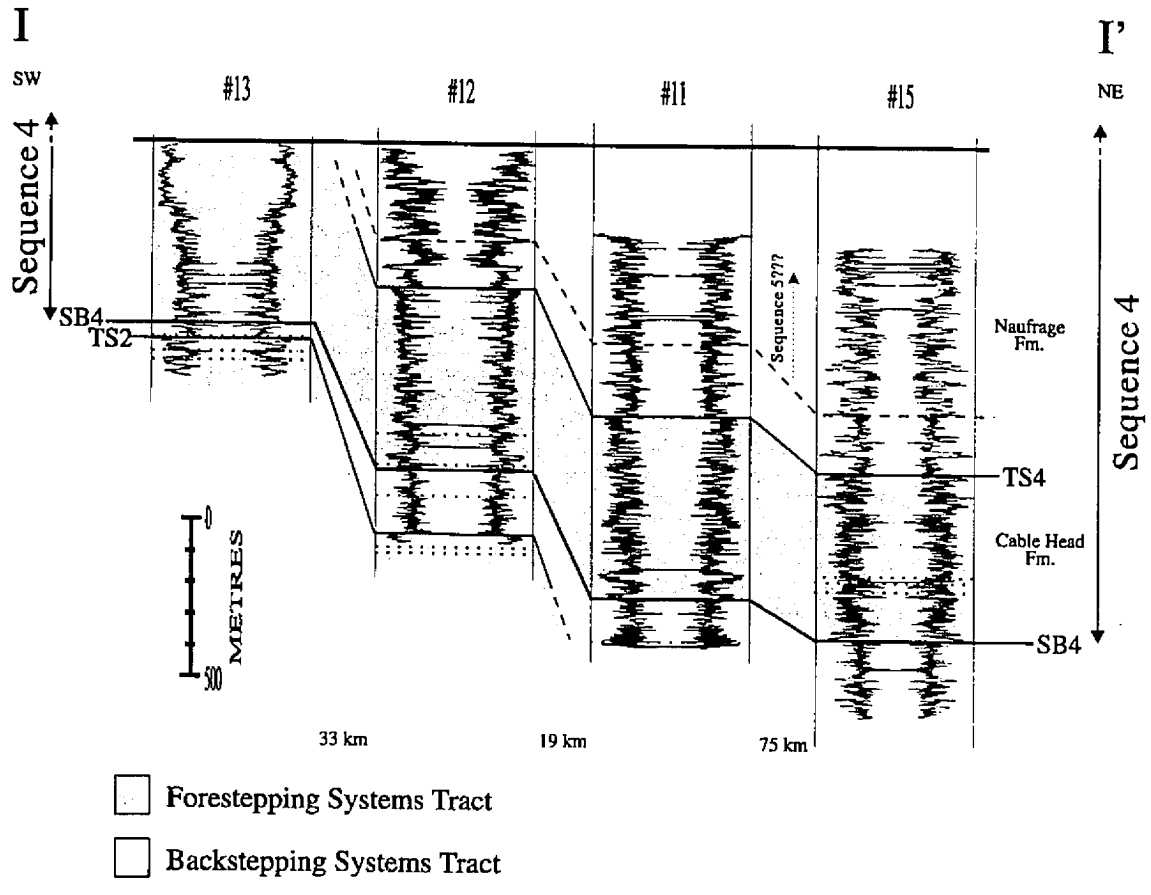


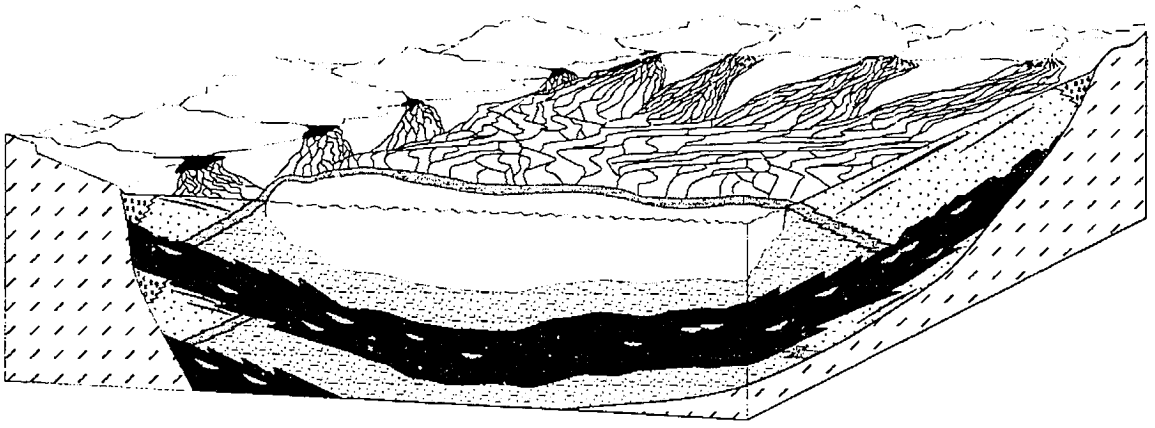

Figure 3.10 CMB stratigraphic cross-section I-I' (location and well names, Fig. 3.6) showing the detailed linking of F-B sequence 4 between four wells using mirrored gamma-ray logs. The associated Sequence 4 forestepping and backstepping systems tracts are coloured grey and white respectively. The base of a speculated fifth F-B sequence is shown, however, limited data for this upper interval of CMB fill prevents formal identification at this time. The section uses sea level as the datum and the locations of probable coals are indicated by dotted lines across the well bore. Vertical scale is indicated and distance between wells is shown.

### 3.2.4 CMB Sequence Stratigraphic Interpretations

#### 3.2.4.1 Forestepping Systems Tracts

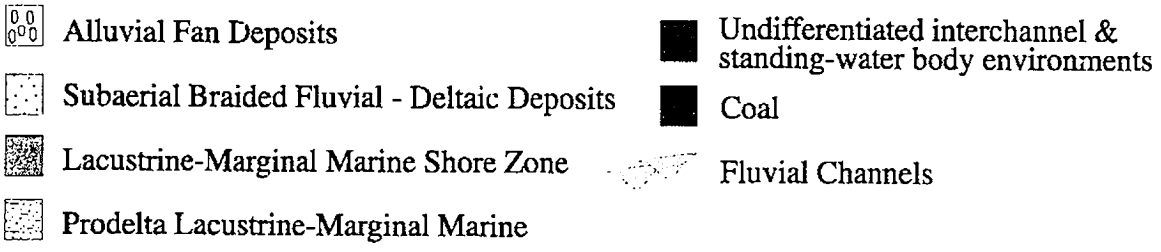
In general (Table 3.2), the FSTs in sequences 1 to 4 exhibit stratal successions that show coarsening upwards trends and high sandstone/shale ratios; both of which are similar features of the Legarreta *et al.* (1993) FSTs (Fig. 3.2). Typically the number of better developed coals increases towards the top of each systems tracts (Figs 3.7, 3.9, 3.10). The trends of sandstone bodies becoming more consolidated (i.e., thicker) towards the top of the systems tracts are supported by wireline log signatures for the FST, which typically display stacked channel fill to deltaic responses becoming increasingly blocky towards the overlying transgressive surface. Again, this is a common feature of the FSTs proposed by Legarreta *et al.* (1993) (Fig. 3.2). The seismic facies analysis of sequences 1 to 4 indicate that each of the FST contains prograding seismic reflectors locally. These deposits based on internal characteristics, are interpreted to be braided fluvial systems that were deposited on an inclined surface that was prograding towards the basin depocentre (Table 3.2) (Fig. 3.11), an interpretation that is consistent with previous studies (Table 2.8)

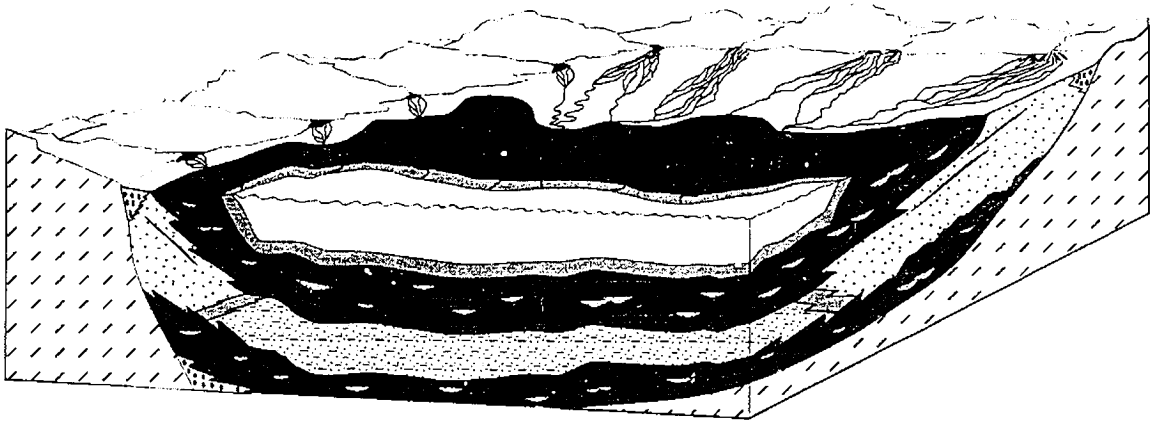
The conformable to unconformable sequence boundary typically underlying the FST suggests that the boundary formed as a result of sediment bypass and erosion due to a relative drop in stratigraphic baselevel (Van Wagoner *et al.*, 1988). An decrease in accommodation would have been associated with the baselevel drop. In conjunction with this, the fluvial systems which deposited the FST transported increased supplies of coarse clastic sediment to the Maritimes Basin, initially resulting in varying degrees of reworking and incision of the underlying finer grained strata. The progradation of the seismic reflectors within the FST indicate that the rate of sediment supply was greater than the rate of accommodation increase (Van Wagoner *et al.*, 1988). The increased sediment flux into the Maritimes Basin filled the available accommodation space resulting in net progradation of the forestepping systems tracts, braided-fluvial systems, from the basin margin to the basin centre (Fig. 3.11)



Sedimentation Rate > Rate of increasing Accommodation

PROGRADATION



Sedimentation Rate < Rate of increasing Accommodation

RETROGRADATION

Figure 3.11 Depositional models for the forestepping systems tracts (top) and the backstepping systems tracts (bottom) in the Central Maritimes Basin.

### 3.2.4.2 Backstepping Systems Tracts

The backstepping systems tracts comprise predominantly fine-grained sediments with low sandstone/shale ratios (Table 3.2). Sandstones occur periodically in the form of isolated channel bodies or crevasse splay deposits. Coal and limestone beds tend to be better developed in the lower portions of systems tracts. The corresponding well logs display serrated log characteristics and seismic facies analysis indicate that the BSTs have a low energy signature corresponding to a mud-rich environment (Legarreta *et al.*, 1993). Locally, some backstepping systems tracts display a fining upwards trend which might be indicative of the onset of aggradation as suggested by Legarreta *et al.* (1993) model (Fig. 3.2), however, there is no apparent surface by which to divide the BST into a lower and upper succession. Overall, the internal characteristics of each backstepping systems tract (Table 3.2) suggests that deposition occurred on broad, low lying, vegetated fluvial floodplains that received fine-grained sedimentation from the periodic flooding of associated channels (Fig 3.11).

Well logs and seismic data display an abrupt change in facies from the FST to BST with no associated erosional event suggesting a decrease in coarse sediment supply to the Maritimes Basin. This decrease in the rate of sediment supply resulted in a relative increase in the rate of accommodation closely associated with a relative rise in stratigraphic baselevel (Schumm, 1993). The rise in baselevel is identified with the transgressive surface which bounds the BST at its base. Increasing accommodation and decreasing sediment supply resulted in the retreat of the braided fluvial systems and the encroachment, or retrogradation, of finer grained fluvial floodplain/lacustrine deposits (Van Wagoner *et al.*, 1988) towards the margins of the basin (backstepping systems tracts) (Fig. 3.11).

### 3.2.5 Duration/Hierarchy

Any given depositional sequence contains numerous sequence boundaries depending on the scale of investigation (Embry, 1995). Scales range from inter-regional sequence boundaries recognized between synrift and postrift deposits to incised channel

scours separating marine from fluvial strata. It is important that after sequence boundaries have been identified, the scale of investigation for the sequence stratigraphic study be examined in order to correctly interpret and develop depositional models and stratigraphic histories (Johnson *et al.*, 1985). In order to do this, two onshore sequence stratigraphic studies are reviewed in the next section, afterwhich, the scale of the CMB sequence analysis is examined.

### 3.2.5.1 CMB High Frequency Sequence Stratigraphic Analysis

**Sydney Subbasin**

Eleven Westphalian D to Stephanian cyclothemic packages have been identified in the Sydney Subbasin (Fig. 2.1) by Gibling and Bird (1994). The cyclothems (Fig. 3.12), which occur in the Sydney Mines Formation (CMB Green Gables Formation equivalent) are 12 to 72 metres thick and can be correlated 45km along strike (Gibling and Bird, 1994). The cyclothems have a mean duration of approximately 200 ka which suggests that although each cyclothem may contain autocyclic successions, allocyclic processes are responsible for the overall cyclicity (Gibling and Bird, 1994; Tandon and Gibling, 1994). Tectonism has not been ruled out as a cause of the cyclicity, but Gibling and Bird (1994) favour glacio-eustatic causes closely associated with Milankovitch obliquity and precession cycles (Tandon and Gibling, 1994).

The cyclothems have been modelled as Galloway high-resolution genetic sequences. Each cyclothem is bounded by a maximum flooding surface (MFS) which is typically placed at the base of distinctive carbonaceous shale or limestone that locally overlies a major coal bed (Fig. 3.12) (Saunders, 1995; Gibling and Bird, 1994). The MFSs in several cyclothems are associated with a change from upper to lower marsh protozoan assemblages (Gibling and Wightman, 1994). Sequence boundaries, reflecting channel incision and prolonged subaerial exposure, have been placed at the bases of incised paleovalleys and the tops of extensive calcrete horizons on the adjacent interfluve (Fig. 3.12) (Saunders, 1995; Gibling and Wightman, 1994). A transgressive surface has not been explicitly defined, however, Saunders (1995) proposed a transgressive surface

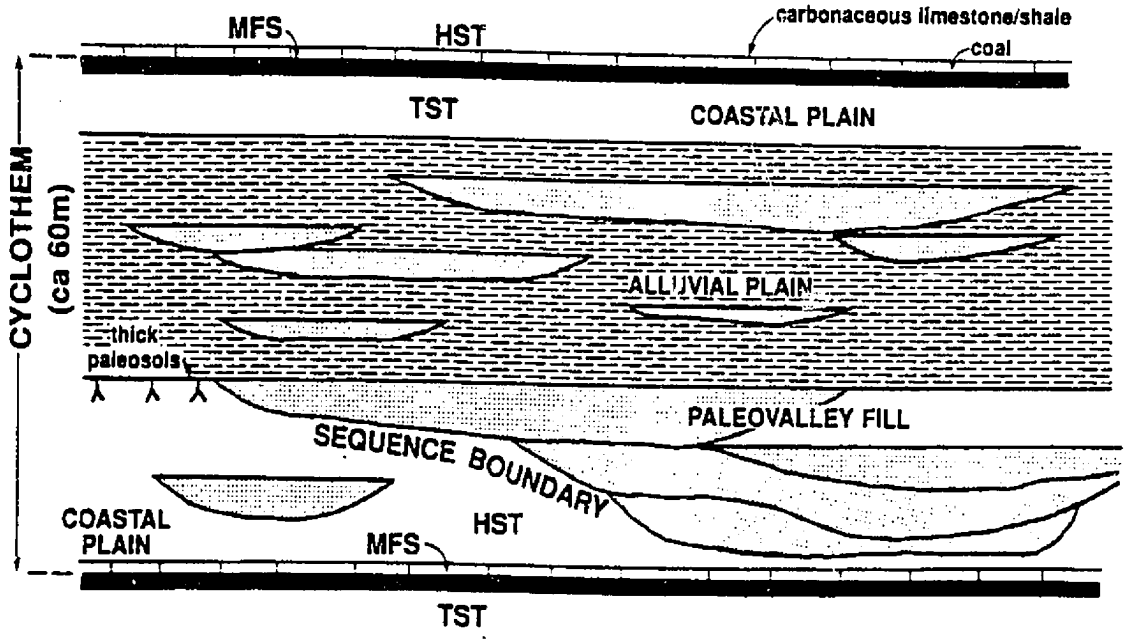



Figure 3.12 Schematic diagram of a well-developed Sydney subbasin cyclothem. The cyclothems have been identified in the Sydney Mines Formation (CMB Green Gables Formation equivalent) (from Gibling and Bird, 1994). HST = Highstand systems tract; TST = Transgressive systems tract; MFS = maximum flooding surface.

below the lowest documented agglutinated foraminiferal bed which, in the case of the Hub Cyclothem, coincided with the top the calcrete horizon.

Each cyclothem is typically composed of three lithologic successions; coastal plain, alluvial plain, and paleovalley fills (Fig. 3.12) (Gibling and Bird, 1994). The paleovalley fills which are assigned to the lowstand and/or transgressive systems tracts (TST) are composed of thick stacked channel deposits with minor grey and red flood-plain deposits bounded by a sequence boundary at the base and at the facies change to alluvial plain strata at the top (Gibling and Wightman, 1994). The alluvial plain strata are assigned to the TST and are composed of red mudstones with isolated channel sandstone bodies (Fig. 3.12) (Gibling and Bird, 1994). The coastal plain succession lies above the MFS and below the sequence boundary and is assigned to a highstand systems tract (HST) (Gibling and Bird, 1994). The HST strata consists of economic coals, bay-fill shale and sandstones with distributary channel deposits (Fig. 3.12) (Gibling and Bird, 1994).

**Cumberland Subbasin**

Sixteen depositional megacycles within the Westphalian A, Boss Point Formation (CMB Brion Island Formation equivalent) have been defined in the Cumberland Subbasin (Fig. 2.1) by Browne and Plint (1994). The megacycles are 15 to 150m thick and have been correlated between Bay of Fundy (Fig. 1.1) outcrop exposures over a distance of more than 12km (Plint and Browne, 1994). The mean duration of each megacycle is estimated at 60 ka and the cyclicity has been attributed to a combination of episodic tectonic subsidence and long-term changes in sediment flux controlled by climate within Milankovitch bands (Plint and Browne, 1994).

Each megacycle is composed of a basal muddy lacustrine facies and an upper sandy braidplain facies bounded by nonerosive flooding surfaces (Fig. 3.13). The lacustrine facies is composed of mudstones, fine sandstones, claystones, limestones and coals which lie abruptly above the braidplain facies of the previous megacycle. These sharp basal surfaces are mappable over distances of 12km and reflect rapid, almost

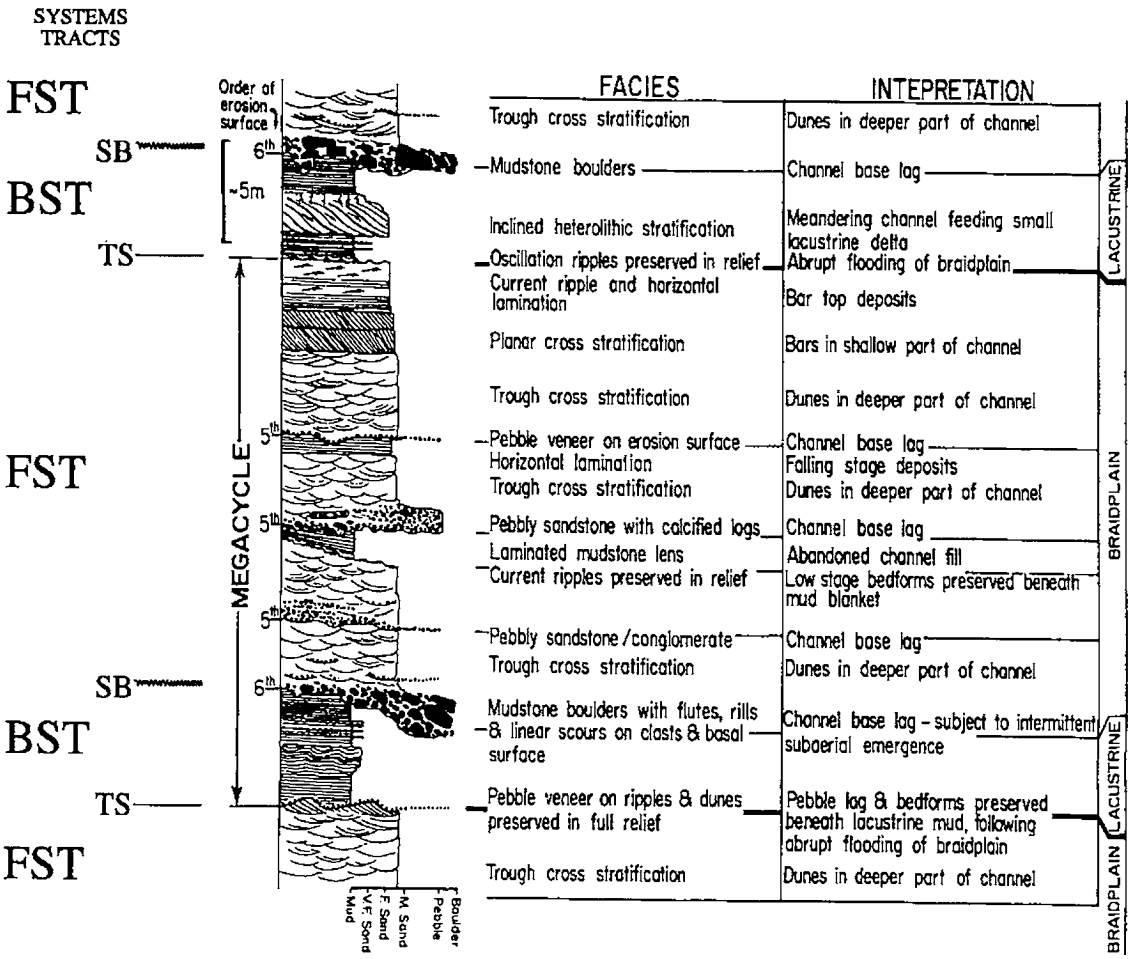



Figure 3.13 Schematic diagram of a typical Boss Point Formation (CMB Brion Island Formation equivalent) megacycle in the Cumberland subbasin (from Browne and Plint, 1994). A speculated alternative interpretation using the conceptual ideas from the F-B sequence analysis method is shown on the left. SB = Sequence boundary; TS = Transgressive surface; BST = Backstepping systems tract; FST = Forestepping systems tract.

instantaneous, flooding of the braidplain environments. The lacustrine successions shoal upwards from mudstones to sandstones that locally have rooted tops composed of decimeter thick mudstone or claystone (Plint and Browne, 1994).

The overlying sandy braidplain facies consists of multistoried channel sandbodies composed of fine- to medium-grained sandstones and conglomerates (Fig. 3.13) (Browne and Plint, 1994). Plint and Browne (1994) proposed that the predominant sediment flux for the braidplain systems came from the southwest and that the braidplain systems prograded to the southeast-northeast. The base of each braidplain facies is marked by an erosional surface which shows up to 15m of relief (Fig. 3.13). Locally, the erosional surface cuts down through the underlying lacustrine facies into the braidplain succession of the underlying megacycle (Browne and Plint, 1994).

An alternative way of interpreting the megacycles documented by Brown and Plint (1994) might be to conceptually apply the F-B sequence analysis method. Instead of choosing the nonerosive surface below lacustrine succession a sequence boundary could be placed at the erosive base of the sandy braidplain facies (Fig. 3.13). The nonerosive surface described by Browne and Plint (1994) could then become the transgressive surface (Fig. 3.13) separating coarse-grained facies from fine-grained facies reflecting instantaneous widespread flooding (i.e., baselevel rise) of the underlying braidplain, as was originally suggested by Plint and Browne (1994). The proposed shoaling of the lacustrine succession, culminating with the rooted zone was interpreted to indicate aggradation (Plint and Browne, 1994). This could be interpreted as indications of the aggradational systems tract (AST) defined by Legarreta *et al.* (1993) (Fig. 3.2), who suggest that, following the FST and BST, there is increased frequency of soil profiles reflecting limiting to decelerating rates of accommodation -- development of the AST.

### 3.2.5.2 CMB Low Frequency Sequence Stratigraphic Analysis

The Central Maritimes Basin sequence stratigraphic study deals with large scale cyclic packages similar in scale to those originally describe by Vail *et al.* (1977). As demonstrated above the CMB sequences outlined in this chapter consist of many smaller,

higher frequency cycles such as those described by Gibling and Bird (1994). To distinguish between major (regional) and minor (local) sequence boundaries some workers have developed classification systems based on the duration of the sequence (Vail *et al.*, 1991) and the type of sequence boundary (Embry, 1993).

Vail *et al.* (1991) proposed that 2nd, 3rd, 4th and 5th order sequences are between 3-50, 0.5-3, 0.08-0.5, and 0.03-0.08 Ma duration, respectively. Application of these criteria to the CMB sequences suggests that F-B Sequences 1 and 3 are 3rd order sequences and F-B Sequences 2 and 4 are 2nd order sequences. The megacycles and cyclothems in the Cumberland and Sydney subbasins, respectively, would be classified as 4th order sequences. Embry (1995, 1993) argued that the methods of Vail *et al.* (1991) are subjective and depending upon which sequence boundaries are selected any sequence duration (or order) can be attained depending on the desired result.

Embry (1995, 1993) proposed that, instead of the duration of sequences, the boundary characteristics should be used to rank sequences. The ranking (Fig. 3.14) uses the character of the basin fill below the sequence boundary, which Embry (1993, 1995) suggested reflects the relative magnitude of the baselevel change causing the boundary surface, to classify individual sequence boundaries on a scale of 1 (large baselevel changes) to 5 (small baselevel changes). Once the boundaries have been categorized, the sequences between boundaries are ranked, equal to the highest order boundary (Fig. 3.14). Embry (1995) further suggested that any one sequence cannot contain a sequence boundary of the same or equal order as its highest order sequence boundary.

The application of the Embry (1995) classification using the relationships between sequence boundaries (events) and underlying CMB strata (both outlined in Chapter 2) identified 1st order sequence boundaries at two locations in the post Early Basin Fill succession; the Namurian-Westphalian event (signifying a basinwide shift in tectonic setting) and the Permian unconformity at the top of the section (Fig. 3.15). 2nd order sequence boundaries were identified at the bases of F-B Sequences 2 and 4. The sequence boundary at the base of F-B Sequence 3 was interpreted as 3rd order as a result of the Chapter 2 investigations. Following the methods of Embry (1995), the ordering of

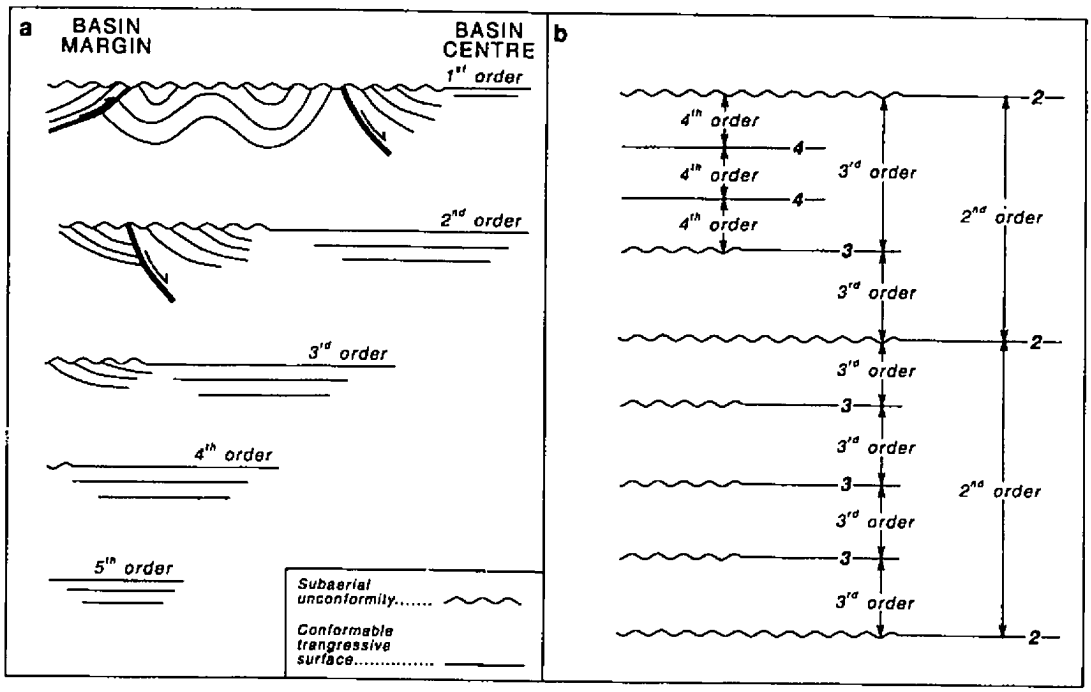



Figure 3.14 (a) Embry's (1993) ranking of sequence boundaries based on character of the underlying basin fill. (b) A sequence order is determined by the highest order of its bounding surfaces. Sequences cannot contain any sequence boundaries of equal or greater order (from Embry, 1993).

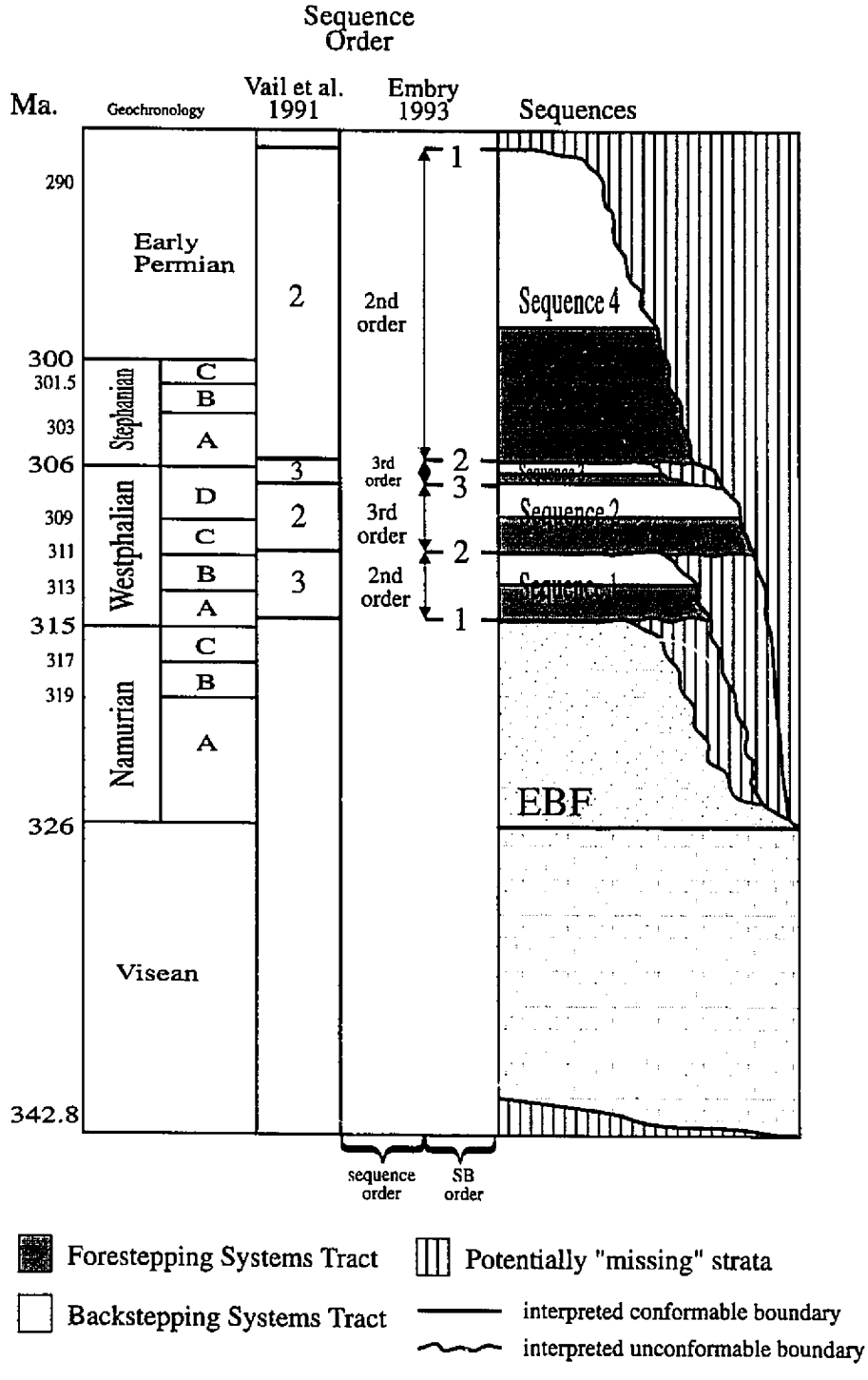



Figure 3.15 A CMB stratigraphic column showing F-B sequences and the results of applying the Vail et al. (1991) and Embry (1993) sequence classification schemes to the basin fill. Both systems identify two 2nd order and two 3rd order depositional sequences in the post-Namurian fill. Absolute time scale on the left is according to Hess and Lippolt (1986), AGSO (1996), and Claoe-Long et al. (1992). EBF = Early Basin Fill

sequence boundaries has resulted in the identification of two 2nd order (F-B Sequences 1 and 4) and two 3rd order (F-B Sequences 2 and 3) sequences in the CMB post-Namurian strata, an arrangement that is essentially the same as the ordering obtained by the Vail *et al.* (1991) method (Fig. 3.15).

### 3.2.5.3 CMB Composite Cyclic Packages

The original sequence stratigraphic concepts presented by Vail *et al.* (1977) were applied at a 2nd-3rd order sequence level of investigation that was able to predict the response of a depositional system to variable eustatic controls using standard seismic data. The integration of seismic, well logs, core and outcrop data in sequence stratigraphic analysis resulted in the identification of smaller, higher frequency cycles (Van Wagoner *et al.*, 1990).

The seismic and well data available for this study are very suitable for the level of basin analysis proposed by Vail *et al.* (1977) (cf., Fig 3.16, 3.5, 3.8). However, as described in the preceding sections, smaller, higher frequency sequences have been identified within the CMB F-B sequence framework at the outcrop scale (Fig. 3.16). This is not surprising considering that sequence stratigraphic concepts are both scale and time independent (Posamentier *et al.*, 1992), implying that 2nd and 3rd order sequences, the basic framework of Vail *et al.* (1977), may contain 4th and 5th order sequences that can be identified if a high resolution dataset is available.

In attempt to resolve the problem of scale and terminology with respect to sequences within sequences, Mitchum and Van Wagoner (1991) suggested a composite sequence that consists of sequence sets which are analogous to the systems tracts within a sequence (Table 3.1). For example, in the southern USA they identified a 3rd order composite sequence made up of lowstand shelf-margin wedge set (381m thick), overlain by a transgressive sequence set (TSS) (119m thick), capped by the highstand sequence set (HSS) (69m thick). A third order MFS separates the TSS from the HSS and the entire composite sequence is bounded by third order sequence boundaries. Each of the sequence sets is composed of a series of stacked 4th order sequences bounded by

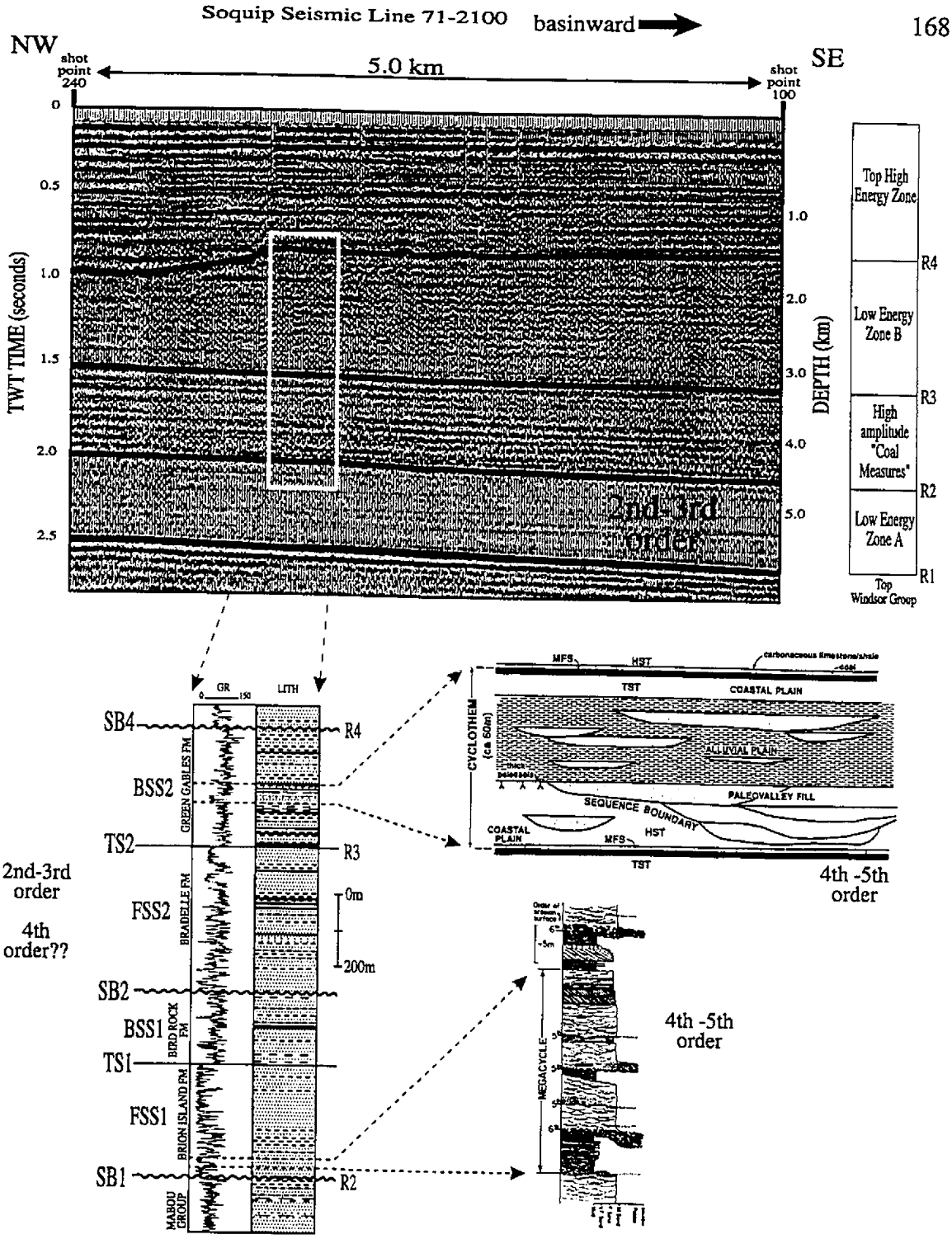



Figure 3.16 Schematic diagram showing the composite nature of the Maritimes Basin fill identified at different scales of investigation which in turn recognizes different levels of sequence hierarchy. Cyclothem and megacycle models from Gibling and Bird (1994) and Browne and Plint (1994), repectively. HST = Highstand systems tract; TST = Transgressive systems tract; MFS = maximum flooding surface; BSS = Backstepping systems set; FSS = Forestepping systems set; TS = Transgressive surface; SB = Sequence Boundary.

sequence boundaries and each containing a maximum flooding surface. A similar situation has been recognized in a Carboniferous succession by Weber *et al.* (1996), who have identified 5th order sequences, stacked within 4th order sequences, each containing a LST, TST, and HST, all of which stack into seismically resolvable, biostratigraphically defined, 3rd order composite sequence.

Applying these concepts to the CMB fill would imply that the four F-B sequences identified in the CMB fill are more correctly categorized as composite 2nd-3rd order F-B sequences, each of which is composed of a basal forestepping system set (FSS) and an upper backstepping system set (BSS) (Fig. 3.16). The FSSs and BSSs likely contain smaller, 4th and 5th order sequences, some of which have been identified by Browne and Plint (1994) and Gibling and Bird (1994) in the Cumberland and Sydney subbasins, respectively (Fig. 3.16). The lower order composite F-B sequences are bounded by 2nd-3rd order sequence boundaries and define a transgressive surface of similar magnitude, whereas, the higher frequency sequences described above are defined with 4th order sequence boundaries/erosional surfaces, transgressive surfaces, and maximum flooding surfaces.

## 3.3 Discussion

### 3.3.1 Methods

Modern sequence stratigraphic concepts and methods are generally applicable to most strata, however, before being applied to any specific basin they should be modified to account for local factors (Posamentier and Vail, 1988). The two most important constraints on this study are the dataset and the predominantly nonmarine nature of the basin fill.

This study used a limited database consisting of multi-reflection seismic data with limited well control. This type of sequence stratigraphic study is classified as low resolution sequence stratigraphy and tends to be model driven (Posamentier and Weimer, 1993). It may be better described, following Shanley and McCabe (1994), as the "world that is visible at the area of investigation" approach. In direct contrast, high resolution

sequence stratigraphy uses closely spaced well logs or outcrop, extensive core and biostratigraphic control, and closely spaced 2-D and 3-D seismic coverage to construct a data-driven exploration model (Posamentier and Weimer, 1993).

The T-R sequence concept of Embry (1995, 1993) was specifically chosen for its applicability to large scale basin analysis issues where the level of detail is relatively limited. The Embry model was successfully applied in the Sverdrup Basin during an investigation of similar scope to the broad CMB basin analysis investigation (Embry, 1993). An appealing feature of the T-R model is that sequence boundaries closely coincide with lithologic boundaries, so that the model was applicable to the stratigraphic framework developed in Chapter 2. In addition the two system tract approach proposed by Embry (1995) did not require the identification of a maximum flooding surface and was appropriate for the low resolution CMB sequence analysis approach.

A limited number of nonmarine sequence stratigraphic models are available in the literature (Olsen *et al.*, 1995; Shanley and McCabe, 1994, 1993; Legarreta *et al.*, 1993; Wright and Marriott, 1993; Posamentier and Vail, 1988). Most use an established model from the open- to marginal-marine realm and modify the parameters for the nonmarine system (e.g. Wright and Marriott, 1993). Others only comment briefly about nonmarine depositional systems during discussion of marine systems (Posamentier and Vail, 1988). On the other hand, Legarreta *et al.* (1993) introduced innovative ideas concerning continental fluvial dominated successions with only limited reference to eustatic dominated systems and with direct references to real examples. These factors, in addition to the similarities between their Argentinean dataset and the CMB dataset, made the Legarreta *et al.* (1993) concepts highly applicable to CMB sequence stratigraphic analysis.

By merging the concepts derived from the work of Embry (1995, 1993) and Legarreta *et al.* (1993) a method was developed that successfully addressed the broad nonmarine regional analysis issues presented by the Central Maritimes Basin fill. The transgressive and regressive terms used by Embry (1993) are broadly comparable with the backstepping and forestepping terms used by Legarreta *et al.* (1993).

### 3.3.2 Sequence Boundaries

Biostratigraphic breaks, seismic sequence boundaries and facies discontinuities clearly suggest that the surfaces under the coarse-grained units should be recognized as sequence boundaries (Lindsay and Korsh, 1989). Although, the sequence boundaries are coincident with lithostratigraphic boundaries, discontinuities in the stratigraphic column are commonly identified as formation boundaries (von der Borsh *et al.*, 1988).

Application of the Embry (1993) approach would have *typically* selected the tops of major sand dominated units, as transgressive surface equivalents and designated them sequence boundaries, but in the context of a marginal-marine setting. In the CMB nonmarine setting, the transgressive surfaces display few of the criteria associated with a regional sequence boundary. In the marine setting, few of the prevailing sequence stratigraphic models place sequence boundaries directly under sand dominated packages (Fig. 3.1), although, at the basin margin Embry (1993) does suggest this location for a sequence boundary. These sands generally form due to progradation of the shoreface seaward and are not typically associated with erosion. An exception is when a coarse-grained incised valley fill overlies a Type 1 unconformity. Typically, the surfaces under coarse-grained packages are rarely classified unless the surface happens to be a regressive surface of erosion (RSE) (Embry, 1995). As a result, surfaces underlying coarse-grained units are typically classified as facies or lithologic boundaries with little chronostratigraphic significance.

Continental systems contrast with marine systems with regards to sequence boundaries. Due to fluctuations in baselevel and accommodation the bases of major fluvial systems are the best candidate for sequence boundary locations. For instance, certain Westphalian B fluvial braidplain deposits in Britain incise tens of metres into underlying finer grained alluvial deposits as a direct result of negative changes in accommodation (Haszeldine and Anderton, 1980). Furthermore, it is typical in a nonmarine setting for multi-storied, laterally extensive, sandbodies to overlie major sequence boundaries (Shanley and McCabe, 1994). Similar observations have been made by Olsen *et al.* (1995) in Utah, where amalgamated fluvial sheets overlie major sequence

boundaries closely associated with the initial fall and subsequent rise of baselevel.

The sequence boundaries in the CMB are generally unconformable to conformable suggesting that the magnitude of erosion on the sequence boundary can change from being erosive on the basin margin to conformable near the basin centre. Shanley and McCabe (1994) suggested that incision is not always associated with the baselevel fall, in fact, a baselevel fall can result in only minor erosion. Legarreta *et al.* (1993) and Jervey (1992) suggested that a nonmarine sequence boundary may change from being erosive on the basin margins to completely conformable near the basin centre, a suggestion that is analogous to the sequence boundary definition of Vail *et al.* (1977).

### 3.3.3 Transgressive Surfaces

The choice of a transgressive surface in any sequence stratigraphic study, marine or nonmarine, is difficult and often ambiguous. Davies *et al.* (1995) stated that an obstacle in the recognition of a transgressive surface is that transgressive surfaces typically occur in a zone that is less than 2 metres thick. Well below the resolution of standard industry seismic or wireline log studies and commonly difficult to resolve with core or outcrops.

Besides the abrupt lithologic contrast between the coarse and fine facies, the transgressive surface was placed at the top of the coarse facies due to the apparent abundance of better developed coal and limestone beds near this location. Limestones in nonmarine settings are often indicators of transgressive surfaces (Shanley and McCabe, 1994). In addition, well developed coals commonly are formed during the late stages of lowstand and the early stages of relative base level rise (Beaubouef *et al.*, 1995). The location of limestones near the base of the finer grained units and the presence of better developed coals at both the bases of the finer grained units and tops of coarser grained units, indicated a transgressive surface near the boundary between the two units.

The placement of a transgressive surface at the top of the coarse-grained succession within the F-B sequence is relative to the scale of investigation. At the level of CMB sequence analysis (2nd-3rd order), using well logs and seismic data, the top of

the coarse-grained facies is the most obvious place to recognize a regionally extensive transgressive surface. The chosen location is easily recognizable at the larger outcrop scale (100s of metres) at the "knife-sharp" contact between Brion Island Fm. and Bird Rock Fm. equivalents (Boss Point and Joggins formations, respectively) in the Cumberland Subbasin (Gibling, M., 1996, pers. comm.) as is the contact between Bradelle and Green Gables equivalents (South Bar and Sydney Mines formations, respectively) in the Sydney Subbasin (cf., Rust and Gibling, 1990). However, as shown on cross-sections G-G', H-H' and I-I' (Figs. 3.7, 3.9, and 3.10) the number of coals increase towards the tops of the forestepping systems sets culminating with abundant coal deposition near the base of the finer grained successions. Detailed outcrop studies (4th-5th order) also identify coal seams prior to the top of the coarse-grained successions (cf., Rust and Gibling, 1990). This implies evidence of increasing amounts of transgression, or minor backstepping, before the top of the main coarse-grained unit suggesting that the sharp lithologic boundary may not entirely reflect a transgressive surface, but a zone of increased transgressive tendencies occurring as the rate of sediment supply is being exceeded by the rate of accommodation increase. Thus the transgressive surface proposed for the 2nd-3rd order scale CMB analysis is abrupt, but at a 4th-5th order scale, the transgression reflects more of a transitional zone of increased transgression which starts below the top of the FSS, greatly accelerating with the onset of 2nd-3rd order backstepping systems set.

An alternative location for the 2nd-3rd order transgressive surface is presented by both Shanley and McCabe (1992) and Posamentier and Vail (1988), who suggest that the change from amalgamated fluvial deposits (the CMB FSS) to more isolated channel deposits with an increasing amount of finer grained material (the CMB BSS) identifies a maximum flooding surface equivalent. Both interpretations assume that the amalgamated fluvial strata is confined to a incised valley which overlies a Type 1 sequence boundary. The filling of the incised valley occurs during transgression and the change in fluvial architecture represents baselevel rise above the confines of the valley, afterwhich accommodation abruptly increases, signifying the maximum flooding surface. The key

component of the argument is the interpretation that the amalgamated sandstones are confined to incised paleovalleys. The scale of investigation is critical to this argument. In 4th order sequences, within the composite CMB F-B sequence framework, Gibling and Bird (1994) have documented fluvial deposits confined to paleovalleys which supports the suggestions of Shanley and McCabe (1992) and Posamentier and Vail (1988), however, at a 2nd-3rd order scale there is no evidence to suggest that the CMB FSSs are confined by any paleovalleys.

CMB data suggest that little erosion occurred during the rise in stratigraphic baselevel associated with the regional transgressive surface, whereas, transgressive surfaces in a open- to marginal-marine setting are typically associated with ravinement (Van Wagoner *et al.*, 1988). This is potentially explained by a rapid baselevel rise such that the boundary is sharp but essentially nonerosive. A similar explanation was proposed for the boundary between coarse-grained and fine-grained strata in the Boss Point Formation megacycles by Plint and Browne (1994). Their study identified erosive surfaces at the bases of the coarse-grained units, but essentially conformable surfaces at the tops. The conformable surfaces were attributed to rapid, almost instantaneous lacustrine flooding over the fluvial deposits.

### 3.3.4 Forestepping-Backstepping (F-B) Sequences

#### 3.3.4.1 Forestepping Systems Sets

The Central Maritimes Basin forestepping systems sets are interpreted in a similar manner to the FSTs of Legarreta *et al.* (1993). Analogous to the FSTs defined by Legarreta *et al.* (1993) the CMB FSSs overlie regional sequence boundaries and typically display both a consolidation of sandbodies towards the top of the succession and a coarsening upwards trend (cf., Fig. 3.2 vs. 3.3). In a comparable study, Larue *et al.* (1995) documented thick (>300m) channel fill and aggradational sheet complexes in the eastern United States, overlying a master erosional surface. The CMB FSSs have a predominantly bedload dominated lithologic signature and show evidence of progradation seismic reflectors, suggesting that deposition of the FSS proceeded in response to an

increase in coarse clastic sediment supply to the Maritimes Basin. This resulted in the rapid filling of available accommodation space associated with a relative lowering of baselevel, causing the progradation of the forestepping systems tracts towards the basin centre (Fig. 3.17) (Schumm, 1993; Van Wagoner *et al.*, 1988). During the progradation of the bedload dominated systems the underlying strata on the alluvial plain were reworked and incised, however, these processes would probably have decreased in intensity towards the top of the systems tract as baselevel drop slowed, then baselevel began to slowly rise. This evolution of the fluvial system is suggested by the increased consolidation of sandstone bodies and development of coals upsection. Melvin (1993) interpreted a similar evolution in fluvial style, from immature braided systems to thicker, less shaly, more fully developed bed-load dominated systems, as the adjustment of a depositional system to an increased supply of coarse sediment.

This study assigns the CMB FSSs to a comparable lowstand systems tract position in the open- to marginal-marine realm. The studies by Hampson (1994), Legarreta *et al.* (1993), and Larue *et al.* (1995) came to similar decisions in assigning strata consisting of laterally extensive, multi-storied, medium- to coarse-grained sandstone sheet bodies developed in a braided fluvial system to lowstand systems tracts.

In contrast to placement of CMB coarse-grained units (FSS) in the lowstand position of the stratigraphic baselevel cycle, prevailing nonmarine sequence stratigraphic models propose alternative locations for amalgamated fluvial sandstones in the baselevel cycle. Shanley and McCabe (1994) suggested that the multi-storied, multi-lateral sandbodies indicate slowing rates of baselevel fall and a slow change to rising baselevel, a suggestion similar to that of Legarreta *et al.* (1993); however, they assigned these deposits to the alluvial transgressive systems tract found within the confines of an incised valley system. Contrary to this, in the same paper, they suggested an alternative interpretation that all those strata contained in the incised valley lying above the sequence boundary belong to the lowstand systems tract, and those strata above the first local flooding surface to the transgressive systems tract, an interpretation they evidently do not support (Shanley and McCabe, 1994). A similar interpretation to the one favoured by

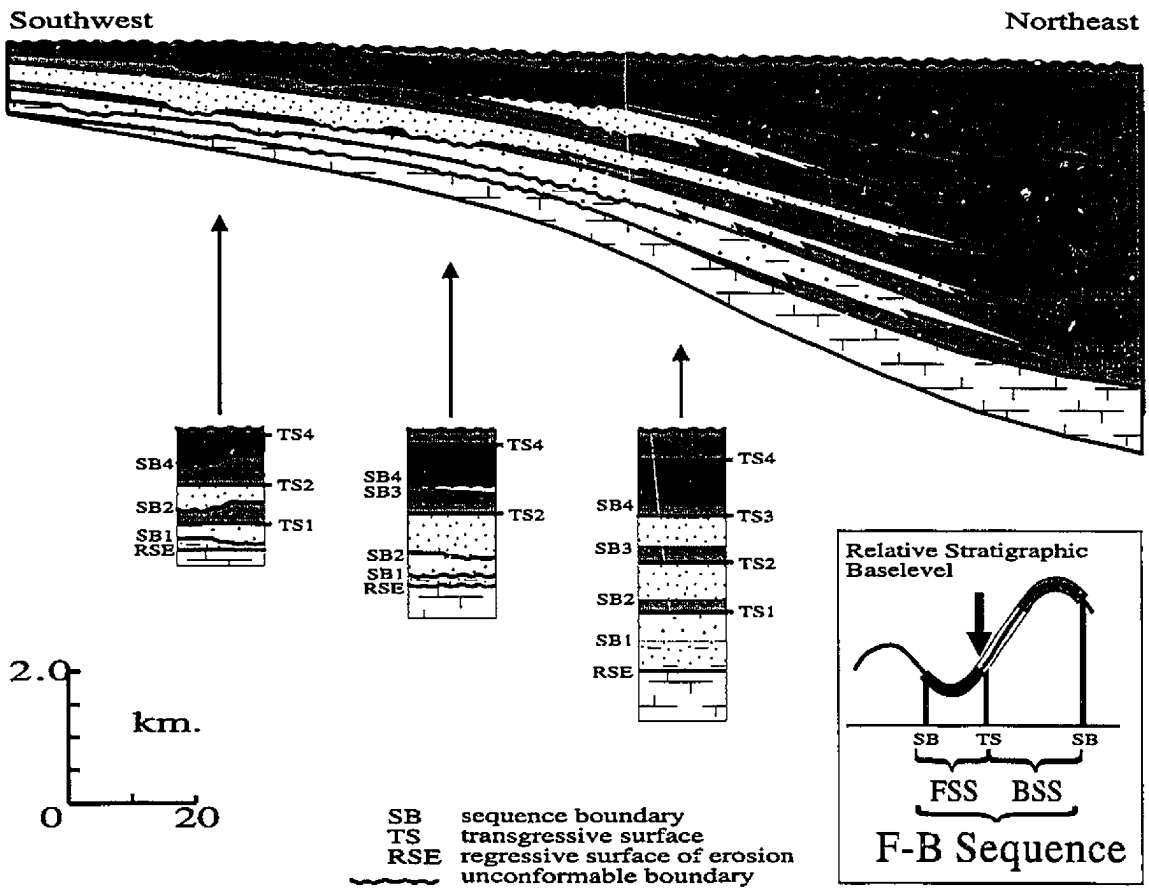



Figure 3.17 Schematic geological cross-section illustrating the application of the F-B sequence method to the CMB fill. The accompanying stratigraphic baselevel cycle shows the development of major systems sets through time; the forestepping systems set during lowering and subsequent early rise of stratigraphic baselevel and the backstepping systems set during rising to early fall of stratigraphic baselevel until the initiation of the next sequence boundary. The arrow on the baselevel curve indicates the preferred location for the development of coals and limestones. See Figure 2.9 for lithology legend. SB = Sequence boundary; TS = Transgressive surface; BSS = Backstepping systems set; FSS = Forestepping systems set.

Shanley and McCabe (1994) is presented by Olsen *et al.*, (1995) who placed a major sequence boundary under their amalgamated fluvial sand sheet (Level 2 of their 4 part alluvial sequence) and suggested that the sandstone facies developed during increasing base level rise in the confines of an incised valley; thereby assigning the sand sheet to a transgressive systems tract. Conceptually, Wright and Marriott (1993) proposed the same scenario as Shanley and McCabe (1994) and would suggest that most amalgamated fluvial strata are deposited in transgressive systems tracts typically within the confines of incised paleovalleys. Applying their model would suggest that the lower portion of the CMB FSS be assigned to a late highstand position and the more consolidated strata at the top of the FSS be assigned to the next successive lowstand position. The lack of evidence for a sequence boundary at this level in the CMB suggests problems with their model results. Alternatively, applying the Posamentier and Vail (1988) model suggests that the widespread amalgamated fluvial deposits found in the CMB FSSs only develop during progradation associated with early to late highstand systems tract development.

The undisputed feature of nonmarine sequence stratigraphic models is the recognition of a major sequence boundary underneath the amalgamated fluvial sandsheets. Conversely, the discrepancy between the CMB F-B sequence analysis and those previously mentioned is the timing of major fluvial deposition with respect to the stratigraphic baselevel cycle. Most of the above mentioned authors believe that coarse amalgamated fluvial sedimentation is confined fill within the incised valleys, and therefore, the deposits must be either transgressive or highstand equivalents. These interpretations seem to regress to standard concepts used in open- to marginal-marine sequence stratigraphic models. On the other hand, in a completely nonmarine setting far removed from eustatic influences, a relative baselevel fall does not necessarily result in fluvial incision, in fact there may be little or no erosion associated with a nonmarine baselevel fall (Shanley and McCabe, 1994).

The evidence in the CMB suggests that the FSSs are not confined by any paleovalley but are thick regionally extensive amalgamated sandstone dominated sheets. A similar situation is recognized in the intracratonic Amadeus Basin where the 400 meter

thick Arumbera Sandstone "blankets" the basin as a result of changes in accommodation associated with a drop in relative sea level (Lindsay, 1987). The Arumbera Sandstone, like the CMB FSSs, displays evidence of progradation towards the basin centre (Lindsay, 1987). Other examples of thick regionally extensive coarse-grained facies overlying major sequence boundaries are presented by Hampson (1994) and Martinsen and Sauar (1994), both of whom identified thick amalgamated sandstone bodies deposited over areas in an excess of 1000 $km^2$ and 6000 sq. miles, respectively. Both studies proposed that the sandstone sheets developed in unconfined low gradient environments.

Fluvial systems will inherently erode, rework and deposit sediments in response to any fluctuations in accommodation (Shumm, 1993). It follows that if a paleovalley does not exist to confine fluvial deposits, the strata deposited during relative low baselevel will develop directly above the sequence boundary. This implies that in the absence of a confining paleovalley, the strata directly overlying the sequence boundary are, as proposed by Legarreta *et al.* (1993), the counterpart of open- to marginal-marine lowstand deposits and not the alluvial transgressive systems tract as proposed by Shanley and McCabe (1994, 1992), Wright and Marriott (1993) and Olsen *et al.* (1995). Placing transgressive fluvial deposits within an incised paleovalley is a concept taken from the open- to marginal-marine realm, a concept that may not apply in nonmarine settings. The primary concern should be to adapt and modify current sequence stratigraphic principles to compensate for the complex nonmarine system (Hamilton, 1995) and not to try and mold the nonmarine system to marine concepts.

### 3.3.4.2 Backstepping Systems Sets

The predominantly fine-grained nature of the BSSs overlying the transgressive surface, with coarse-grained sedimentary facies represented by isolated channel bodies, suggests that the CMB backstepping systems sets developed primarily in response to a decreased sediment supply to the Maritimes Basin. The decreased sedimentation rates resulted in an increase of accommodation space closely associated with a relative rise in stratigraphic baselevel (Van Wagoner *et al.*, 1988). This is a suggestion that is supported

by the work of many others (Martinsen and Sauar, 1994; Shanley and McCabe, 1994; Allen and Posamentier, 1993) who have concluded that changes from amalgamated fluvial deposits to isolated channels and abundant overbank fines reflects a change to increased accommodation closely associated with rapid baselevel rise. In the CMB, the relative rise in baselevel forced the retreat of the fluvial systems and the retrogradation, or backstepping, of finer grained fluvial-lacustrine strata onto the basin margins.

The classification of all strata above the transgressive surface into the backstepping systems tract was a suitable method of investigation in the CMB. It seemed inappropriate to divide the BSSs into smaller sequences because of the lack of any definable surface within the BSSs. Its has been suggested by other workers (e.g., Olsen *et al.*, 1995; Wright and Marriott, 1993) that a surface does exist and that the strata above the amalgamated coarse-grained facies is divisible. Had a higher degree of resolution been possible, a 2nd-3rd order maximum flooding surface may have been defined, however, it was well below the resolution of this study.

## 3.4 Concluding Statement

Aside from a few studies (Rehill *et al.*, 1995; Gibling and Bird, 1994) sequence stratigraphic concepts have not been traditionally applied to the Maritimes Basin fill. The reasons for this are unknown, but one may speculate that the predominantly nonmarine nature of the fill, the lack of definitive chronostratigraphic markers and the lack of regionally recognizable surfaces of discontinuity have frustrated attempts to use sequence stratigraphy in the basin.

The recognition of regionally extensive sequence boundaries (Fig. 3.17) and the development of the F-B sequence method has helped to better understand the nonmarine nature of the Central Maritimes Basin fill. Application of the F-B method at the regional scale has aided in the identification of two 2nd order and two 3rd order composite depositional sequences (Fig. 3.17) in the post-Namurian basin fill which are in turn composed of smaller 4th and 5th order sequences. Each 2nd-3rd order composite sequence is bounded at the top and bottom by regionally identifiable sequence boundaries

with an equally areally extensive transgressive surface recognized within each sequence. The composite sequences generally consist of a coarse-grained basal succession, overlain by a finer grained succession (Fig. 3.17)

The basal coarse-grained members consist of thick amalgamated fluvial channel units here termed forestepping systems sets. These forestepping systems sets typically developed in the CMB when the rate of sediment supply to the Maritimes Basin exceeded the rate of accommodation increase and relatively lowered stratigraphic baselevel. The internal characteristics of the forestepping systems sets imply they were deposited as part of an extensive braided fluvial system that was prograding towards the depocentre (Fig. 3.17)

Overlying the forestepping systems sets are the transgressive surfaces, above which lie the finer grained backstepping systems sets. These deposits are composed predominantly of overbank fines with locally developed isolated fluvial channel and crevasse splay deposits. The backstepping systems set deposits resulted when the rate of sediment supply to the braided fluvial systems was exceeded by the rate of accommodation increase. This resulted in a relative rise in stratigraphic baselevel which forced the retreat of the fluvial systems back to the basin margin and initiated the backstepping deposits.

# CHAPTER 4 - CONTROLS ON CENTRAL MARITIMES BASIN SEQUENCE DEVELOPMENT

## 4.1 General Statement

It has been proposed in the previous chapter that the Post-Mabou Group sedimentary fill in the Maritimes Basin consists of four forestepping-backstepping (F-B) sequences that are regionally extensive. Each F-B sequence is composed of a basal prograding and upper retrograding sedimentary succession. According to Shanley and McCabe (1994), such a cyclical stacking pattern is best explained by variations in the relative rates of change of accommodation and sediment supply.

The primary controlling factors affecting the rates of change of accommodation and sediment supply are tectonism, eustasy, and climate which are closely inter-related (Fig. 4.1) (Van Wagoner *et al.*, 1988). Recent sequence stratigraphic studies have attempted to illustrate the relative importance of each control with respect to stratigraphic development by examining the relationships through time between primary control fluctuations and the initiation of sequences and sequence boundaries.

This chapter examines the changes in tectonism, climate, and eustasy that may have affected the relative rates of change of accommodation and supply and produced the present Central Maritimes basin fill geometries.

### 4.1.1 Regional vs. Local Processes

Regional, or allocyclic, depositional packages develop as a result of changes in the supply of energy or material to a system (Beerbower, 1964). Cyclic packages resulting from such extrabasinal effects can be caused by changes in regional, possibly global, tectonism, climate, and eustasy (Beerbower, 1964). Conversely, local, or autocyclic, development of sedimentary packages results from no change in energy or material input into the sedimentary system, but involves a redistribution of these elements within the system (Beerbower, 1964). Autocyclic mechanisms include channel avulsion and delta lobe switching (Miall, 1984). Autocyclic packages are generally laterally

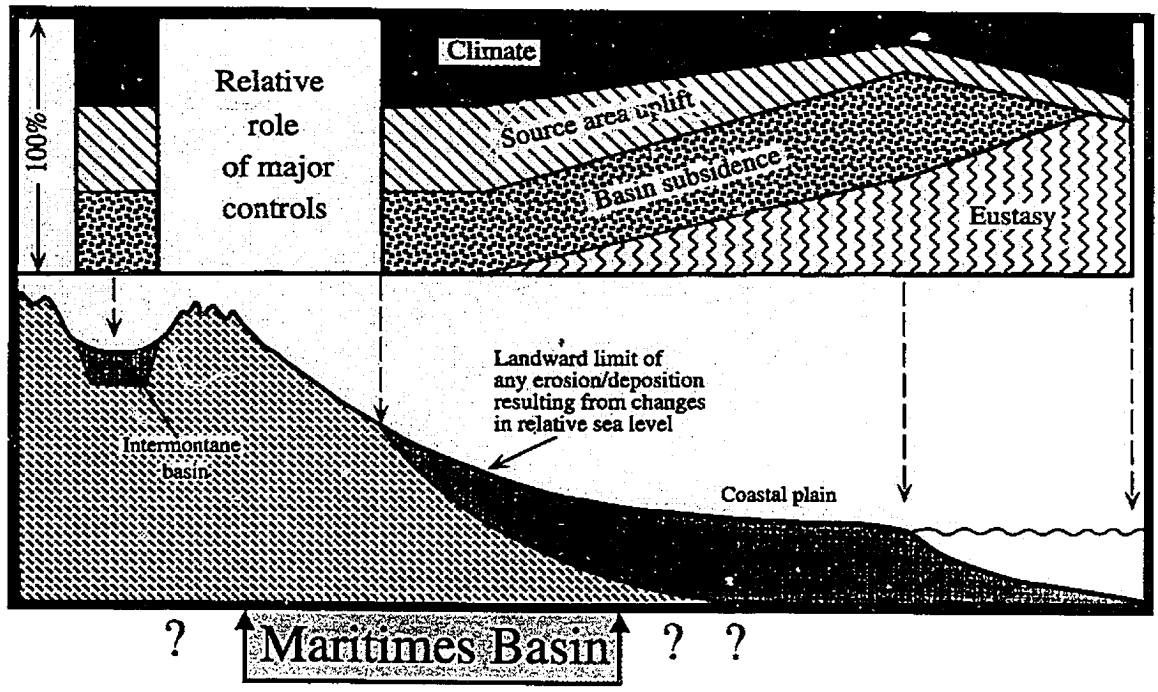



Figure 4.1 The major controls on sequence development in continental settings with the potential paleomorphological location of the Maritimes Basin indicated (modified from Shanley and McCabe, 1994)

restricted (Riegel, 1991; Belt, 1984; Horne *et al.*, 1978); they may exceed several hundred kilometres, nonetheless, this is considerably smaller than allocyclic packages that may be laterally continuous for thousands of kilometres (Connolly and Stanton, 1992). Characteristically, autocyclic packages change or pinch out laterally; as a result, limestone units, for example, are correlative only as zones and not as continuous beds (Galloway and Brown, 1973).

Most stratal bodies have been affected by a combination of intrabasinal and extrabasinal forces (Beerbower, 1969), with locally dominant autocyclic mechanisms superimposed on regionally dominant allocyclic mechanisms (Bhattacharya and Walker, 1992; Riegel, 1991; Ferm, 1975; Galloway and Brown, 1973; Beerbower, 1969; Westoll, 1968; Moore, 1959). The four F-B sequences, defined in Chapter 3, probably resulted from a combination of both allocyclic and autocyclic processes, with their regionally extensive character favouring an allocyclic control. It is the basinal scale stratal bodies that will now be examined for controlling allocyclic mechanisms.

## 4.2 Controls on Deposition

The development of the cyclic succession of prograding and retrograding sequences in the CMB is a result of the interaction between rates of supply and accommodation. The forestepping systems sets developed when the relative rate of increase in accommodation was less than the relative rate of sediment supply, resulting in progradation. The backstepping systems sets developed when the rate of increase in accommodation exceeded the rate of sediment supply, resulting in retrogradation.

Sediment supply in a continental setting is primarily controlled by the interaction between tectonic uplift of source area and climate. Accommodation is controlled directly by changes in stratigraphic baselevel closely associated with the tectonic subsidence of the basin and eustasy. In predominantly continental settings such as that proposed for the Maritimes Basin, Shanley and McCabe (1994) suggest that eustasy plays a minor role in depositional sequence development; however, evidence of marine incursions in the Maritimes Basin has been documented, thus eustasy cannot be ignored.

### 4.2.1 Sediment Supply

#### 4.2.1.1 Tectonism

Tectonism can affect both accommodation, supply, and climate on a wide range of geologic time scales. Within a basin, tectonism controls the rate of differential subsidence which can be a primary control on changes in accommodation and thus changes in stratigraphic baselevel. Outside the basin, tectonism in the source area controls supply by the new, or renewed, exposure of bedrock (e.g., Amano and Taira, 1992). Weather patterns (i.e., climate), which can also affect rates of sediment supply, are potentially affected by orogenic development. The difficulty lies in the correlation of tectonic events with chronostratigraphically significant sequence boundaries and sequences in the basin fill. The recognition and absolute timing of tectonic activity can be established through direct and indirect methods which include the dating of faulting and folding events, disconformities (representing uplift, erosion, or hiatus), subsidence, and sedimentation patterns.

A problem with invoking regional tectonism as a potential control on the cyclic development of Maritimes Basin strata is the lack of resolution usually associated with the timing of tectonic events. As proposed in Chapter 3, the CMB fill consists of four F-B sequences deposited over a 26 million year interval with three of the sequences deposited within nine million years (Fig 2.6). Geochronological studies by Secor *et al.* (1986) indicated three major tectonothermal events (295-315 Ma, 285-295 Ma, 268-285 Ma) in southern Carolina which they attributed to continent-continent collision between Laurentia and Gondwana. In a similar study, $^{40}Ar/^{39}Ar$ results from Alabama and Georgia suggested that penetrative deformation and amphibolite-facies metamorphism occurred during a comparable time period of 292 to 320, which was also attributed to tectonism related to the Alleghanian orogeny (Steltenpohl and Kunk, 1993). The age dates of faults, folds or metamorphic events, such as those above, are typically associated with an uncertainty of plus or minus a few million years (e.g., Waldron *et al.*, 1989), suggesting that a precise correlation between the absolute timing of regional tectonic events and individual sequence development is unlikely. Nonetheless, it does appear from the dates

above, that during the deposition of the CMB F-B sequences there was regional tectonic activity occurring in the Carboniferous Appalachian mountain belt (cf., Hatcher *et al.* 1989).

The stratigraphic record within a sedimentary basin contains direct and indirect indicators of local and regional tectonic activity. For example, dating faunal breaks in the stratigraphic column by recognizing regional or local discontinuities can help to constrain the timing of tectonism (Shanmugam, 1988), although caution should be exercised as other controls may be responsible for the discontinuity. Another method of constraining tectonism comes directly from the stratigraphic record contained in the basin fill. Tectonic subsidence histories which show the flexure/movement of the basement give direct indications as to the timing of tectonism (Jordan *et al.*, 1988). A final method of recognizing regional tectonism is by investigating sedimentation patterns in basins adjacent to a common orogen (Jordan *et al.*, 1988) for indications of synchronous activity.

#### 4.2.1.1.1 Tectonism and Sediment Supply

The early basin fill succession, composed of Horton, Windsor and Mabou groups (pre Namurian-Westphalian event strata), was derived from local sediment sources (Belt, 1968a); conversely, the Cumberland and Pictou groups (post Namurian-Westphalian event strata) likely received sediments from a distal source to the south (van de Poll, 1973). Gibling *et al.* (1992b) demonstrated that the general paleoflow direction for the Westphalian strata in the Maritimes Basin was to the north-northeast (Fig. 4.2), and Archer and Greb (1995) proposed that the paleoflow for similar aged Carboniferous strata in the eastern United States was to the south-southwest. These opposed paleoflow directions for comparably aged strata suggest that a major continental drainage divide separated the Maritimes Basin from the eastern United States Late Carboniferous depocentres (Fig. 4.2) (van de Poll, 1973).

Geodynamic models (Beaumont *et al.*, 1987; Quinlan and Beaumont, 1984) suggest renewed collision between the North American and West African cratons during the Alleghanian orogeny. The collision may have occurred at an oblique angle (Keppie,

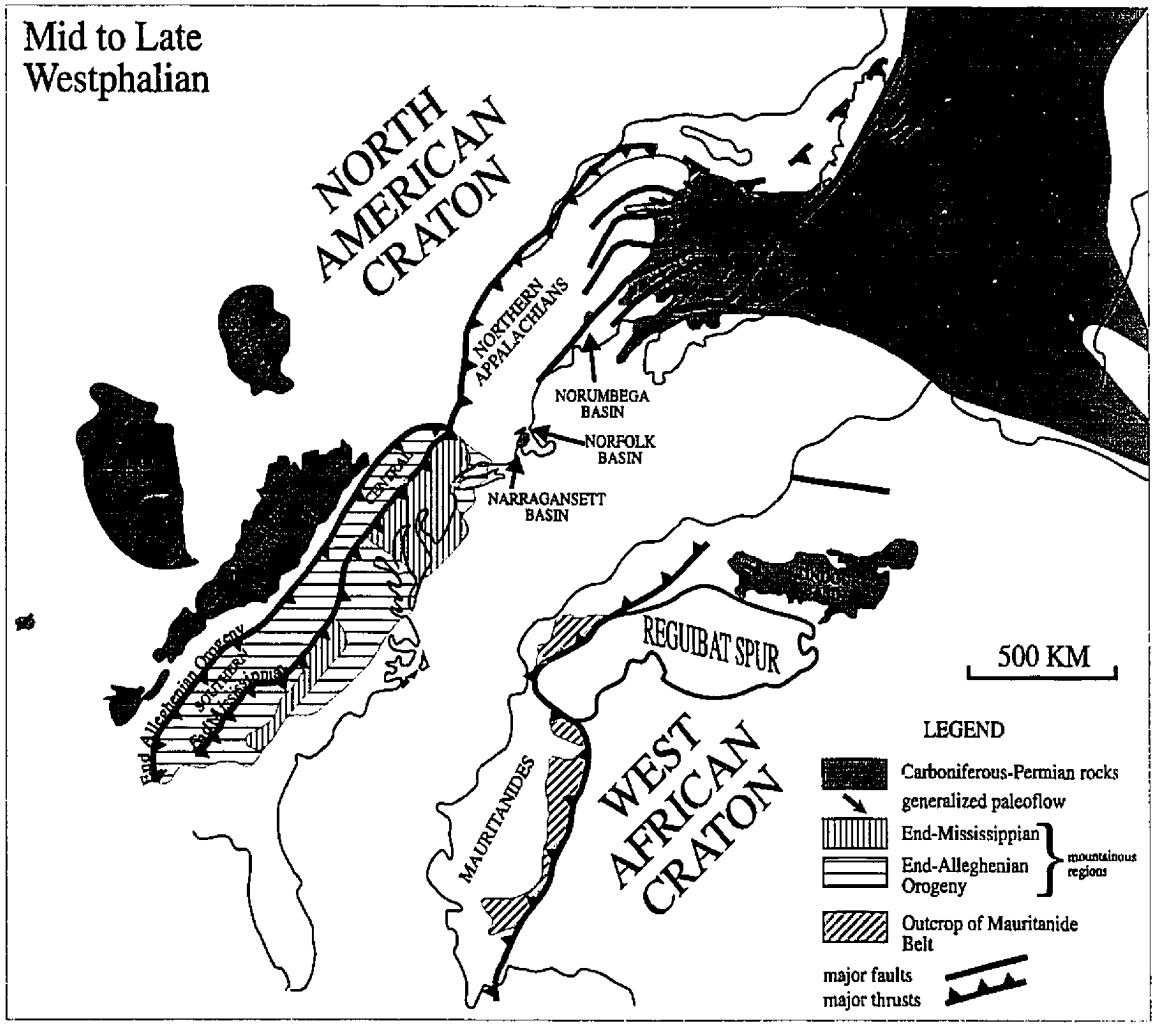



Figure 4.2 Late Carboniferous paleogeographic reconstruction showing the proposed oblique collision between the North American and West African Craton with the Reguibat Spur shown as the proposed "indentor" (modified from Gibling et al., 1992b; original continental reconstruction from Scotese and McKerrow, 1990). Opposed paleoflow directions are recognized on opposite sides of the main collisional zone which was the approximate location of an Andean scale mountain system during the Carboniferous. Additional Late Carboniferous paleoflows for the Michigan Basin from Shideler (1969), the Illinois Basin from Trask and Palmer (1986) and the Bloyd Sandstone (lower left) from Archer and Greb (1995).

1982) similar to the situation proposed by Ferril and Thomas (1988) for the Acadian orogeny with the Reguibat Spur (Fig. 4.2) identified as a potential "indentor" (Lefort, 1987). The repeated stacking of major thrust sheets during the collision, combined with deposition of Pennsylvanian and Permian strata thickened the load on the lithosphere by an additional 4-18km in the central and southern Appalachian region (Beaumont *et al.*, 1987). The models further suggest that the amount of loading decreased from north to south with maximum loads located over the present central Appalachian region (Quinlan and Beaumont, 1984). Loading of this magnitude during the Carboniferous is thought to have resulted in the development of a central Andean style topography in the central-southern Appalachian region, which had relief of between 3.5 to 4.5 km and a width of 250-300 km (Slingerland and Furlong, 1989).

Slingerland and Furlong (1989) proposed that more than half the load was removed before the Late Triassic, with some portions potentially removed during the Carboniferous. The Beaumont *et al.* (1987) model proposed that erosion of the overthrust sheets did not occur until the Late Permian. Estimates by Gerlach and Cercone (1993), using vitrinite reflectance data, suggest that between 1.2 and 3.4 km of former Devonian and Carboniferous overburden have been removed from the New York State area of the eastern United States. In a comparable area, estimates using apatite fission track analysis suggest the removal of 2-4 km of Carboniferous and Permian strata by the Early Cretaceous (Miller and Duddy, 1989).

Tectonism in a source area exposes new bedrock which is subsequently eroded and transported to a sedimentary basin, and the resulting sedimentation patterns can be used as indirect indicators of tectonic activity (Jordan *et al.*, 1988). The types of sediment and the rates at which they are supplied to the system may be closely associated with the unroofing event, however, there may be lag times between the tectonic event and final deposition of the eroded material as a result of the reworking, storage and transport by fluvial systems (Jordan *et al.*, 1988). Nonetheless, in the general vicinity of an active orogen the associated sedimentary basins connected via different drainage basins should contain similar records of regional tectonic development.

With this in mind, Late Paleozoic depocentres to the south of the present Maritimes Basin that may have shared a common source area have been evaluated for indications of common unroofing events (Fig 4.3). The next section outlines a series of cyclic fining upwards packages (early, mid and late), herein referred to as phases of clastic deposition, interpreted from the post Namurian-Westphalian event stratigraphic ill in the Pennsylvanian Anthracite Region and Appalachian, Illinois, Michigan and Narragansett/Norfolk basins (Figs. 4.2, 1.4). A fuller description and interpretation of each clastic phase is located in APPENDIX IV.

#### 4.2.1.1.2 Late Carboniferous Sedimentation to South of the CMB

Except for the Pennsylvania Anthracite Region and Narragansett/Norfolk basin area (Fig 1.4), the middle to late Mississippian period in the eastern United States was characterized by a major transgression of epeiric seas which deposited a regionally extensive marine unit composed of shaly dolomitic limestone, grey to white limestone, impure argillaceous limestone, calcareous siltstones and red to grey shales (Arkle, 1974). The marine inundation was followed by the deposition of the regressive Mauch Chunk Formation and equivalents (Fig. 4.3) (Donaldson and Shumaker, 1981). This formation is generally composed of a grey to red, fine- to medium-grained, thinly bedded sandstone and shale sequence which is commonly capped by the Mississippian-Pennsylvanian unconformity and overlain by coarser grained Pennsylvanian strata (Tankard, 1986; Arkle, 1974).

The Mississippian-Pennsylvanian unconformity (Fig. 4.3) is a regionally extensive erosional surface which formally separates the Kaskaskia from the overlying Absaroka sequence (Sloss, 1963). Development of the surface has been attributed to a Middle Carboniferous worldwide eustatic event (Donaldson *et al.*, 1985). Alternatively, Quinlan and Beaumont (1984) suggested that episodes of overthrusting (start and finish) closely coincide with start and finish of the major unconformities documented by Sloss (1963) and further proposed that the Mississippian-Pennsylvanian unconformity was caused by this mechanism. Tankard (1986) suggested that the unconformity reflects a quiescent

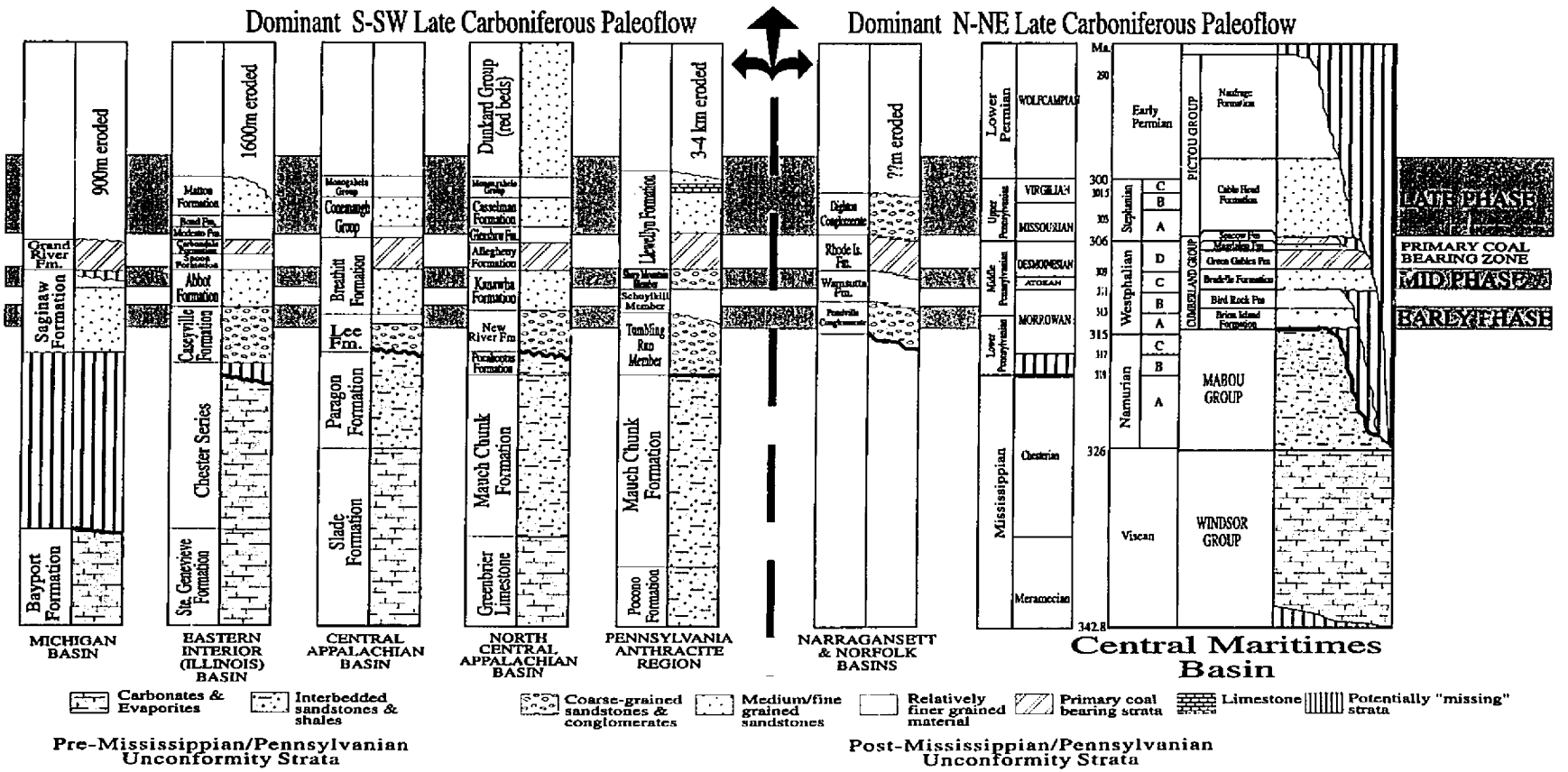



Figure 4.3 A compilation of regional stratigraphy for the Late Palaeozoic depocentres on the eastern margin of North America. In almost all of the basins, stratigraphically equivalent strata above the Mississippian/Pennsylvanian unconformity strata exhibit relatively coarser grained sedimentation. In addition, all the basins shown have a common primary zone of coal-bearing strata in the mid to late Westphalian. The heavy dashed line between the Narragansett/Norfolk and Pennsylvania Anthracite Region stratigraphic columns is the schematic location of the Carboniferous Appalachian mountains which formed a paleodrainage divide (as shown by the heavy black arrows). Correlations between European and continental American stages from Calder and Gibling (1994). Narragansett and Norfolk basin stratigraphy from Skehan et al. (1986); Pennsylvania Anthracite Region stratigraphy from Wood et al. (1986, 1956); North Central Appalachian Basin stratigraphy from Donaldson and Shumaker (1981); Central Appalachian Basin from Tankard (1986) and Arkle (1974); Eastern Interior Basin stratigraphy from Trask and Palmer (1986) and Pryor and Sable (1974); Michigan Basin stratigraphy from Landing and Wardlaw (1981) and Shideler (1969). Erosional estimates by Damberger (1971), Cercone (1984), and Gerlach and Cercone (1993).

period signalling the conclusion of Acadian deformation in the Appalachians. It is probable that the development of the unconformity reflects both eustatic and tectonic processes (Greb and Chesnut, 1996).

It has been suggested that the Mississippian-Pennsylvanian unconformity is the product of Namurian C erosion (Ettensohn and Chesnut, 1989), implying that the post Namurian-Westphalian event Maritimes Basin strata are time correlatives to strata which overlie the regionally extensive Mississippian-Pennsylvanian unconformity (Fig. 4.3). Donaldson and Shumaker (1981) and Tankard (1986) correlated the progradation of three clastic wedges across the Appalachian Basin with renewed Alleghanian thrusting (see also Beaumont *et al.*, 1987). The timing and characteristics of these clastic phases (early, mid and late) of deposition are interpreted for the Pennsylvanian Anthracite Region, Narragansett/Norfolk, Appalachian, Illinois and Michigan basins in the sections below.

The interpreted early phase of clastic deposition occurs in all the basins investigated (Fig. 4.3) and typically consists of a coarse-grained basal member with an overlying relatively finer grained member (Table 4.1, APPENDIX IV). The basal member commonly lies on the Mississippian-Pennsylvanian unconformity and consists of mature to immature, coarse-grained sandstones and conglomerates composed predominantly of orthoquartzite (Skehan *et al.*, 1986; Wood *et al.*, 1986, 1956; Arkle, 1974). The bed-load dominated nature of the basal succession, in addition to the general coarseness and regional distribution of the basal sandstones are interpreted to reflect renewed uplift of the source area (Tankard, 1986; Wood *et al.*, 1986; Donaldson and Shumaker, 1981; Arkle, 1974). An overlying finer grained unit is composed of fluvial floodplain and estuarine bayfill deposits which typically consists of thin discontinuous coal, marlstones and shales (Table 4.1, APPENDIX IV).

The early clastic pulse is closely associated with an influx of aluminum-rich clays which are attributed to tropical soil formation during renewed uplift of the source area (Donaldson and Shumaker, 1981). Weaver (1960), recognized a regionally extensive variation in clay mineral composition across the Mississippian-Pennsylvanian unconformity, from predominantly a montmorillonite-mixed-layer clay facies to an illite-

Table 4.1 Summary of interpreted early phases of clastic development in the eastern United States Late Carboniferous successions. Correlations between European and continental American stages from Calder and Gibling (1994). Narragansett and Norfolk basin stratigraphy from Hower *et al.* (1993), Skehan *et al.* (1986), Lyons *et al.* (1976), Oleksyshyn (1976), and Towe (1959); Pennsylvania Anthracite Region stratigraphy from Hower *et al.* (1993), Wood *et al.* (1986, 1956) and Arkle (1974); Central Appalachian Basin stratigraphy from Greb and Chesnut (1996), Archer and Greb (1995), Tankard (1986), Donaldson and Shumaker (1981), and Arkle (1974); Eastern Interior Basin stratigraphy from Archer and Greb (1995), Trask and Palmer (1986) and Pryor and Sable (1974); Michigan Basin stratigraphy from Archer and Greb (1995), Landing and Wardlaw (1981) and Shideler (1969).

| | Narragansett & Norfolk Basins | Pennsylvania Anthracite Region | Central Appalachian Basin | Eastern Interior (Illinois) Basin | Michigan Basin |
|---|---|---|---|---|---|
| Stratigraphic Units | Pondville Conglomerate Wamsutta Formation | Tumbling Run Member Schuylkill Member (Pottsville Fm.) | New River Formation (Lee and lower Breathitt Fms. of Tankard, 1986) | Caseyville Formation | Saginaw Formation |
| Ages | Late Namurian C to Early Westphalian C | Late Namurian C to Late Westphalian B - Early Westphalian C | Late Namurian C to Early - Mid Westphalian B | Late Namurian C to Early Westphalian B | Late Namurian C to Late Westphalian B - Early Westphalian C |
| General Lithologies and Comments | **(basal)** immature quartzites, c.g. sandstones and conglomerates **(upper)** red conglomerates, sandstones, and shales | **(basal)** mature conglomerates and c.g sandstones with slight f.u. trend, subgreywacke and orthoquartzites **(upper)** same as above but finer grained with more coal development, unit is preferentially weathered. | **(basal)** c.g orthoquartzite sand-stones and pebble conglomerates in multi-story sheet-like sand bodies, local paleovalley fills minor shales and siltstones **(upper)** thin coals and seat earths capped by mudstones, with isolated thin sandstones | **(basal)** mature, quartz rich sandstones and pebble conglomerates in multi-story sheet-like sandbodies, local paleovalley fills minor shales and siltstones **(upper)** thin discontinuous coals shales, mudstones and minor sandstones. | **(basal)** mature, m.g. to c.g., grey-buff, quartzose sandstones in linear, multi-story sand belts **(upper)** mudstones, shales with thin sandstones, limestones and discontinuous coals. |
| Depositional Environments | **(basal)** fluvial/alluvial fan **(upper)** fluvial floodplain | | **(basal)** fluvial-deltaic braided river system **(upper)** transgressive estuarine bayfills | **(basal)** braided fluvial evolving to meandering river system **(upper)** transgressive estuarine bayfills | **(basal)** bed-load dominated fluvial-deltaic system **(upper)** broad alluvial plains with low stream gradients |

chlorite-kaolinite-mixed-layer clay facies. Recent work by Hower *et al.* (1993) suggests a predominance of Fe-rich chlorites in the Late Namurian to Permian strata in the Pennsylvania Anthracite Region.

The interpreted mid phase of clastic deposition (Fig. 4.3, Table 4.2, APPENDIX IV) in the Appalachian basin comprises the lower part of what Donaldson (1974) referred to as the West Virginia deltaic complex. The basal sandstones and conglomerates are less mature, contain more feldspar, and coal development tends to be more extensive as compared to the underlying early clastic phase (Trask and Palmer, 1986; Landing and Wardlaw, 1981; Arkle, 1974; Shideler 1969). The sandstones in the bottom portion of the middle clastic phase occur as multi-story channel bodies that coalesce to form relatively continuous sandstone sheets (Table 4.2) (Tankard, 1986) which are interpreted to be the product of bed- to suspended-load fluvial systems (Tankard, 1986; Donaldson and Shumaker, 1981; Shideler, 1969). The basal part of the coarse-grained succession fines upwards into finer grained sandstones, overbank mudstones, shales with local thin limestones and coals, all of which increase in proportion towards the top of the clastic phase (Arkle, 1974; Pryor and Sable, 1974).

Marine strata increase in proportion towards the top of the basal succession associated with the mid clastic phase (APPENDIX IV). The basal coarser grained succession is conformably overlain by a succession of relatively finer grained strata composed of minor sandstones, siltstones and shales and locally some conglomerates (Wood *et al.*, 1986). This part of the intermediate phase is characterized (Table 4.2) by well-developed cyclic deposits (cyclothems) which contain widespread coal and limestone deposits (Fig. 4.3) (Trask and Palmer, 1986; Arkle, 1974) representing the most important coal-bearing phase in the eastern United States. Further increases in marine influence are displayed by the uppermost strata in the intermediate phase, culminating with a major transgressive event (Donaldson and Shumaker, 1981; Arkle, 1974; Pryor and Sable, 1974).

Renewed uplift in the Early to Mid Stephanian led to a late phase of Carboniferous clastic deposition (Fig. 4.3, Table 4.3, APPENDIX IV) in the eastern

Table 4.2 Summary of interpreted intermediate phases of clastic development in the eastern United States Late Carboniferous successions. Correlations between European and continental American stages from Calder and Gibling (1994). References for stratigraphy are the same as Table 4.1.

| | Narragansett & Norfolk Basins | Pennsylvania Anthracite Region | Central Appalachian Basin | Eastern Interior (Illinois) Basin | Michigan Basin |
|---|---|---|---|---|---|
| Stratigraphic Units | Rhode Island Formation | Sharp Mountain Member (Pottsville Fm.) lower Llewellyn Formation | Kanawha, Allegheny and Glenshaw formations (upper Breathitt Fm. and lower Conemaugh Group) | Abbot, Spoon, Carbondale, Modesto and Bond formations | Grand River Formation |
| Ages | Early Westphalian C to Early Stephanian | Early Westphalian C to Stephanian | Westphalian B to Early Stephanian | Westphalian B to Early Stephanian | Mid Westphalian C to Late Westphalian D |
| General Lithologies and Comments | lithic greywacke sandstones conglomerates, siltstones and green-black shales, abundant anthracite to meta anthracite coal deposits | **(basal)** mature conglomerates and c.g sandstones with slight f.u. trend, subgreywacke and orthoquartzites, better developed coals **(upper)** shale, siltstones, sandstones, local conglomerates, noticeable absence of gravel and c.g. sandstones, major coal development (40 named coals) | **(basal)** f.g. to c.g orthoquartzite sandstones with local pebble conglomerates, sands occur in multi-story channel sand sheets number of shales, siltstones and coals increase upwards **(upper)** finer grained sandstones, shales, limestones and well developed coals, capped by extensive marine limestones, shales, local cherts and ironstones. | **(basal)** qtz-feldspathic sandstones, and pebble conglomerates, less mature, overlain by f.g. to m.g. sandstones, shales, thin coals and limestones, sands occur in a series of extensive sheets and/or bodies **(upper)** cyclothem deposition, shales, mudstones and minor sandstones and limestones with major coal beds, increased marine deposition upwards, major marine limestones cap the sequence | mature, c.g, brownish-red feldspathic quartz arenites, local conglomerates, incision into underlying Saginaw Fm., local coal beds top is an erosional surface |
| Depositional Environments | medial to distal alluvial fan | **(basal)** fluvial **(upper)** broad alluvial plain | **(basal)** fluvial-deltaic braided river system **(upper)** alluvial to coastal plain followed by marine transgression | **(basal)** bed-load evolving to suspended-load fluvia systems **(upper)** alluvial to coastal plain followed by an extensive marine transgression | bed-load dominated braided fluvial system |

Table 4.3 Summary of interpreted late phases of clastic development in the eastern United States Late Carboniferous successions. Correlations between European and continental American stages from Calder and Gibling (1994). References for stratigraphy are the same as Table 4.1.

| | Narragansett & Norfolk Basins | Pennsylvania Anthracite Region | Central Appalachian Basin | Eastern Interior (Illinois) Basin |
|---|---|---|---|---|
| Stratigraphic Units | Dighton Conglomerate | upper Llewellyn Formation | Casselman and Monongahela formations | Matton Formation |
| Ages | Early Stephanian A to Late Stephanian B | Early Stephanian A to Early Permian | Mid Stephanian A to Late Stephanian C | Late Stephanian A to Mid Stephanian B |
| General Lithologies and Comments | heterogeneous, c.g sandstones and conglomerates, >70% quartzite, other clasts include granite and scattered metamorphics and volcanics, shales are absent top is an erosional surface | **(basal)** mature gravels and c.g. sandstones that occur as extensive blankets/sheets, minor shales and siltstones, some coals **(upper)** finer grained with less coal development, increased marine deposition upwards, marine limestones near the top of the sequence, capped by an erosional surface | **(basal)** redbed succession predominantly medium to coarse sandstones, shales and siltstones extensive subaerial exposure **(upper)** red-grey shales, minor subgreywacke sandstones, thin coals and lacustrine limestones | thick well developed sandstones, shales, thin argillaceous limestones, thin coals, less evidence of marine deposition as compared to the underlying Bond Formation top is an erosional surface |
| Depositional Environments | proximal alluvial fan with braided fluvial influences | **(basal)** alluvial fan to fluvial systems **(upper)** alluvial to coastal plain followed by local marine transgressions | **(basal)** fluvial-deltaic **(upper)** lacustrine and alluvial plain | low lying coastal plain |

United States (Wood *et al.*, 1986). Proximal deposits, near the Appalachian source area, typically consist of basal coarse-grained redbed successions that display evidence of extensive subaerial exposure (Arkle, 1974; Donaldson and Shumaker, 1981). Locally, the basal strata were deposited as extensive blankets of coarse sandstones and gravels (Table 4.3) (Wood *et al.*, 1986). Distal equivalents consist of thick, well developed sandstone bodies, shales, thin argillaceous limestones and thin coals, with significantly less evidence of marine incursions as compared mid clastic phase (Pryor and Sable, 1974). Finer gained strata above are typically composed of red and grey shales, subgraywacke sandstones, clay-shale and extensive coals and lacustrine limestones (Table 4.3, APPENDIX IV) (Donaldson and Shumaker, 1981; Arkle, 1974). The upper parts show increasing marine incursions, probably from the west, culminating in the development of the major marine limestones (Fig. 4.3) (Wood *et al.*, 1986).

In the Appalachian Basin, the last phase of clastic deposition is locally overlain by a thick (100m) grey shale succession which is then overlain by the redbed dominated Dunkard Group (Fig. 4.3) (Arkle, 1974). The group is characterized by a return to low gradient alluvial plain environments with predominantly suspended-load fluvial systems consisting of medium- to coarse-grained channel sandstones, overbank deposits, coals and limestones (Donaldson and Shumaker, 1981; Beerbower, 1969). There is a noticeable absence of marine fossils, suggesting a return to a continental setting (Arkle, 1974; Beerbower, 1969).

#### 4.2.1.2 Climate

The ability of climate to influence the development of a depositional system has in the past received little attention, however, the increasing number of studies dealing with strata in continental settings has placed climate and tectonism in key roles for sequence development (Shanley and McCabe, 1994). It has been suggested that climatic fluctuations are a primary control on sediment supply in continental systems (Blum and Valastro, 1994; Schumm, 1993; Cecil, 1990), but, as mentioned at the start of this chapter, climate is inherently linked to both eustasy and tectonism (Fig. 4.1). Large

fluctuations in climate, such as from wet to d may affect the supply of sediment to drainage basins and may correlate with the development of sequences and sequence boundaries (Blum and Valastro, 1994; Cecil, 1990).

Few paleoclimatic studies have focussed exclusively on the Maritimes Basin region. Six Carboniferous paleoclimate curves were compiled from the literature, although the curves focus on the eastern United States (U.S.) coal basins (Figures 4.4 and 4.5). Curves #1 and #2 are defined on the occurrences of climatically sensitive paleobotany recovered from Late Paleozoic coals (Winston, 1990). Curves #3, #4, and #5 were constructed based on the climatic sensitive lithologic successions, i.e. coals and leached paleosols indicate wet environments whereas limestones, dolomites, evaporites, and caliche suggest dry conditions (Cecil *et al.*, 1985; Donaldson *et al.*, 1985). Philips *et al.* (1985) developed Curve # 6 by plotting the abundance of identified bituminous Pennsylvanian coal resources for the eastern U.S. Therefore, besides inferring periods of wet and dry conditions, this curve shows the time of principle Pennsylvanian coal development which is generally in agreement with the timing of major Late Paleozoic coal development suggested by Donaldson *et al.* (1985). It is important to note that the curves shown were developed based on the present strata in the sedimentary basins and that the climate may have been different in the source area.

Much like the Maritimes Basin, these eastern U.S. basins occupied a generally subequatorial position (Fig. 4.4) for the majority of the Carboniferous, however, the Maritimes Basin differs slightly in that it was located within the Appalachian mountain belt and along the main suture zone between Gondwana and Laurussia (Fig. 4.4) (Rowley *et al.*, 1985). The broadly similar paleogeographic and paleoclimatic conditions between the Maritimes Basin and the eastern United States coal basins would imply a general applicability of the paleoclimate curves to the Maritimes Basin. However, Calder and Gibling (1994) suggested that rain-shadow effects could have played an important part in the Maritimes Basin region.

The Carboniferous climate shifted from predominantly arid conditions to a fluctuating semi-arid to wet-dry tropical climate from the Visean to mid Namurian, with

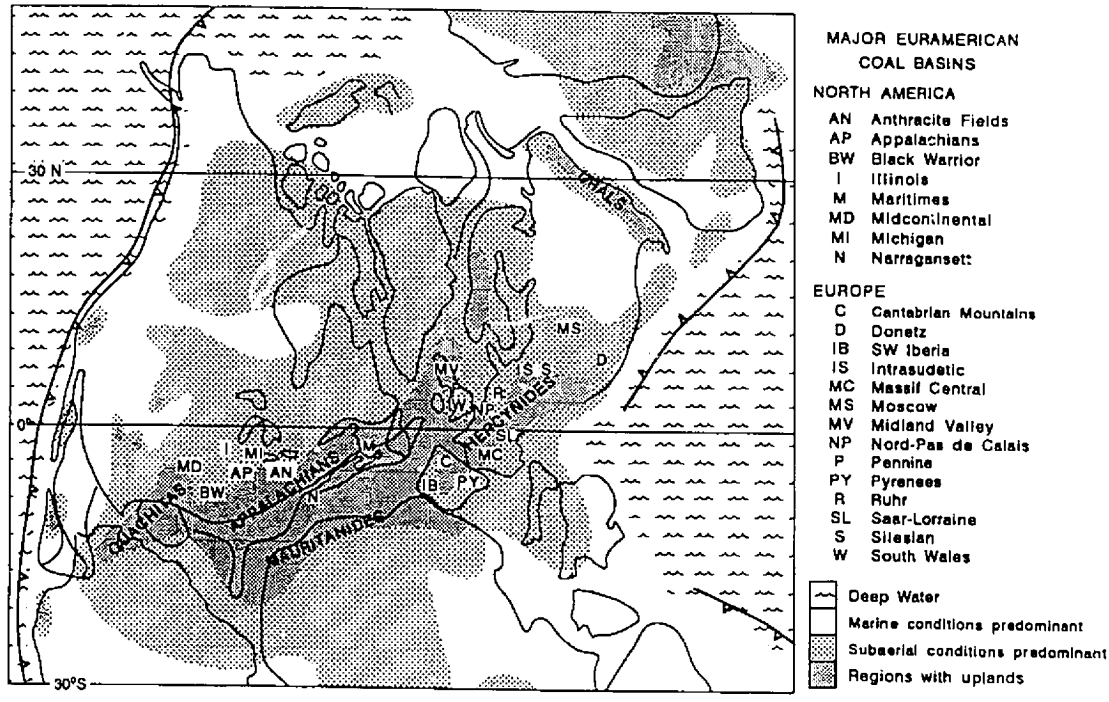



Figure 4.4 Generalized Late Carboniferous (306Ma) paleogeographic reconstruction showing the approximate location of the paleoequator with respect to the Maritimes Basin (M) and similar Carboniferous depocentres (from Calder and Gibling, 1994; original paleomagnetic reconstruction from Scotese and McKerrow, 1990).

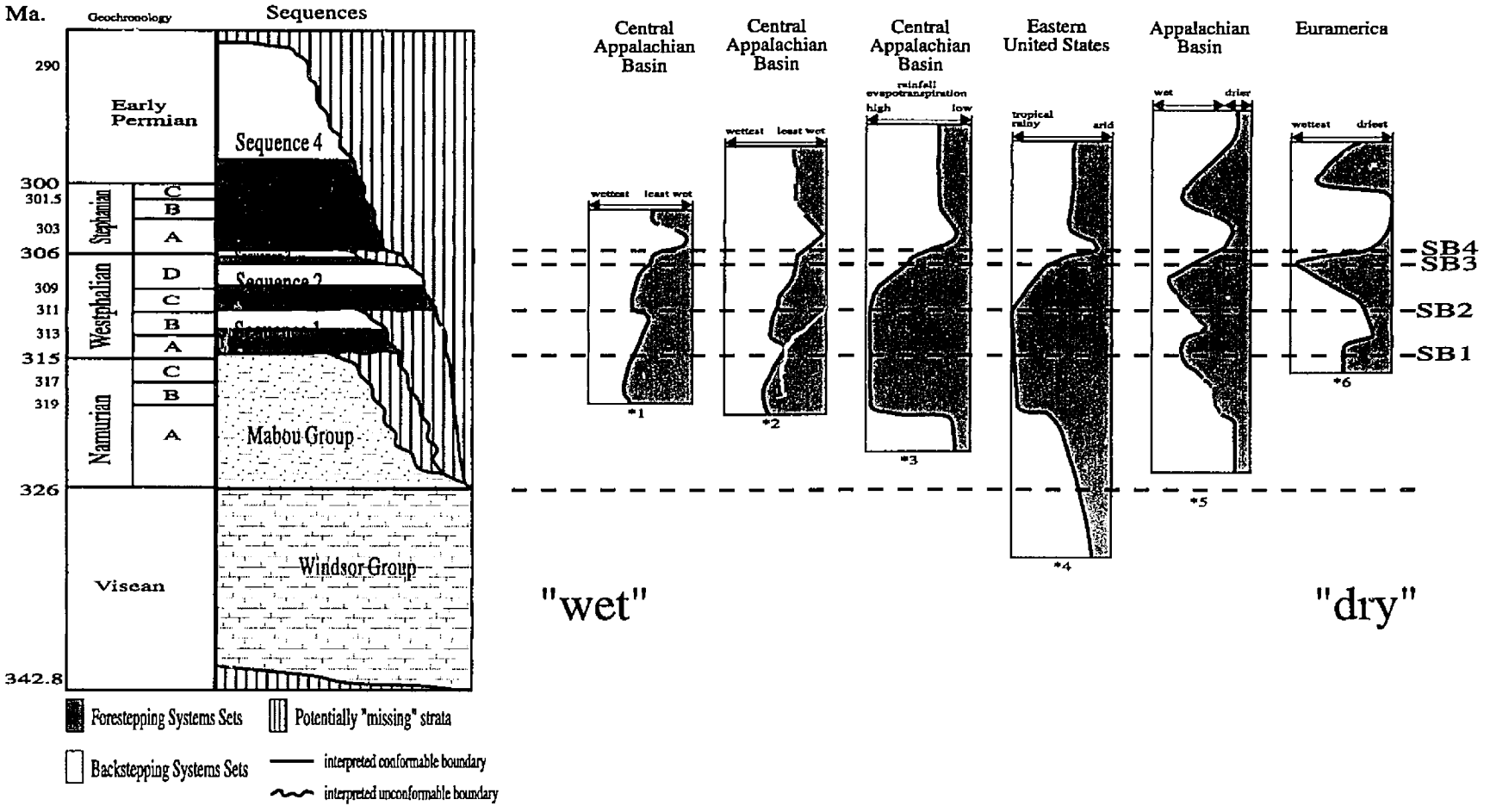



Figure 4.5 Central Maritimes Basin sequences and sequence boundaries with interpreted paleoclimate trends for Late Paleozoic depocentres. #1 from Winston (1990); #2 from Winston and Stanton (1989); #3 from Cecil et al. (1985); #4 from Cecil (1990); #5 from Donaldson et al., (1985); #6 from Phillips et al. (1985). SB = sequence boundary.

better conditions dominating by the late Namurian - early Westphalian (Cecil, 1990). Figure 4.5 demonstrates that, overall, the Westphalian was a predominantly wet period with a slight drying trend during the Westphalian B (Fig. 4.5, curves #1, #5 and #6) and a return to wetter conditions for the Westphalian C and D. During the middle to late Westphalian, the Maritimes Basin was in a sub-equatorial position, favouring the significant growth and accumulation of Carboniferous vegetation that resulted in major coal development over most of the area (the Euramerican Coal Province: Calder and Gibling, 1994). During Westphalian C and D, Euramerica northward and the climate progressively changed from dominantly humid to arid conditions, culminating in an abrupt drying event near the Westphalian-Stephanian boundary as shown by all the curves (Fig 4.5) (Rowley *et al.*, 1985). This drying event lasted for the duration of the Stephanian and much of the Permian and was followed by a return to wetter conditions in the latest part of the Permian (Philips *et al.*, 1985).

The presence of an Andean scale mountain system in the Appalachian region (Slingerland and Furlong, 1989) may have had a profound effect on regional weather patterns. Rowley *et al.* (1985) suggested that the high relief of the Carboniferous mountains resulted in a monsoonal paleoclimate for the Euramerican Coal Province, producing strongly seasonal conditions.

Fluctuations between wet and dry climatic periods on a timescale of $10^6$-$10^7$ years during the Carboniferous were probably due to drifting of the continents northward combined with the monsoonal conditions brought on by Alleghanian mountain building. A comparison of CMB sequence and sequence boundary occurrences with the paleoclimate curves reveals that the initiation of sequence boundary SB4 and development of F-B Sequence 4 coincides closely with the abrupt drying event recorded for the Stephanian (Fig. 4.5, curve #6). A less distinct correlation is made between the Westphalian A-B drying event and the occurrence of F-B Sequence 1.

#### 4.2.1.2.1 Climate and Sediment Supply

The paleoclimate curves suggest no consistent correlation between Carboniferous

climatic fluctuations and the occurrences of CMB F-B sequences and sequence boundaries, however, the role of climate was nonetheless important in CMB sedimentation. The principal development and accumulation of Westphalian C-D peats in the Euramerican Coal Province (e.g. Trask and Palmer, 1986; Donaldson *et al.*, 1985; Philips *et al.*, 1985) required strongly humid conditions (Calder and Gibling, 1994). This major phase of peat development was common to both the Maritimes Basin region and the eastern U.S. in the later stages of F-B Sequence 2 and the upper mid phase of clastic deposition, respectively.

The decreasing coal development in F-B Sequence 3 and the general absence of coal in Sequence 4 (Stephanian to Permian) suggest that the CMB moved out of the "coal window" (Calder and Gibling, 1994). This supports previous interpretations of a progressive northward migration of the Euramerican Coal Province in association with the Carboniferous to Permian drying trend shown by the paleoclimate curves (Fig. 4.5). Further evidence of an increasingly arid environment is the increase in "reddening" of strata towards the top of the CMB stratigraphic column, which has been previously attributed to decreased rainfall (Rust *et al.*, 1987). A similar upward trend in reddening is observed with the onset of the late phase of clastic development in the eastern U.S. (Arkle, 1974). The change to arid conditions, which are typically associated with low rates of erosion and transport (Cecil, 1990), may be one of the causes of overall decreasing sedimentation rates during CMB F-B sequence development. Specifically, the lower rates associated with CMB F-B Sequence 4 (Stephanian-Permian) may be associated with the Stephanian drying event (Fig. 4.5).

Climate may have had some effect on the composition of the basal sandstones overlying the Mississippian-Pennsylvanian unconformity (F-B Sequence 1, Early Phase of clastic deposition). It has been suggested that relatively quartz rich sandstones can be derived from spodosols developed under tropical rainy conditions (Cecil, 1990). The mineralogically mature basal sandstones may have been further developed as a result of prolonged reworking by fluvial systems (Greb and Chesnut, 1996).

### 4.2.2 Accommodation

#### 4.2.2.1 Tectonism and Accommodation: Basin Subsidence

Accommodation, which is closely linked to changes in stratigraphic baselevel, can be created by relative subsidence of the basement. The basin subsidence, or total subsidence, is the net result of subsidence due to sediment loading (sediments and water) and tectonism. Backstripping removes the effects of sediment loading from the total subsidence, resulting in an estimate of tectonic subsidence. Backstripping is achieved by reconstructing a basins burial history revealing the depth and thickness of stratigraphic units as a function of time. Well data required for the construction of a burial history plot primarily consist of biostratigraphically interpreted age-depth pairs, gross lithology, paleobathymetry, and absolute sea level fluctuations (Allen and Allen, 1990; Ungerer et al, 1984).

Burial history plots are constructed by removing and decompacting successive stratigraphic units from youngest to oldest using standard porosity/depth relationships (Waples *et al.*, 1992; Allen and Allen, 1990). As each unit is removed from the stratigraphic column its thickness is corrected for the effects of compaction (i.e. decompacted) by moving the particular unit up a porosity vs. depth curve to the present day datum (Allen and Allen, 1990).

The primary cause of compaction is the mechanical loading of a unit by the overlying strata (Allen and Allen, 1990). The compaction and evolution of a stratal unit is complicated by overpressure, cementation, type of sediment, sedimentation rate, mineral transformation and diagenesis (Lerche, 1990), however, these important parameters are commonly not taken into consideration in preliminary burial history analysis which using mechanical decompaction methods. These methods generally assume that the thickness of a stratigraphic unit is reduced by a predictable amount based on lithology, porosity and depth of burial. The methods use the inferred initial porosities of the rock unit and apply compaction calculations such as those developed by Sclater and Christie (1980), who suggested that porosity exponentially decreases with depth. Falvey and Middleton (1981) suggested that the porosity of a unit decreases as a function of the

increase in overlying load on the unit. Baldwin and Butler (1985) integrated previous compaction curves and lithologic relationships to introduce the solidity, the complement to porosity, to reconstruct the original unit thicknesses. The choice of any compaction/porosity model depends on the depth and type of rock that is to be decompacted.

To investigate the subsidence of the basin through time, the decompacted sedimentary package is corrected for any changes in bathymetry or absolute sea level fluctuations through time to obtain a reference level for subsidence studies. The total subsidence of the basin is calculated according to this reference level. Assuming simple Airy isostasy, the effect of the mechanical loading due to sedimentation can be calculated and removed from the total subsidence of the basin leaving the amount of subsidence due to tectonism (Ungerer *et al.*, 1984).

A wide variety of commercial modelling packages are available and are well documented (Williamson, 1992; Waples *et al.*, 1992 -- **BasinMod**; Forbes *et al.*, 1992; Ungerer *et al.*, 1990 --**Temispack**; Negroni *et al.*, 1988 -- **MATOIL**; Wygrala, 1988; Welte and Yalcin, 1988 -- **Integrated Exploration Systems**). This study uses BasinMod software developed by Platte River Associates to aid in the reconstruction of subsidence, compaction, thermal and maturation histories. Thermal and maturation histories for the CMB are discussed in Chapter 5.

Fundamental components of the CMB burial histories are age/depth pairs and interval lithologies. Age/depth pairs were synthesised by integrating the CMB biostratigraphic database (APPENDIX I) and the stratigraphic framework introduced in Chapter 2. As mentioned previously, absolute Carboniferous ages were defined from Hess and Lippolt (1986), Claoe-Long *et al.* (1992) and AGSO (1996). Lithologic mixes for desired intervals (ie. between age/depth pairs) were extracted from Well History reports, digital Canadian Stratigraphic Services Logs, and wireline logs.

To construct the subsidence histories for the present fill, the burial histories were constrained between the time of initial deposition of the Horton Group (~360 Ma), and the youngest strata intersected (~280 Ma). Events after ~280 Ma are complicated by

uplift and erosion and are not pertinent to the early subsidence history of the present basin fill. Changes in bathymetry or absolute sea level over this duration were assumed to be negligible due to the predominantly continental nature of the basin fill.

Subsidence and compaction histories for the CMB were calculated using the methods outlined by Sclater and Christie (1980). This method assumes a reduction of porosity with increasing depth according to the relationship, $f=f_0e^{-cz}$, where f is the reduced porosity, $f_0$ is the initial porosity, c is the decompaction factor and z is the depth (Sclater and Christie, 1980). For comparison, the methods proposed by Falvey and Middleton (1981) and Baldwin and Butler (1985) were applied to the same set of CMB wells and the resulting subsidence curves and rates were not significantly different from those computed using the Sclater and Christie (1980) method.

#### 4.2.2.1.1 Results of CMB Subsidence Reconstructions

Burial histories were reconstructed for each CMB study well. The representative curves in Figure 4.6 depict the tectonic subsidence in the Central Maritimes Basin and show the amount of basin subsidence had there been no sedimentary rocks present (i.e., no loading effects). Most curves show comparable trends in basin development with major "deepening" events occurring both during initial basin formation (Tournaisian) and the Westphalian. Overall, the subsidence analysis suggests that typically between 1200 to 2000m of tectonic subsidence occurred in the Tournaisian to Early Permian period. Most wells in the CMB were drilled on large structural highs, however, wells #17 and #15 (Fig. 4.6, see Fig. 2.3 for locations) were drilled on more subtle highs and still display comparable trends in subsidence. As well, post-depositional Windsor Group salt flowage has been documented (Bell and Howie, 1990), therefore, CMB reconstructed subsidence histories are assumed to be a minimum estimate.

An important feature demonstrated by the subsidence analysis is that the early subsidence history of the CMB consisted of two phases of development: pre and post Namurian-Westphalian event. Subsidence rates typically decrease from the Tournaisian to Late Namurian from values of 180 m/My to 35 m/My (Fig. 4.6). The post Namurian-

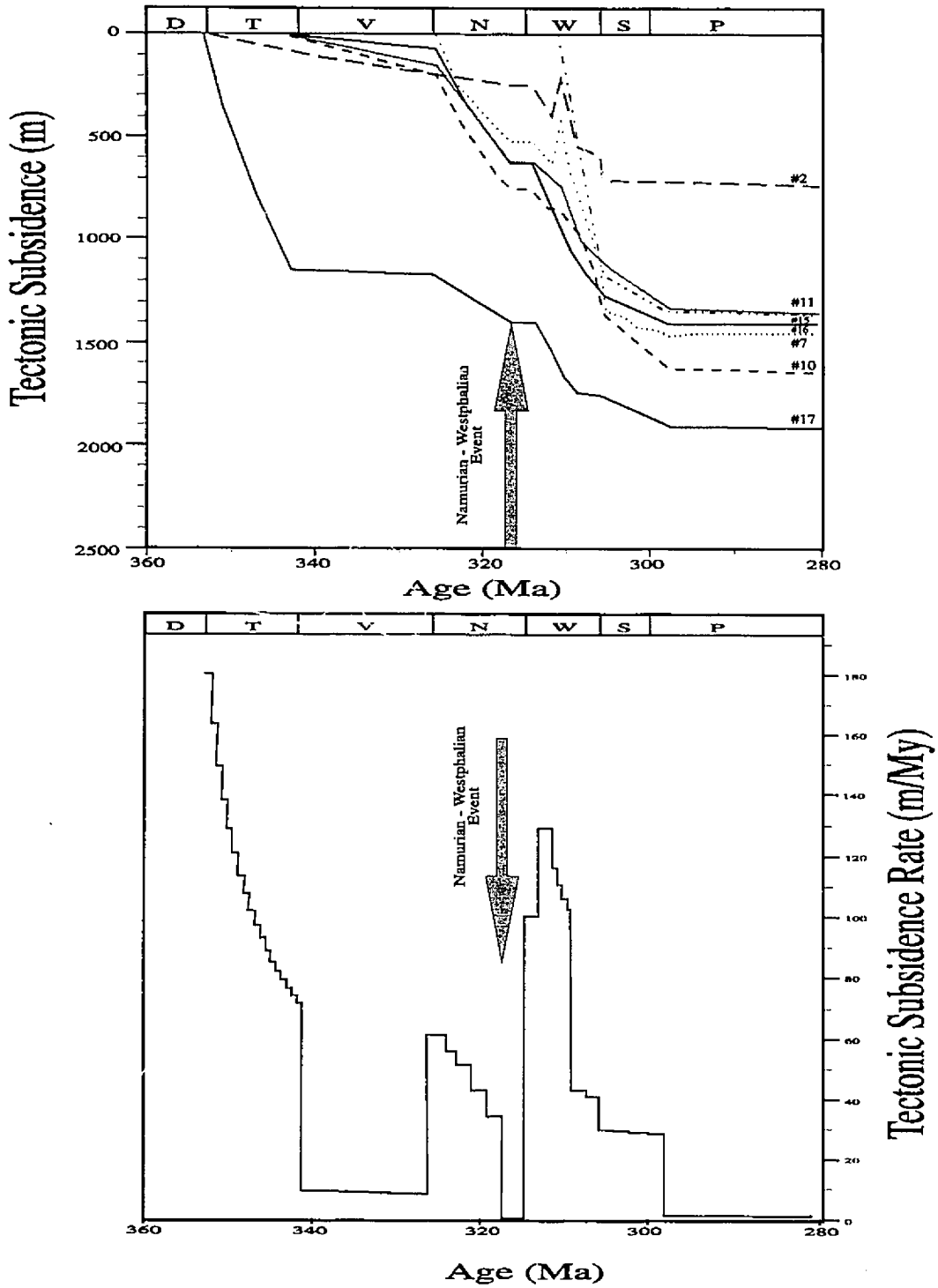



Figure 4.6 (Top) Tectonic subsidence curves for seven offshore locations in the Maritimes Basin (see Fig. 2.3 for well locations) showing similar abrupt "deepening" events during the early Westphalian. (Bottom) Pseudo-composite tectonic subsidence rate curve constructed using post Visean values from Green Gables No.1 (#11) and pre Namurian values from Bradelle L-49 (#17) showing an abrupt increase in tectonic subsidence during the early Westphalian. D = Devonian; T = Tournasian; V = Visean; N = Namurian; W = Westphalian; S = Stephanian; P = Permian.

Westphalian event stratigraphic record generally demonstrates an abrupt increase in subsidence rate in the Early Westphalian to 100 m/My and a subsequent decrease to 30 m/Ma in the Early Permian (Fig. 4.6). Locally, wells in the central portion of the CMB (wells #15, #8, #7 and #9, see Fig. 2.3 for locations) and the Sydney subbasin (#1, #2 and #27, see Fig. 2.3 for locations) display initial subsidence rates in excess of 200 m/My with the East Point E-49 and Hastings No. 1 locations showing rates close to 300m/My for the Early Westphalian.

A similar abrupt early Westphalian increase in subsidence rate is observed in the southern Appalachian Black Warrior Basin (Fig. 1.4) by Whiting and Thomas (1994). They calculate rates of typically 50m/My between 334-322Ma (Visean-Namurian), which increase to values between 65 and 95m/My at 315 (Namurian-Westphalian), and further increase to rates in excess of 220m/My at 313 Ma. The rapid Early Westphalian increase is attributed to renewed Appalachian driven subsidence. Other subsidence studies (Klein and Kupperman, 1992) also suggest a large increase in subsidence rate occurred immediately following the Mississippian-Pennsylvanian unconformity, associated with the deposition of early Morrowan sandstones in the Central Appalachian, Forest City and Black Warrior basins (Fig. 1.4).

Windsor Group subsidence and sediment accumulation rates are difficult to reconstruct due to post depositional salt flowage (cf., Bell and Howie, 1990). Only 5 study wells fully penetrated a Windsor Group stratigraphic section (Table 2.1; wells #12 --627m, #13 --139m, #17 --37m, #18 --124m, and #28 --1172m) and the thickness of Windsor strata varies widely from location to location. The low subsidence values displayed by Figure 4.6 reflects the thin interval (37m) of Windsor Group penetrated in Bradelle L-49. However, relative to the Mabou and Horton group depositional intervals, the subsidence rates during Windsor Group deposition were lower in most cases.

Similar to tectonic subsidence, the accumulation of sediments during the development of the Maritimes Basin was not at a uniform rate, instead, CMB data indicate that two principle pulses of sedimentation occurred during the formation of the Maritimes Basin; from the Tournasian to Late Namurian and from the Early Westphalian

to the Permian. The start of each pulse is associated with an abrupt increase in sedimentation rate followed by a gradual decrease through time.

Compaction corrected, sediment accumulation curves for all 28 study wells were compiled and an average "best fit" curve for the CMB stratigraphic column was constructed (Fig. 4.7). Sediment accumulation rates typically decrease from the Tournaisian to Late Namurian from values of 200 m/My to 80 m/My. Corresponding accumulation rates for the post Namurian-Westphalian event stratigraphic record typically decrease from values between 200 and 400 m/My to rates less than 100 m/My (Fig. 4.7). Locally, Late Westphalian sedimentation rates can exceed 800m/Ma in the central portion of the CMB. Ravenhurst and Zentilli (1987), Ryan (1993), and St. Peter (1993) manually calculated accumulation rates for similar Maritimes Basin successions (Table 4.4). Though these studies did not account for compactional effects, the mean accumulation rates differ only slightly and similar trends are apparent in all four studies shown in Table 4.4.

The subsidence and sedimentation rates noted are *typical* of the overall trends identified during the subsidence reconstruction process and do not represent the maxima or the minima for the outlined time intervals. The resolution of the subsidence modelling is limited by the biostratigraphic resolution (see Chapter 2, for a full discussion) and the general trends recognized likely contain fluctuations beyond the resolution of the data. Nonetheless, the large thickness of basin fill (>10km), accumulated over a relatively short period of time (<25 Ma), is assumed to overwhelm any specific age/depth problems. In any case, all model calculations are computed at 2 million year time steps over 200 metre stratigraphic intervals; this approach is assumed to provide a broad definition of both subsidence and sediment accumulation well within the resolution of the biostratigraphic data.

Multiple events (Namurian-Westphalian, Mid-Westphalian and Westphalian-Stephanian events) are represented within the CMB fill by conformable to unconformable stratal relations. To account for erosion in the BasinMod burial histories, estimates of the amount and duration of the erosional event are imputed as deposition and erosion pairs.

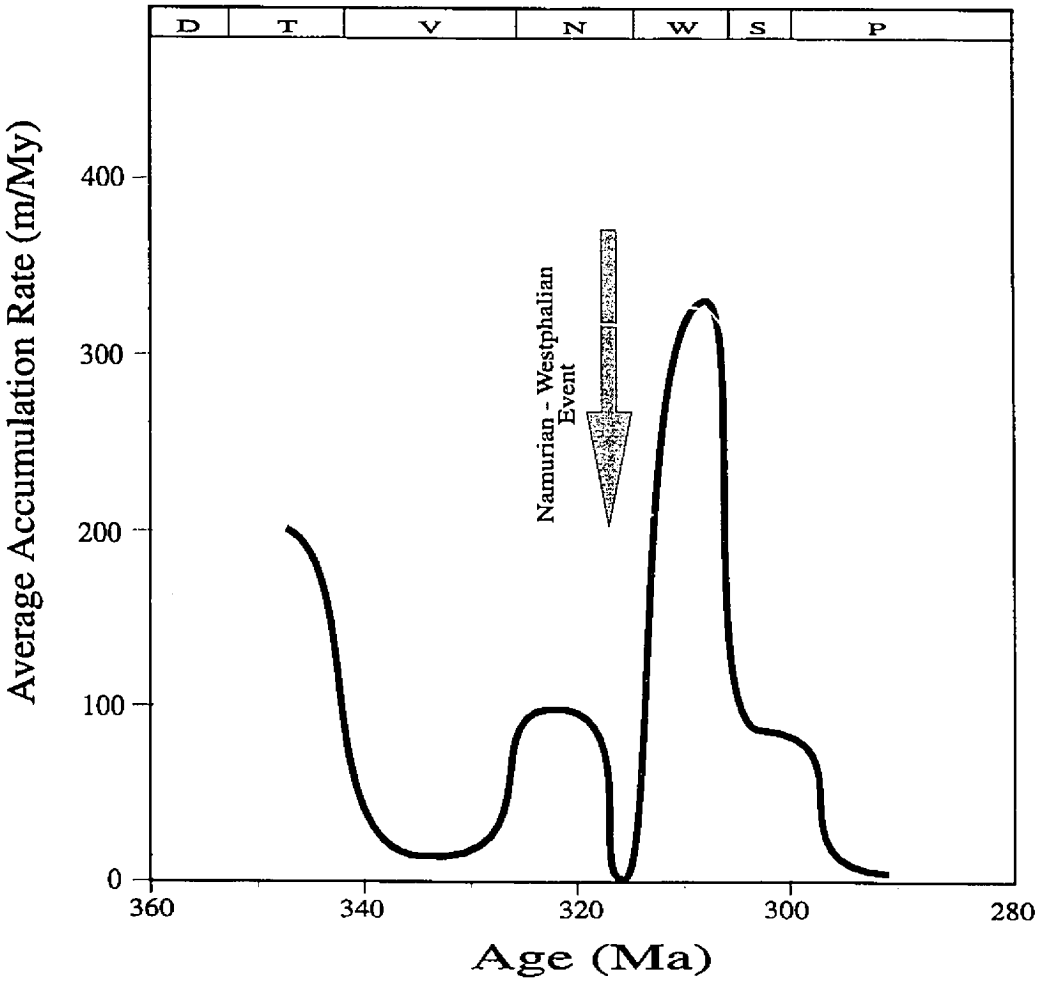



Figure 4.7 Average sediment accumulation rate versus time plot for 28 study wells. The plot shows two separate decreasing trends; from the Tournasian to Late Namurian and from the Early Westphalian to Permian. D = Devonian; T = Tournasian; V = Visean; N = Namurian; W = Westphalian; S = Stephanian; P = Permian.

Table 4.4 Late Paleozoic accumulation rates for the Maritimes Basin calculated by Ryan (1993), St. Peter (1993) and Ravenhurst and Zentilli (1987) for the Cumberland and Moncton subbasins and eastern P.E.I. subsurface, respectively. Times scales by Hess and Lippolt (1986), Claoe-Long *et al.* (1992) and AGSO (1996) were used to modify original calculations unless specified. The grey zone corresponds with the locally derived early basin fill succession associated with Horton, Windsor and Mabou group deposition, whereas, the upper portion of the table coincides with the regional development of CMB forestepping-backstepping sequences and sequence boundaries, suggesting that the new influx of sediment was critical for sequence development.

| **Unit** | **Ryan (1993)**[1] | **St. Peter (1993)** | **Ravenhurst and Zentilli (1987)** | **this study** |
|---|---|---|---|---|
| | (m/My) | (m/My) | (m/My) | (m/My) |
| Pictou Group | 200 | 68 | 166[6] | ~<100 |
| Cumberland Group | 600 | 150[3] | 750[5] | 200-400 |
| Mabou Group | 75 | - | 154[4] | 80 |
| Windsor Group | 50 | 80[2] | 179 | 25 |
| Horton Group | 100 | 228 | 272 | 200 |
| Fountain Lake Grp. | 300 | - | | - |

[1]used Harland *et al.* (1989)
[2]combined Windsor/Mabou Groups
[3]early Westphalian only
[4]Canso-Riversdale Groups
[5]Westphalian B
[6]Westphalian C and younger

The timing of the event is subsequently shown as period of subsidence (deposition) and uplift (erosion) on the burial history curve. Periods of nondeposition on the other hand are shown as plateaus on burial history plot. Only the Namurian-Westphalian event (317-315 Ma) was consistently included in all the models as a period of hiatus due to its regional significance to the CMB basin history. The other events were assumed to have had minimal effects on the overall subsidence history and were only taken into account if complete stratigraphic units were missing (e.g., Fig. 4.6 curves #2 and #7; complete removal of Brion Island and Bird Rock formations by the Mid-Westphalian event). Even when these events are included, they show up only as minor spikes or plateaus in the subsidence histories and do not significantly change the overall trends.

#### 4.2.2.2 Eustasy

Invoking eustatic controls on the development of depositional packages implies recognition of globally synchronous events that affect relative changes in sea level that are closely linked to absolute stratigraphic baselevel (Vail *et al.*, 1977). Eustatic fluctuations occur over a variety of time scales and are caused by a number of factors. Large scale changes in ocean volume are typically caused by glaciation/deglaciation or changes in ocean basin size due to global tectonism (Williams, 1993).

Agglutinated foraminiferal studies in the Sydney and Cumberland subbasins and offshore in the Central Maritimes Basin have indicated that large sections within the coal-bearing interval were deposited under restricted-marine conditions (Thibaudeau and Medioli, 1986; Wightman *et al.*, 1993, 1994a; Archer *et al.*, 1995; APPENDIX II). In support of marine influenced deposition, Grant and Moir (1992) mapped the coal-bearing interval under the CMB over an estimated area of 66 000 km$^2$, similar to areas underlain by documented cyclothems in the central United States that developed under marine conditions (Grant, 1994). The typically high sulphur contents of the Maritimes Basin coals represent further evidence of restricted-marine conditions (Gibling *et al.*, 1989).

Several exploration wells that penetrated Late Carboniferous strata in the Whale Basin and on the Labrador and Eastern Newfoundland shelves (Fig. 4.8, Table 4.5)

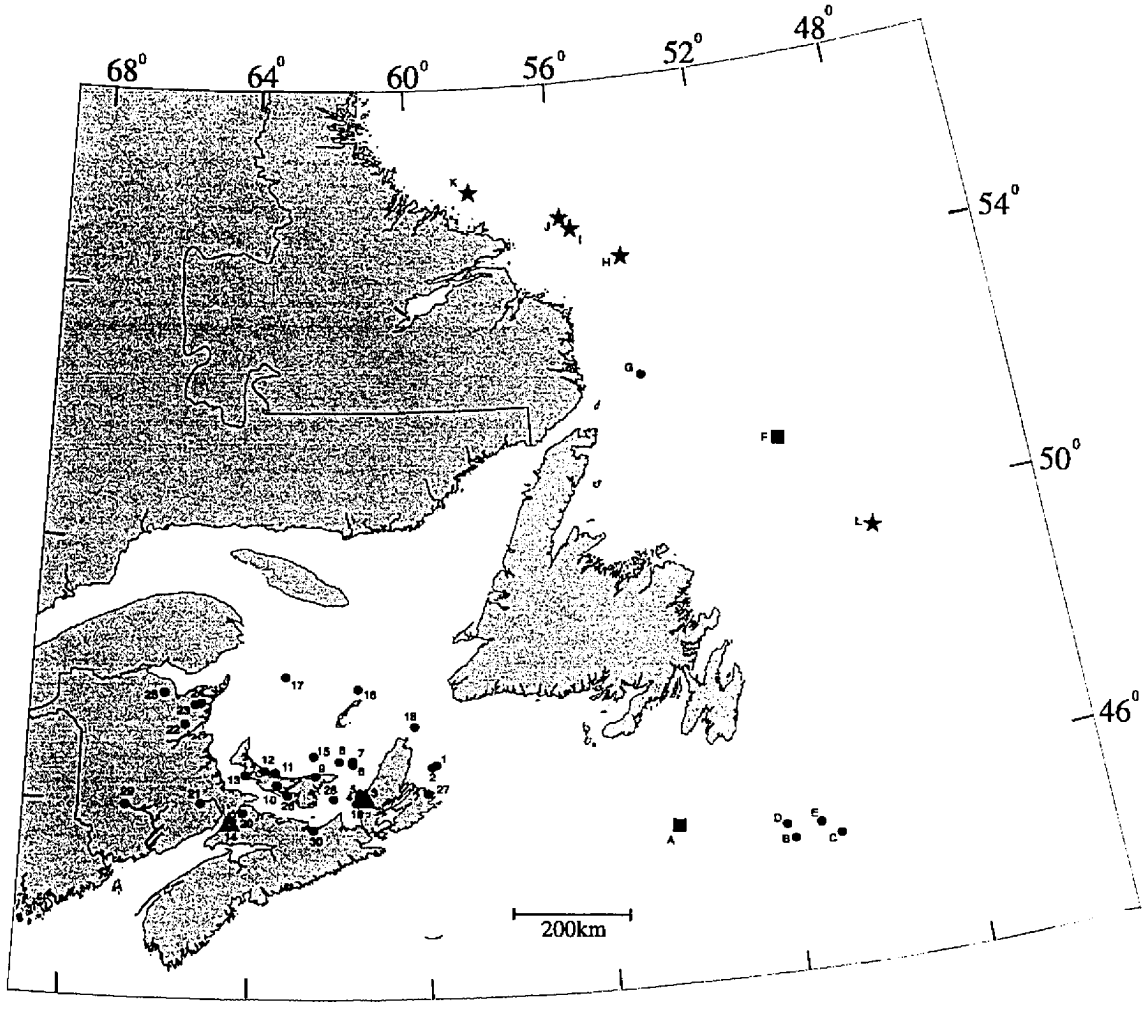



Figure 4.8 Location map for the 12 offshore wells, outside the CMB, which penetrated Carboniferous aged strata. The location of the 28 wells and 2 major coastal reference sections used in this study are shown for reference. Outlying wells which penetrated Late Carboniferous carbonates are denoted with stars and those that encountered significant (>500m) successions of clastics and coal-bearing strata are indicated by squares. Those wells denoted by dots (B-D, F-G), only encountered pre-Westphalian strata.

Table 4.5 List of wells outside the CMB which penetrated Carboniferous strata with their associated technical details. The wells which penetrated Late Carboniferous carbonates are shown in bold. See Figure 4.8 for well locations. Carb = Carboniferous strata penetrated; PostCarb = Post Carboniferous strata penetrated.

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m)/ Water Depth (m) | Total Depth (m) | PostCarb (m) | Carb (m) |
|---|---|---|---|---|---|---|---|---|---|
| A | Elf Hermine E-94 | 45.39147 | -54.49853 | 18-Oct-71 | 31-Dec-71 | 25.9/82.6 | 3267.5 | 1522 | 1633 |
| B | Amoco Imperial Gannet O-54 | 45.06515 | -52.63603 | 24-Sept-71/6-Mar-72 | 27-Sept-71/24-Apr-72 | 29.9/100 | 3048.0 | 1779 | 1020 |
| C | Amoco Imperial Skelly Phalarope P-62 | 45.19702 | -51.404 | 24-Oct-74 | 05-Jan-75 | 29.9/73.2 | 3162.0 | 2361 | 478 |
| D | Amoco Imperial Skelly Razorbill F-54 | 45.2236 | -52.13957 | 02-May-73 | 04-Jul-73 | 25.9/69.2 | 3135.0 | 2526 | 503? |
| E | Amoco Imperial Skelly Sandpiper 2J-77 | 45.61092 | -51.68349 | 15-Jun-73 | 20-Jun-73 | 25.9/90.2 | 3525.0 | 2883 | 526 |
| F | BP et al. Hare Bay E-21 | 51.17283 | -51.07419 | 14-Jun-79 | 18-Oct-79 | 24.2/239.1 | 4874.0 | 3138 | 1472 |
| G | Eastcan et al. Verrazano L-77 | 52.4438 | -54.19754 | 08-Oct-80 | 10-Oct-80 | 12.8/182.9 | 1509.0 | spud | 264 |
| H | BP Columbia et al. Indian Harbour M-52 | 54.36426 | -54.39773 | 21-Aug-75/6-Sept-76 | 23-Oct-75/6-Nov-76 | 29.9/197.8 | 3958.2 | 3257 | 474? |
| I | Total Eastcan et al. Roberval K-92 | 54.85987 | -55.74327 | 2-Oct-78/4-Jul-79 | 27-Oct-78/3-Oct-79 | 12.5/268.5 | 3874.0 | 3263 | 330 |
| | | | | 9-Oct-80/1-Jul-82 | 14-Oct-80/8-Jul-82 | 12.5/268.5 | 3874.0 | | |
| J | EastCan et al. Gudrid H-55 | 54.90557 | -55.87529 | 14-Jul-74 | 03-Oct-74 | 12.2/299.3 | 2838.0 | 2352 | 143 |
| K | Total Eastcan et al. Tyrk P100 | 55.49712 | -58.23076 | 18-Jul-79 | 26-Aug-79 | 12.3/117 | 1739.0 | 1573 | 4? |
| L | Texaco Shell et al. Blue H-28 | 49.62416 | -49.30054 | 28-Apr-79 | 26-Aug-79 | 15/1486 | 6103.0 | 3750 | 852 |

contain dolomites and limestones dated as Westphalian D to Stephanian (Moir, 1986). The carbonate section is unconformably overlain by the Lower Cretaceous volcanics of the Alexis Formation. The well history reports indicate that the Late Carboniferous strata typically consist of brown grey to light brown to buff, microcrystalline dolomite with interbedded thin limestones and shales. The dolomites are locally argillaceous with variable porosity. Miller and D'eon (1987) interpreted these rocks as shallow marine reef/lagoonal deposits laid down on a stable continental platform in an epeiric sea. Additional Late Carboniferous limestones are found on the Eastern Newfoundland Shelf in the Blue H-28 well (Fig. 4.8). In this well a 95m thick limestone unit lies stratigraphically 88m above a succession of interbedded sandstones and shales that have been dated as Namurian to Visean (Barss, 1983), implying that the limestone could be Westphalian.

The age of these carbonates is a source of controversy (Bell and Howie, 1990; Jenkins, 1984). It has been suggested that material from which late Westphalian - Stephanian dates were obtained was not in situ (i.e., contaminants) (Jenkins, 1984), however, the samples came directly from conventional cores, the favoured medium for subsurface sampling. Bell and Howie (1990) further proposed that the carbonates cannot be late Westphalian - Stephanian because of the absence of similar types of rocks on either side of the present Atlantic Ocean. However, in light of the evidence for Late Carboniferous marine incursions in the Maritimes Basin, the carbonates on the Labrador and Eastern Newfoundland shelves could be distal marine equivalents of the Maritimes Basin fill.

Accepting the Late Carboniferous age of these carbonates places a Carboniferous marine environment close to the Maritimes Basin, suggesting that eustatic fluctuations may have affected the deposition of the basin fill.

The fluctuations of sea level through the Carboniferous are shown by the compilation of relative sea level curves shown in Figure 4.9. The schematic relative sea level curve for the CMB Late Paleozoic portion was developed using the ratio of restricted-marine foraminifera to freshwater thecamoebians (APPENDIX II). The curves

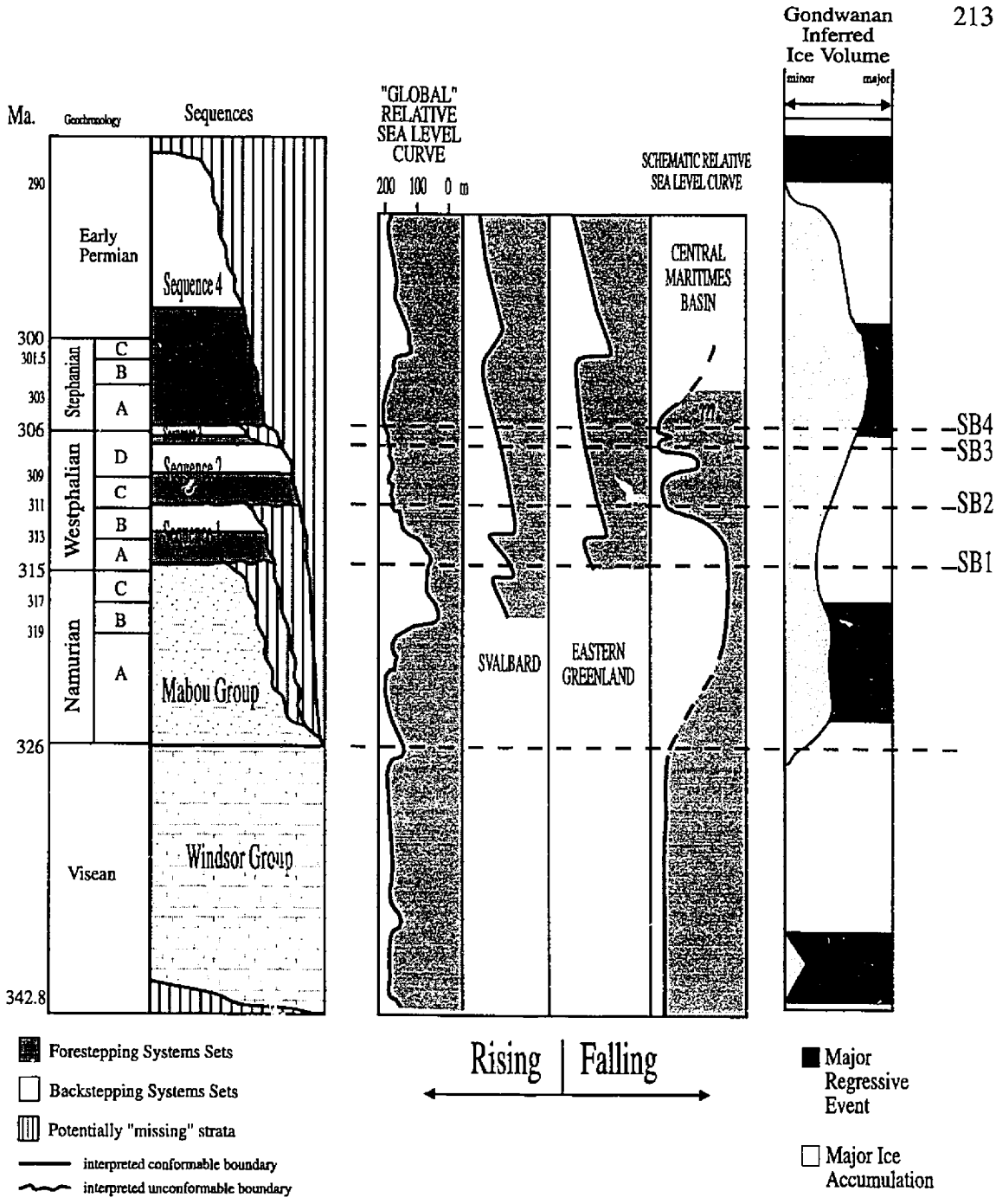



Figure 4.9 Central Maritime Basin sequences and sequence boundaries with a compilation of interpreted relative sea level curves. The CMB schematic relative sea level curve is shown for comparison (Fig 2.29). The curve on the left is from Ross and Ross (1987) and the Svalbard/Eastern Greenland curves are from Stemmerik and Worsley (1988). The generalized Ross and Ross (1987) global eustatic curve is based on observed transgressive and regressive depositional sequences dated using macrofossil zonations. The Stemmerik and Worsley (1989) sea level curve was inferred from successions showing major platform to basin transitions. An inferred ice volume curve for Gondwana is shown on the right (from Veevers and Powell, 1987). SB = sequence boundary.

show a similar trend of higher sea level during the Early Carboniferous, lowering slightly in the late Namurian to early Westphalian, followed by a general increase in sea level from the Westphalian to Early Permian. At this scale, no direct correlations are apparent between the development of CMB F-B sequences and sequence boundaries and changes in Carboniferous sea level except that F-B Sequence 1 developed during a time of relative low sea level while the upper F-B sequences apparently developed during times of higher sea level.

As mentioned above, glaciation and deglaciation have been linked to relative fluctuations in sea level (Williams, 1993). Veevers and Powell (1987) constructed an inferred ice volume curve for Gondwana which is here (Fig. 4.9) compared to the occurrences of CMB sequences and sequence boundaries. The most noticeable correlations between the two data sets are the major regressive events proposed by Veevers and Powell (1987) which coincide with the Mabou Group of the early basin fill succession and the forestepping systems set (FSS) of F-B Sequence 4. On the other hand, Gonzalez-Bonorino and Eyles (1995) suggested that the maximum accumulation of ice occurred during the Namurian, afterwhich, ice volume decreased steadily throughout the Late Carboniferous. Their interpretation would support that the deposition of the Mabou Group coincided with a major regressive event, but that no regressive event correlates with the FSS of FB Sequence 4.

## 4.3 Discussion

### 4.3.1 Supply

#### 4.3.1.1 Sediment Supply and Tectonism

There is an ongoing debate as to the significance of coarse clastic sedimentation in sedimentary basins with respect to when an active orogen sheds sediments. The traditional viewpoint proposes that during new, or renewed, uplift, new source areas are exposed resulting in the erosion and transportation of coarse-grained sediments to the basin (Wiltschko and Dorr, 1983). Over time, as the source wears down, the volume of coarse sediment will decrease resulting in an overall fining upwards sequence (Heward,

1978). Conversely, Blair and Bilodeau (1988) proposed that the onset of abrupt tectonic activity, which exposes unweathered strata, is correlated with fine-grained sedimentation in the basin. As tectonism wanes, erosion and supply of coarse-grained sediments increase resulting in an overall coarsening upwards cycle. These types of tectonic cycles have been recognized in the Western Canada foreland basin by Leckie and Smith (1992) and successfully modelled by Stockmal *et al.* (1992).

Regardless of which proposal is correct, discrete packages of coarse-grained strata are typically used as a record of geologic events (Jordan *et al.*, 1988), although the timing of the events would be reversed depending on which proposal is applied. It follows that in the general vicinity of an active orogen, the associated sedimentary basins connected via different drainage basins might be expected to contain similar records of regional tectonic development.

With this in mind, Late Paleozoic basins to the south of the present Maritimes Basin that may have shared a source of supply with the Maritimes Basin during the Late Carboniferous were investigated. The detailed stratigraphies are different and the established stratigraphic divisions locally do not reflect any tectonic cyclicity, however, broad interpretations of relatively coarse packages versus relatively fine packages were correlatable between all the basins at the scale of development of F-B sequences and sequence boundaries in the Maritimes Basin (Fig. 4.3).

A significant observation resulting from the southern Late Paleozoic analysis is the recognition that a strong resemblance exists between the Mississippian-Pennsylvanian unconformity in the eastern U.S. and the Namurian-Westphalian event in the Maritimes Basin (Fig. 4.3). Coincidently, both hiatuses occurred during the Late Namurian and are regionally extensive. In addition, stratigraphic successions above and below the hiatuses are broadly similar between the two regions. The strata immediately below both events are typically fine-grained interbedded sandstones and shales, underlain by Visean marine units; lying unconformably above both hiatuses are thick successions of coarse-grained Westphalian to Permian clastics. Another shared feature is that both boundaries are associated with a clay mineralogic anomaly. To the south, a contrast between a

montmorillonite-mixed-layer clay facies and an illite-chlorite(Fe-rich)-kaolinite-mixed-layer clay facies is recognized (Hower *et al.*, 1993; Weaver, 1960); in the CMB an anomaly is suggested by the INRS-Petrole mineralogy data (Fig. 2.31) which details an abrupt increase in Fe-rich chlorites; however, additional clay geochemical analysis is required to strengthen this interpretation. The evidence suggests that the Mississippian-Pennsylvanian unconformity and the Namurian-Westphalian event reflect a common allocyclic event.

Overlying the hiatuses are the first of three, initially coarse-grained, fining upwards cycles (Fig. 4.3). The first phase of coarse clastic development was initiated during the Late Namurian - Early Westphalian interval in both the Maritimes Basin and the eastern U.S. The duration of the tectonic periodicity in the eastern Appalachian region is estimated to be 3-5 million years (Tankard 1986); the corresponding CMB F-B Sequence 1 developed over a comparable period of 3.6 million years. This first influx of new sediments consisted of the Brion Island Formation and the Morrowan sandstones (i.e. Lee, Caseyville, New River fms.) of the Maritimes Basin and eastern U.S., respectively. The successions are typically coarser grained than any of the overlying Westphalian to Permian strata and tend to have a higher proportion of quartz. A similar feature shown by both coarse-grained successions is the predominance of multi-story, regionally extensive sandstone sheets and belts in the lower part of the cycle, suggesting bed-load dominated systems (Archer and Greb, 1995). The basal coarse-grained successions evolve in both regions into relatively finer grained successions that tend to have better coal development. The development of the basal coarse-grained, quartz-rich sandstones in the eastern United States has been associated with the onset of Alleghanian thrusting and renewed uplift of the source area (Greb and Chesnut 1996; Tankard, 1986), which would suggest that the deposition of F-B Sequence 1, broadly correlatable with the onset of Morrowan sandstone deposition, developed as a consequence of the same mechanism -- Alleghanian tectonism in the source area.

The second phase of coarse clastic sedimentation (Fig. 4.3) is recorded by the lower part of the West Virginia deltaic complex (Donaldson, 1974) and CMB F-B

Sequence 2 (Bradelle - Green Gables fms.) in the eastern United States and Maritimes Basin, respectively. The phase was initiated during the middle Westphalian and lasted approximately 4.2 million years in the CMB, which is again similar to what Tankard (1986) suggested for tectonic periodicity in the eastern Appalachian region and to the approximate duration suggested by biostratigraphy (Table 4.2). The basal sandstones in both regions tend to be coarse- to medium-grained and occur as multi-story, regionally extensive sand sheets and belts. Feldspar content, as indicated from CMB well cuttings descriptions and available eastern U.S. literature, increases upsection in both regions, as does the quantity of coal. Coal development in the eastern United States and the Maritimes Basin reaches a maximum during the deposition of the upper member of the intermediate clastic depositional phase, or the backstepping systems set of F-B Sequence 2, respectively (Fig. 4.3).

The last phase of coarse clastic deposition (Fig. 4.3) coincided approximately with the Westphalian - Stephanian boundary and is associated with the Grafton Delta Phase of the West Virginia deltaic complex (Donaldson, 1974) in the eastern United States, and F-B Sequence 4 in the CMB. Duration in the CMB was approximately 16.5 Ma which is significantly longer than the previous two phases. Duration of this phase is uncertain in both regions due to the erosion of Late Carboniferous and Permian successions. The remaining strata, however, are closely associated with redbed lithologies that fine upwards from extensive blankets of coarse well developed sandstones and gravels (Wood *et al.*, 1986), to finer grained strata which contain shales, siltstones, thin limestones and poorly developed coals (Arkle, 1974).

The Central Appalachian basin contains one additional phase of coarse clastic deposition which is represented by the Early Permian, redbed dominated Dunkard Group (Arkle, 1974; Beerbower, 1969). An age equivalent coarse-grained sequence has not been defined in the CMB due to limited lithologic and biostratigraphic data for the upper interval of CMB fill and the inherent problems with the post-Carboniferous hiatus. However, the BSS of F-B Sequence 4 shows local signs of coarsening upwards (Fig. 3.10), therefore, a Dunkard Group equivalent may exist in the CMB but has not been

formally identified in this study.

Based on the strong similarities recognized between the Mississippian-Pennsylvanian unconformity and the Namurian-Westphalian event as well as the resemblance of Late Carboniferous basin fill characteristics, it is suggested that the Maritimes Basin and the Late Paleozoic basins of the eastern United States contain three broadly similar phases of coarse clastic sedimentation, and that these phases developed as a direct result of renewed Alleghanian tectonism in the source area (Donaldson and Shumaker, 1981; Tankard, 1986; Archer and Greb, 1995).

#### 4.3.1.2 Tectonic vs. Climatic

According to the model proposed by Cecil (1990), climatic cycles required to produce the multiple successions in the CMB would have to oscillate between tropical rainy conditions (nonseasonal to weakly seasonal) required for peat development, wet-dry seasonal climates favourable for siliciclastic deposition and long dry/short wet climates for reduced erosion and fine-grained sedimentation. It might be expected that if fluctuations such as this, at the sediment source, were the major control on sequence development there would be a predictable, or consistent, climatically sensitive lithologic succession exhibited by each of the CMB F-B sequences. In fact, successions sensitive to climatic influences appear to be distributed randomly throughout the CMB F-B sequences; for example, the basal quartz-prone sandstones in F-B Sequence 1, the focussed development of Coal Measures in F-B Sequence 2, and an overall increase in redbed content upsection.

The climatic development of the CMB F-B Sequences would require periodicities in the order of $10^6$ - $10^7$ years over a 25 million year interval. The paleoclimate curves for the U.S. basins do not display this periodicity, although the resolution of the curves may not be capable of this precision. Nevertheless, most authors (cf., Calder and Gibling, 1994; Tandon and Gibling, 1994; Cecil, 1990) agree that climate is most likely a primary control on intermediate ($10^5$ years) and short term ($10^4$ years) stratigraphic cycles, although it is has been suggested (Cecil, 1990) that the Carboniferous stratigraphic cycles

in the Appalachian Basin may be due to long term climatic fluctuations ($10^5$ - $10^7$ years). In view of these considerations, it is unlikely that climate was the primary control on sediment flux into the CMB, although it cannot be ruled out entirely as a secondary control of more locally derived sequences.

The similarity of the three post Namurian clastic phases in the Maritimes Basin and the eastern United States, collectively underlain by a regionally extensive hiatus, strongly implies a primary tectonic control on sediment supply. Similar large scale (>150m), basin wide cyclic packages of coarse- and fine-grained strata in the Hornelen Basin have been attributed to tectonism in the source area (Steel, 1976), as have large cyclic depositional packages in the Pyrenees which have been linked specifically to thrust related pulses of sedimentation that have approximately the same durations (6.5-12 million years) as the CMB sequences (Puigdefabregas *et al.*, 1986). In the Western Canada foreland basin, Leckie and Smith (1992) and Stockmal *et al.* (1992) have recognized six regionally extensive 2nd order coarse- and fine- grained clastic wedges that developed in response to terrane accretion. In a similar eastern Australian geologic regime, Arditto (1991) identified 6 million year cycles that broadly fine upwards which where attributed to foreland basin related tectonism. The durations of the CMB F-B sequences are in general comparable to the thick (100-3000m) tectonic cyclothems reported by Blair and Bilodeau (1988), which have durations from 2 to 15 million years. These tectonic cyclothems are typically regionally extensive successions that are composed of a cyclic succession of coarse- and fine-grained strata which formed as a result of active versus quiescent tectonic periods (Blair and Bilodeau, 1988).

Tectonism and climate probably both played a role in sediment supply (Blum and Valastro, 1994; Shanley and McCabe, 1994; Schumm, 1993; Cecil, 1990). A similar situation existed in the Hornelen Basin where Steel (1976) found it difficult to differentiate climatic from tectonic controls but essentially opted for tectonism. The data in the CMB suggest that tectonism was of primary importance for larger scale sequence development and climate likely played a secondary role for smaller scale sequences. A similar relationship was suggested by Magnavita and da Silva (1995) who proposed that

long term stratigraphic cycles tend to be related to tectonism and that climate is more important for short term cycles.

### 4.3.2 Accommodation

#### 4.3.2.1 Eustasy

Although there seems to be no direct correlation between eustatic fluctuations and the occurrences of CMB F-B sequences and sequence boundaries, there remains evidence of restricted-marine incursions in the mid Westphalian. The relative importance of eustatic controls may have increased during the Westphalian as suggested by the global sea level (Ross and Ross, 1987) and increased occurrences of restricted-marine agglutinated foraminifera in the CMB (Fig. 4.9).

As described in the previous chapter, relative sea level controls have been successfully applied to smaller scale sequence development in the Sydney subbasin (Gibling and Bird, 1994). The onset of cylcothemic deposition documented in the Sydney Mines Formation (Green Gables Formation equivalent; Backstepping systems set of F-B Sequence 2) by Gibling and Bird (1994) correlates closely with the onset of a similar period of extensive cyclothemic development in the Carbondale Formation (upper member of the intermediate phase) in the Illinois Basin (Trask and Palmer, 1986); both stratigraphic units developed during periods of relative high stratigraphic baselevel and overlie major fluvial successions.

Invoking primary eustatic controls for F-B sequence development is difficult in light of the absence of any open marine indications within the Maritimes Basin Late Carboniferous section. The Westphalian D - Stephanian marine carbonates on the Labrador and Eastern Newfoundland Shelves suggest that open-marine conditions lay in close proximity to the Maritimes Basin in the Late Carboniferous. Reconstructions of the north Atlantic region during the Carboniferous suggest that the Barents Shelf region (Fig. 4.10) represented the nearest open ocean environment to the Maritimes Basin (Ziegler, 1988). It is postulated, based on the Early Westphalian and Permian reconstructions by Ziegler (1988), that a narrow seaway connected the present Labrador and Eastern

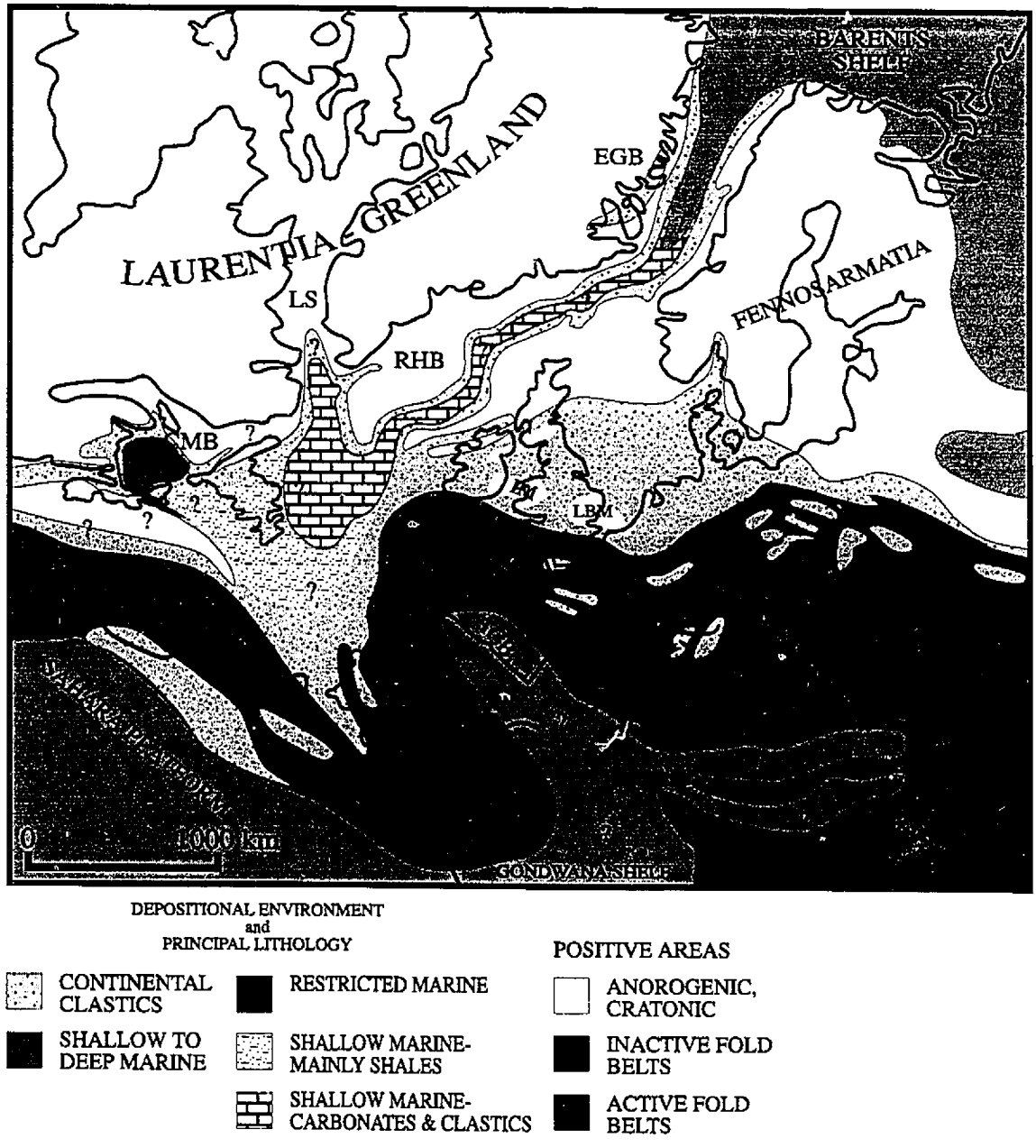



Figure 4.10 Postulated Late Westphalian paleogeographic reconstruction showing environments present during the deposition of F-B Sequences 2 and 3 (modified from Ziegler, 1988). The CMB is still dominated by continental sedimentation sourced from the Appalachian orogen, however there is an encroachment of marine waters from the Barents Shelf region towards the CMB region. CMB = Central Maritimes Basin; LS = Labrador Shelf; ACB = Aquitaine Cantabrian Basin; EGB = East Greenland Basin; IM = Irish Massif; LBM = London-Brabant Massif; RHB = Rockall-Hatton Bank.

Newfoundland Shelves to the Barents Shelf region during the Late Westphalian, and that incursions of marine waters were able to reach the Maritimes Basin (Fig. 4.10) during periods of relatively high stratigraphic baselevel. This hypothesis is supported by the recent identification of a mid Carboniferous rifting event in Greenland-Barents sea area, which resulted in the development of 3rd order cyclic shelf deposits composed of carbonates, mixed carbonates-siliciclastics and carbonates-evaporites (Stemmerik, 1996).

#### 4.3.2.2 Tectonic vs. Eustatic

Several key lines of evidence suggest that tectonism was the primary control on variations in the relative rates of change of accommodation. Most importantly, the regionally extensive, 100s of metres thick cyclic coarse- and fine-grained F-B sequences favour a tectonic origin. Comparable 150-200m thick coarsening upwards Devonian successions in Norway have been attributed to increased tectonic subsidence (Steel, 1976). Other thick successions of cyclic coarse- and fine-grained packages have been identified as tectonically controlled by Blair and Bilodeau (1988). St. Peter (1993) and Ryan and Zentilli (1993) have recognized large scale cyclic packages in the Moncton and Cumberland subbasins, respectively, and have attributed the cyclicity to tectonism, however, they do not distinguish between supply and accommodation controls.

The overall preservation of each forestepping and backstepping systems set basinward and incision of sequences towards the southwest (Figures 2.9, 2.10) would suggest that subsidence outpaced incision during stratigraphic baselevel changes. In addition, the updip amalgamation of the coarse-grained units (Figures 2.9, 2.10) suggests that differential subsidence occurred between the basin margins and the basin centre resulting in thicker accumulations basinward. Local differential subsidence is displayed in both the Cumberland and Antigonish subbasins which contain anomalously thick post-Visean successions of strata. Similar observations have been made with respect to the Lee Formation (Fig. 4.3) in the central Appalachian Basin by Greb and Chesnut (1996), who implied tectonic control of accommodation.

Eustatically controlled sequence development is generally associated with some

type of basal paleovalley (Posamentier and Allen, 1993); at the 2nd-3rd order CMB F-B sequence scale the regionally extensive disconformities (Namurian-Westphalian, Mid Westphalian and Westphalian-Stephanian) show no evidence that any paleovalleys are confining F-B sequences. At a smaller scale, however, it has been shown in the previous chapter that sequences at the tens of metres scale are associated with paleovalley incision (Gibling and Bird, 1994). It is also common in eustatic sequences to have significant erosion associated with the transgressive surfaces (Van Wagoner *et al.*, 1988), however, CMB data suggest that little erosion occurred during the abrupt rise in stratigraphic baselevel associated with any transgressive surface.

Based on the available evidence the primary control on accommodation for the large scale (2nd-3rd order) F-B sequences is interpreted to be tectonic subsidence. Eustatic controls, like climate, played a secondary role in the development of smaller scale (4th-5th order) sequences within the CMB F-B sequence framework. Similar conclusions have been proposed by Willard and Klein (1990), Greb and Chesnut (1996) and Archer and Greb (1995) for comparable Late Carboniferous strata in the eastern United States.

### 4.3.3 Late Carboniferous Tectonic Classification

One goal of this study is to develop a provisional basin depositional model with analogues to other basins, based on all available data. This part of the study entailed a synthesis of the stratigraphic, sedimentologic, and structural observations within the basin fill and a determination of whether these data were consistent with current tectonic syntheses. As mentioned previously, the scope of investigations in this study encompassed post-Windsor Group strata because the older rocks (Horton and Windsor Groups) in the Central Maritimes Basin generally are not penetrated by a significant number of wells (<10) and tend to be poorly imaged on seismic records. For this reason, the models proposed for early basin formation such as rifting (Belt, 1968b) or strike-slip pull apart (Bradley, 1982) are not discussed in detail.

The data within the CMB are best explained by a two phase model of basin

development. The first phase of basin development (pre Namurian-Westphalian event) involved deposition of the Horton, Windsor and Mabou groups and, as mentioned in Chapter 1, has been attributed to either rifting (Belt, 1968b) or strike-slip pull apart (Bradley, 1982). More recently, McCutcheon and Robinson, 1987 have suggested that the Maritimes Basin developed due to passive subsidence related to continental rifting caused by Acadian crustal loading. Quinlan *et al.* (1988) proposed a model for Maritimes Basin development which suggested the re-extension/relaxation of older Acadian thrust faults formed the basin. Using the classification scheme of Kingston *et al.* (1983), Ryan (1993) proposed that overall, the Maritimes Basin could be classified as a Continental Wrench (LL) or Lateral Basin .

Exposures onshore indicate that the Horton/Fountain Lake Groups were deposited in a series of fault bounded basins, typically half-graben in nature (Hamblin and Rust, 1989; Bell and Howie, 1990; Sanford and Grant, 1990). An extensional rift type model is supported by data from the subaerial volcanics within the older Fountain Lake Group which tend to have a bimodal (basalt and rhyolite) composition and exhibit textures, chemistries and stratigraphic relationships commonly found in non-marine settings related to intraplate continental rifting (Gibling *et al.*, 1992a). The offshore data show thick localized accumulations of Horton/Fountain Lake Group equivalents that accumulated during a period of high subsidence and sediment accumulation rates (Figs. 4.6, 4.7, 4.11 and 4.12). Offshore Horton Group strata are generally found in isolated SW-NE trending, fault-bounded subbasins in the southern portion of the CMB (Durling and Marillier, 1993a; Marillier *et al.*, 1989). Subbasin fills are typically 2 to 4 km thick but reach 8 km locally (Durling and Marillier, 1993a). The overall cyclic nature of the Horton Group may suggest that regional tectonics, associated with a mid-crustal decollement (Martel and Gibling, in press), controlled sedimentation, conversely, in other localities, rapid vertical and lateral facies changes in addition to thick packages of sediment suggest that sedimentation was controlled by local tectonics (Hamblin and Rust, 1989; Boehner *et al.*, 1986). Besides evidence for an early extensional regime (Belt, 1968b), strike-slip structural features, such as in the Deer Lake subbasin, suggest that

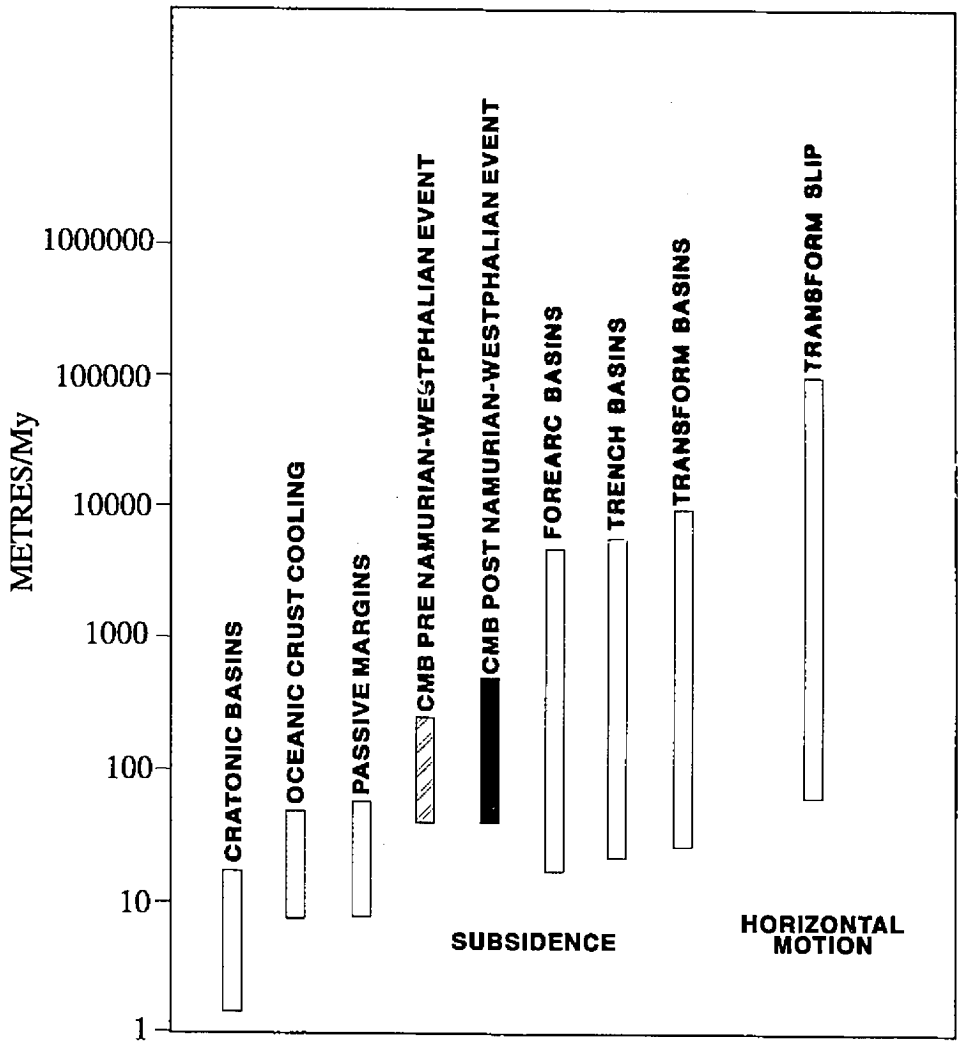



Figure 4.11 Log plot showing relative rates for tectonic subsidence and horizontal plate motion in comparison to the ranges shown for the pre and post Namurian-Westphalian event phases in the Central Maritimes Basin (from Stow et al., 1985 and Deming, 1994).

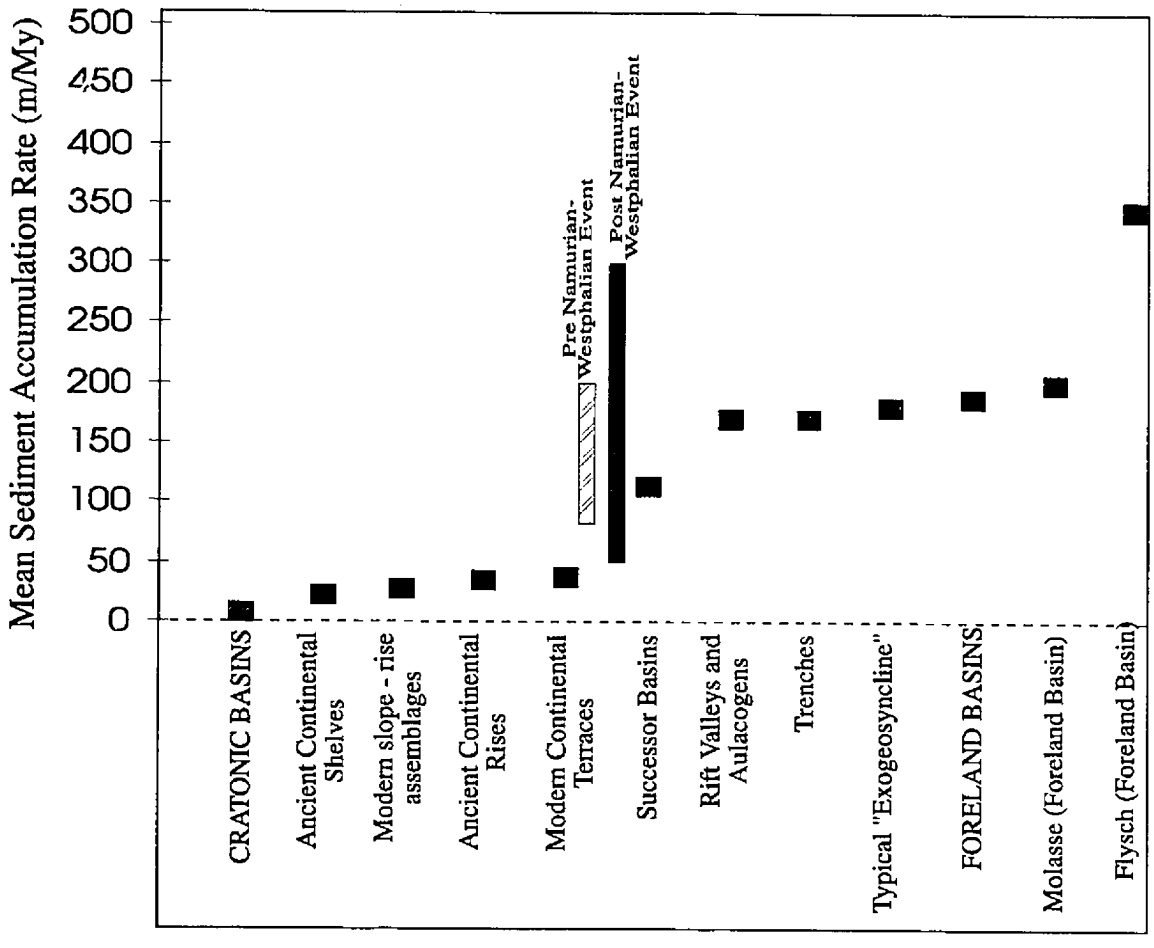



Figure 4.12 Plot showing the mean accumulation rates of major basin types in comparison to the ranges shown for the pre and post Namurian-Westphalian event phases in the Central Maritimes Basin (from Schwab, 1986).

there was a strike-slip component associated with early Maritimes Basin development (Hyde *et al.*, 1988; Bradley, 1982).

As thermal recovery commenced, the early, relatively coarse-grained Horton/Fountain Lake Group succession was blanketed by the marine Windsor Group, which was subsequently covered by the fine-grained Mabou Group with subsidence and sedimentation rates decreasing with time. The complete early basin fill succession is capped by the regionally extensive Namurian-Westphalian hiatus. Overall, the succession (fluvial red-beds and volcanics overlain by shallow marine strata then fine-grained strata capped by a major hiatus) closely resembles the intracratonic rift succession described by Lindsay and Korsch (1989) which formed during crustal extension and thermal recovery. Decreasing subsidence and sedimentation rates for the early basin fill succession are, as suggested by St. Peter (1993), consistent with both a continental rift or a pull-apart model (Figs. 4.6, 4.7, 4.11 and 4.12) (Deming, 1994).

The traditional viewpoint (e.g., McCutcheon and Robinson, 1987; Bradley, 1982) that the early stage of Maritimes Basin development was followed by thermal sagging associated with decreasing subsidence and sedimentation rates is not supported by CMB data, because a second phase of basin development is recorded by the strata in and around the Central Maritimes Basin. Previously, Keppie (1982) suggested that the change in basin fill character from the early basin fill succession to the post Namurian basin fill reflects a change in the Late Carboniferous tectonic regime. Similar proposals were made by Gibling *et al.* (1987), Gibling (1995), and St. Peter (1993), whom, based on observations of the timing of thermal events, biostratigraphic breaks in the rock record, changes in tectonic style and stratigraphic relationships, suggested that the history of Maritimes Basin development is composed of at least two separate phases of development.

The second phase of Maritimes Basin development, following the scheme of Kingston *et al.* (1983), is based on the plate tectonic setting and mechanisms that caused basin subsidence. The Maritimes Basin unconformably overlies continental crust (Fig. 1.6) and was located near a main suture zone formed during the convergence of the

Gondwana and Laurussia continental plates (Fig. 4.4). According to the scheme, this would indicate that the Maritimes Basin is a Continental Wrench (LL) Basin, as was suggested by Ryan (1993). However, with continued plate convergence, Kingston *et al.* (1983) suggested that a Continental Wrench (LL) Basin may eventually become uplifted, eroded and evolve into a foldbelt.

There is ample tectonothermal evidence to suggest that the oblique convergence between Gondwana and Laurussia, along the Variscan Foldbelt, continued after the original Maritime Basin forming events (Steltenpohl and Kunk, 1993; Hatcher *et al.*, 1989; [illegible] or *et al.*, 1986). As a result of a continued Late Carboniferous transpressional regime, it is postulated that the post Namurian-Westphalian event strata in the CMB were deposited in a Continental Wrenched Foldbelt Basin (LL/FBb) which resulted from Variscan oblique collision (Fig. 4.13). This classification is based on geologic observations to be further discussed in the following sections. These will include a discussion of basin fill characteristics, subsidence and accumulation rate histories, the absence of a structural western margin, the presence of a Late Carboniferous thrust faulted eastern margin, similar types of tectonic regimes along the Variscan Foldbelt and the close resemblance between the Maritimes Basin and the Appalachian Basin. The proposed two phase tectonic development for the Maritimes Basin is similar to the one proposed by Keppie (1982), who proposed an early Magdalen Pull-Apart Basin phase and a later Pictou Foreland Basin phase, both as a result of transpression. It may be that the Late Carboniferous Maritimes Basin was analogous to a hypothetical wrenched Appalachian Foreland Basin caused by Variscan Foldbelt oblique collision.

It has been shown that the Late Carboniferous basin fills in the CMB and Appalachian Basin display similarities in lithologic character, depositional regime and relative timing of Late Carboniferous sedimentation events. The regionally extensive packages underlying the Gulf of St. Lawrence, apart from post-depositional salt flowage, are relatively undeformed compared to the onshore zone that extends from near the New Brunswick - Nova Scotia border east and northeast to the Sydney subbasin -- an area coincident with the most tectonized and metamorphosed region in the Maritimes Basin.

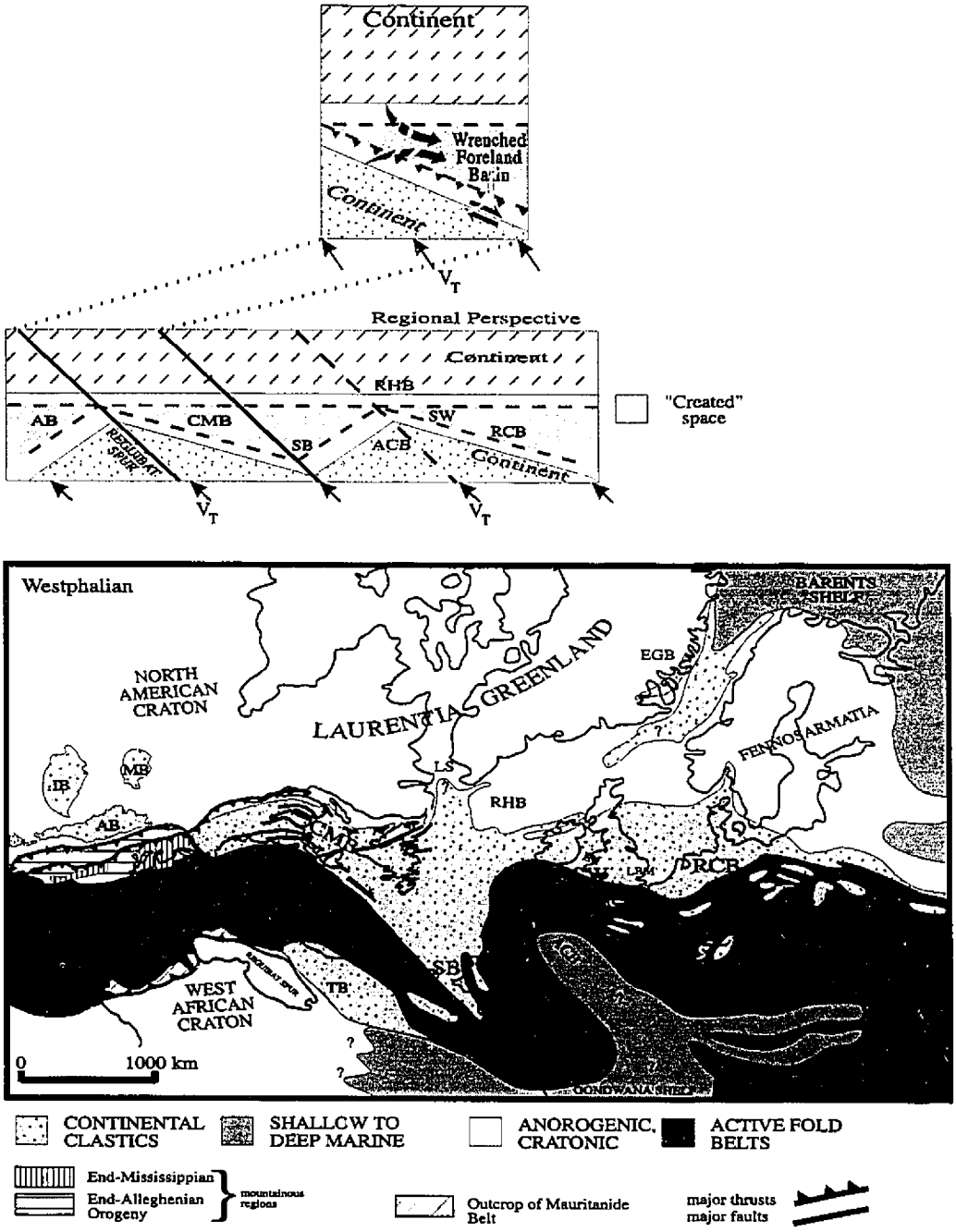



Figure 4.13 (Top) A schematic model showing the development of a foreland basin due to an oblique collision between two continental plates. The foreland basin forms due to compressional wrench tectonics with a predominantly dextral sense of movement. Sediment transport is transverse and longitudinal away from the indentor. (from Johnson, 1995a). (Bottom) Early Westphalian paleogeographic reconstruction showing both an oblique collision between plates and environments present during the deposition of F-B Sequence1 (modified from Ziegler, 1988, Gibling et al., 1992 and Scotese and McKerrow, 1990). At this time, the CMB was dominated by continental sedimentation sourced from the Appalachian orogen with the nearest marine influence located near the Barents Shelf. CMB = Central Maritimes Basin; LS = Labrador Shelf; ACB = Aquitaine Cantabrian Basin; EGB = East Greenland Basin; IM = Irish Massif; LBM = London-Brabant Massif; RHB = Rockall-Hatton Bank; TB = Tindouf Basin; AB = Appalachian Basin; IB = Illinois Basin; MB = Michigan Basin; SB = Southwest Iberia; RCB = Rhur coal basin; SW = Southern Wales region; VT = an arbritrary plate velocity.

In the central-southern Appalachians, Rast (1984) recognized a broadly similar relationship between the essentially undeformed Carboniferous rocks in the Black Warrior and Appalachian basins and the deformed and metamorphosed Carboniferous rocks to the southeast in Virgina, Tennessee and eastern Alabama.

The strongest evidence in support of two phases of basin development comes from the subsidence and sediment accumulation histories. The abrupt increase in both subsidence and sedimentation rates at the beginning of the Westphalian are incompatible with current models involving rifting or strike-slip followed by thermal sag (Joy, 1993; Bradley, 1982). The data indicate a significant increase in tectonic activity, the magnitude of which is comparable to that of the original phase of basin development (Figs. 4.11, 4.12), however, the blanketing nature of the F-B successions does not support deposition in a rift type situation. The range of CMB subsidence and sedimentation rates fall within various geological scenarios, one of which is a foreland basin environment (Figs. 4.11, 4.12).

The overall geometry of the CMB, as mentioned in chapter 1, is asymmetric in form with a relatively gentle slope from the present northwest-west-southwest margins to the basin axis, then a relatively steep gradient to the south-southeast coastline (Figs. 2.14, 2.15) (cf., Durling and Marillier, 1990). This general geometry is not unlike a typical cross section from the deformed thrust belt to the opposite basin margin in a foreland basin (c.f., Tankard, 1986; Puigdefabregas *et al.*, 1986). However, onshore in a zone that extends from near the New Brunswick - Nova Scotia border east and northeast to the Sydney subbasin, local strike-slip pull-apart basins such as the Stellarton Subbasin developed during the Late Carboniferous. These basins developed in close proximity to the Hollow and Cobequid-Chedabucto fault systems (Fig. 1.7), the latter representing the Variscan Front (Fig. 4.13) (Rast and Grant, 1973). It is likely that the transpressional regime, which may have been focussed along these major fault systems during the Late Carboniferous, consisted of shear/wrench and oblique compressional forces that both influenced the development of Maritimes Basin features to varying degrees. For instance, the Stellarton, and possibly the Cumberland, subbasins (Fig. 2.1) may have been affected

by shear/wrench tectonic events, whereas, the CMB and New Brunswick Platform show no significant evidence for a pull-apart, or wrenched, origin as proposed by Bradley (1982).

Compressional faults are key elements in foreland type basins and Late Carboniferous (Namurian-Westphalian) thrust faulting has been recognized throughout the south-southeastern margin of the Maritimes Basin from southern New Brunswick (Gussow, 1953; Rast, 1984), southeastern New Brunswick (Plint and van de Poll, 1984), southwestern Nova Scotia (Waldron et al, 1989; Durling, in press), central Nova Scotia (Durling *et al.*, 1995) to the Cabot Strait region (Langdon and Hall, 1994). Nance (1987) proposed that Late Carboniferous (early Westphalian) deformation consisted of extensive thrust faulting, dextral strike-slip movement and extension, all of which could be explained through a framework of convergent wrench tectonics at the restraining bend of the Cobequid-Chedabucto fault system. Although Nance (1987) implied localized southern New Brunswick thrust faulting, the evidence of thrusting throughout the onshore region mentioned above suggests that Late Carboniferous thrusting was a more widespread event. It does however, appear that thrusting events are focussed along the Cobequid-Chedabucto and Hollow fault systems which would place the Sydney Subbasin on the southeast side of the thrust fault system.

The Sydney Subbasin has been previously interpreted as a strike-slip basin which developed from divergent fault splays originating from the Cobequid-Chedabucto faults system during the Variscan foldbelt collision (Gibling *et al.*, 1987). The relationship between a Late Carboniferous thrustbelt, Variscan oblique collision and a strike-slip setting for the Sydney Subbasin might be explained by the extrusion tectonics model as proposed by Tapponnier *et al.* (1982). The extrusion tectonics model suggests that plate collisions are associated with major strike-slip faults which relieve the build up of force in the system by extruding tectonic blocks away from the primary zone of collision, or indentor. In the Maritimes Basin, the model would suggest the Sydney Subbasin formed as a result of primary strike-slip displacement along the bounding faults (Cobequid-Chedabucto Fault to southeast and the Aspy Fault to the northwest) as proposed by

Gibling *et al.* (1987), due to the oblique collision at the restraining bend of the Cobequid-Chedabucto fault system. According to the model, the basement underlying the Sydney Subbasin would have been extruded away from the junction between Cobequid-Chedabucto and Hollow fault systems creating the accommodation space for Late Carboniferous sediments.

The Variscan Foldbelt which extends from the Mauritanides in West Africa, to the Appalachian-Ouachitan belts of North America, past the London-Brabant Massif in Europe (Fig. 4.13) (Matte, 1991) is commonly associated with fold and thrust belt development. Drozdzewski (1989) proposed that the Ruhr coal basin (Fig. 4.13) is an external fold and thrust belt associated with the Variscan Front and that the recognized (Namurian-Westphalian) thrust faults sole out at different stratigraphic and structural levels which suggests no regional basal detachment zone. In the Southern Wales region (Fig. 4.13), Late Carboniferous rocks exhibit overthrusting from the south (towards the north) with the development of an epi-continental basin to the north of the main thrust zone (Rast and Grant, 1973). Pique and Skehan (1992) identified early to middle Carboniferous southwest directed thrusts in Southwest Iberia (Fig. 4.13). The Variscan Foldbelt in the Northern Appalachians is associated with significant northwest directed overthrusting due to the plate collision (Rast, 1984). Similarly, the Appalachian-Ouachitan belts of North America are dominated by overthrusting due to plate collision (Hatcher *et al.*, 1989; Rast, 1984).

A peculiar feature displayed by the Maritimes Basin is that all deformation is concentrated on the south-southeastern margin in an onshore zone extending from near the New Brunswick - Nova Scotia border east and northeast to the Sydney subbasin -- an area coincident with the most tectonized, thermally mature (see Chapter 5 for a fuller discussion of organic maturation) and metamorphosed region in the Maritimes Basin. It might be expected, given that most structural models proposed for the Maritimes Basin involve rifting or wrenching, that some indications of a structural western basin margin should be present but in fact there is no evidence of major deformation found to the northwest-west-southwest of the deformed zone mentioned above. In the CMB, the

Westphalian Coal Measures onlap older rocks to the northwest-west-southwest but are truncated towards the south-southeastern margin (Grant, 1994). On northern Gaspé Peninsula (Fig 1.1), flat lying, relatively undisturbed, Canso-Riversdale equivalents rest unconformably on Devonian basement in close proximity to the Appalachian Front (Fig. 1.6) (Rust, 1984). In a comparable location on the other side of the Gulf of St. Lawrence, flat lying Windsor Group and Carboniferous redbeds are found on Port au Port Peninsula and Red Island, respectively (Fig. 1.1), in close vicinity to the mapped Appalachian Front (Fig. 1.6) (Grant, A., 1996, pers. comm.; Sanford, B., 1996, pers. comm.). These locations suggest that the Appalachian Front was not active during the Carboniferous period which is further supported by mapping by Sanford and Grant (1990), who show Carboniferous overlying Ordovician-Silurian Anticosti Basin strata in the northern Gulf of St. Lawrence. These data suggest in general that a structural western margin for the regional Maritimes Basin is not present, which is again consistent with a foreland basin scenario (Tankard, 1986).

Overall, the Variscan Foldbelt has been severely eroded and dismembered by subsequent tectonism such as that related to the opening of the Atlantic Ocean (Matte, 1991). As mentioned previously, anywhere between 3 and 6 km of strata have been removed by Permo-Triassic erosion implying that the present Maritimes Basin is an erosional remnant of a much larger Carboniferous basin (Hendricks *et al.*, 1993). In light of this, it is safe to assume that the structural and stratigraphic record in the Maritimes Basin is not complete everywhere and that evidence of younger events, i.e., thin skinned Westphalian thrusting similar to that proposed for the Ruhr basin (Drozdzewski, 1989), may have been subsequently removed. This is especially relevant to the Maritimes Basin where the erosional mechanisms were likely focussed in areas of intense deformation, such as the onshore zone extending from the New Brunswick - Nova Scotia border east and northeast to the Sydney Subbasin. In this area the stratigraphic record might be the most incomplete of all. An analogous, albeit hypothetical, situation might be if the Cordilleran Front Ranges and Alberta Foothills in Western Canada had been removed by erosion would the Western Canada foreland basin be recognized as a foreland basin?

## 4.4 Concluding Statement

The regionally extensive CMB F-B Sequences developed as a result of a series of episodic allocyclic processes. The primary control on variations in the relative rates of change of accommodation and sediment supply in the Maritimes Basin was tectonism (Fig 4.14). Post Namurian-Westphalian event sediment supply was controlled by renewed Alleghanian thrusting in the Carboniferous Appalachians which abruptly increased the sediment flux into the CMB. Sedimentation rate decreased with time, however the influx of sediment occurred as a series of three discrete pulses of coarse- and fine-grained sediments which are attributed to three periods of tectonic activity in the sediment supply area (Fig. 4.14). This oscillating sediment supply aided in the development of the stacked cyclic forestepping-backstepping systems sets identified in the CMB fill. The corresponding accommodation in the CMB depositional system was controlled by increased tectonic subsidence during the Westphalian, primarily due to the onset of Alleghanian thrusting to the south, combined with related local activity. Initial subsidence rates, similar to sedimentation rates, were relatively high and diminished through time. It is probable that several episodes of differential tectonic subsidence of the Maritimes Basin in association with several episodes of renewed uplift of the Carboniferous Appalachians interacted with each other in order to develop the cyclic F-B sequences in the basin fill. The dominant control dictated the geometry of the resulting cycle; tectonic subsidence > sediment supply developed a backstepping systems set, whereas when tectonic subsidence < sediment supply, a forestepping systems set developed.

Secondary controlling mechanisms, climate and eustasy, were superimposed on regionally dominant tectonic mechanisms and fulfilled important roles in the development of smaller scale sequences (Fig. 4.14). Eustatic and climate fluctuations may have played a significant part in the development of major coal deposits in the Middle to Late Westphalian. The overall reddening upwards of strata, and lower sedimentation rates of F-B Sequence 4 may have been influenced by climate. Evidence for restricted-marine conditions within the Maritimes Basin and open-marine conditions

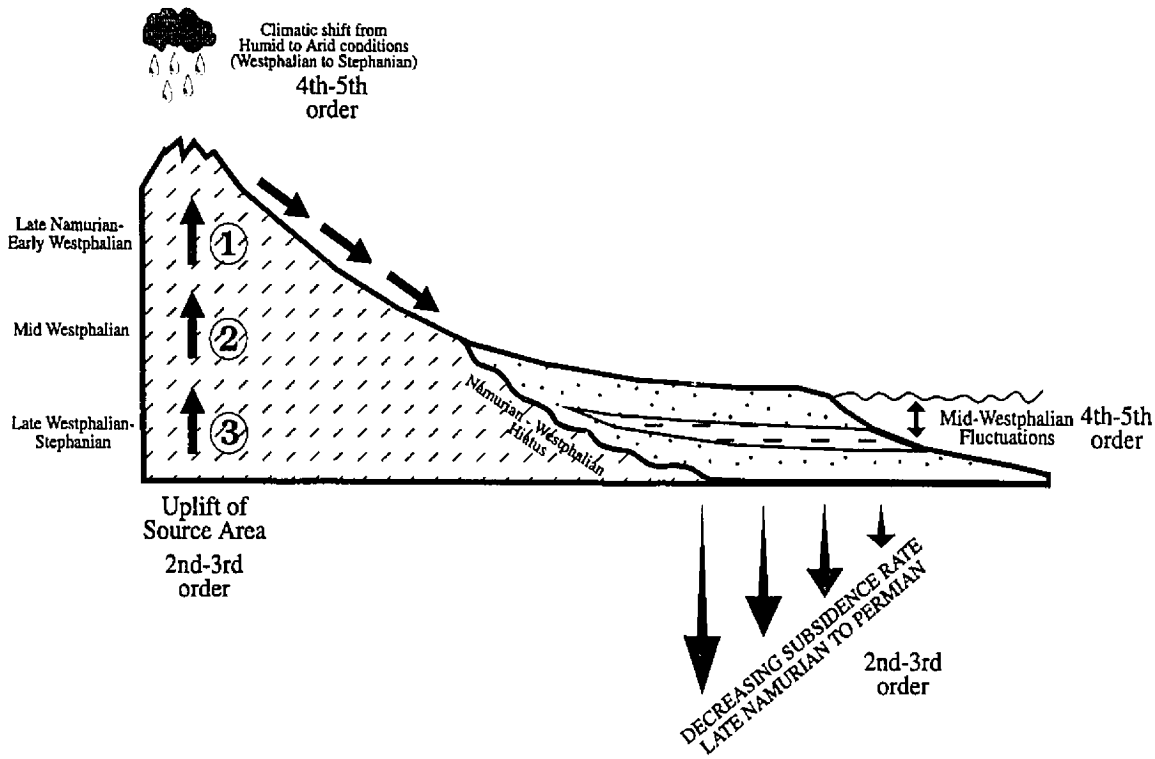



Figure 4.14 Summary schematic showing the major controls on sequence development for Upper Carboniferous-Permian strata in the Central Maritimes Basin. After the Namurian-Westphalian event, increased subsidence in association with several episodes of source area uplift resulted in the development of 2nd-3rd order cyclic sequences. Climatic and eustatic fluctuations may have played a secondary role (4th-5th order scale) in depositional package development.

in close proximity to the Maritimes Basin suggest that eustasy may have exerted a strong secondary control on smaller scale sequence development within F-B Sequence 2 and potentially F-B Sequence 3.

Based on post Namurian basin fill characteristics, subsidence and sedimentation rate histories, the absence of a structural western margin, the presence of a Late Carboniferous thrust faulted eastern margin and the close resemblance between the Maritimes Basin and the Appalachian Basin, it is postulated that the post Namurian Maritimes Basin developed as a Continental Wrenched Foldbelt Basin analogous to a hypothetical wrenched Appalachian Foreland Basin caused by Variscan Foldbelt oblique collision.

# CHAPTER 5 - CENTRAL MARITIMES BASIN PETROLEUM SYSTEM

## 5.1 General Statement

The Central Maritimes Basin is a large, little explored frontier basin with ample evidence of having generated and retained significant volumes of hydrocarbons. The offshore portion, however, has not been an active area of exploration since the late 1970's. Few studies explain why exploration wells did not encounter commercial volumes of hydrocarbons. To help renew interest in the offshore area, it is necessary to explain the past failures, develop new plays and address questions of hydrocarbon generation and timing. This chapter outlines the nature of the petroleum system operating in the CMB, and then develops a hydrocarbon charge model which defines the interaction through time of the petroleum system elements and processes.

## 5.2 Central Maritimes Basin Petroleum System

A petroleum system includes major geologic elements and processes that are essential for an oil and gas deposit to exist in nature (Magoon and Dow, 1994; Perrodon, 1992). The essential elements for a viable hydrocarbon system to occur include source, reservoir, seal and overburden rocks. The processes required for hydrocarbons to accumulate are trap formation and the generation-migration of hydrocarbons. It is the degree of dynamic interaction of system elements and processes that dictates whether or not a basin contains commercial quantities of hydrocarbons.

### 5.2.1 Source Rocks

The primary element of the petroleum system is the availability of a mature source rock from which to generate hydrocarbons. Without a mature source rock, the delineation of reservoirs, seals and traps is meaningless because there will be no hydrocarbons to accumulate (Perrodon, 1992). In the Maritimes Basin, the Tournaisian Horton Group

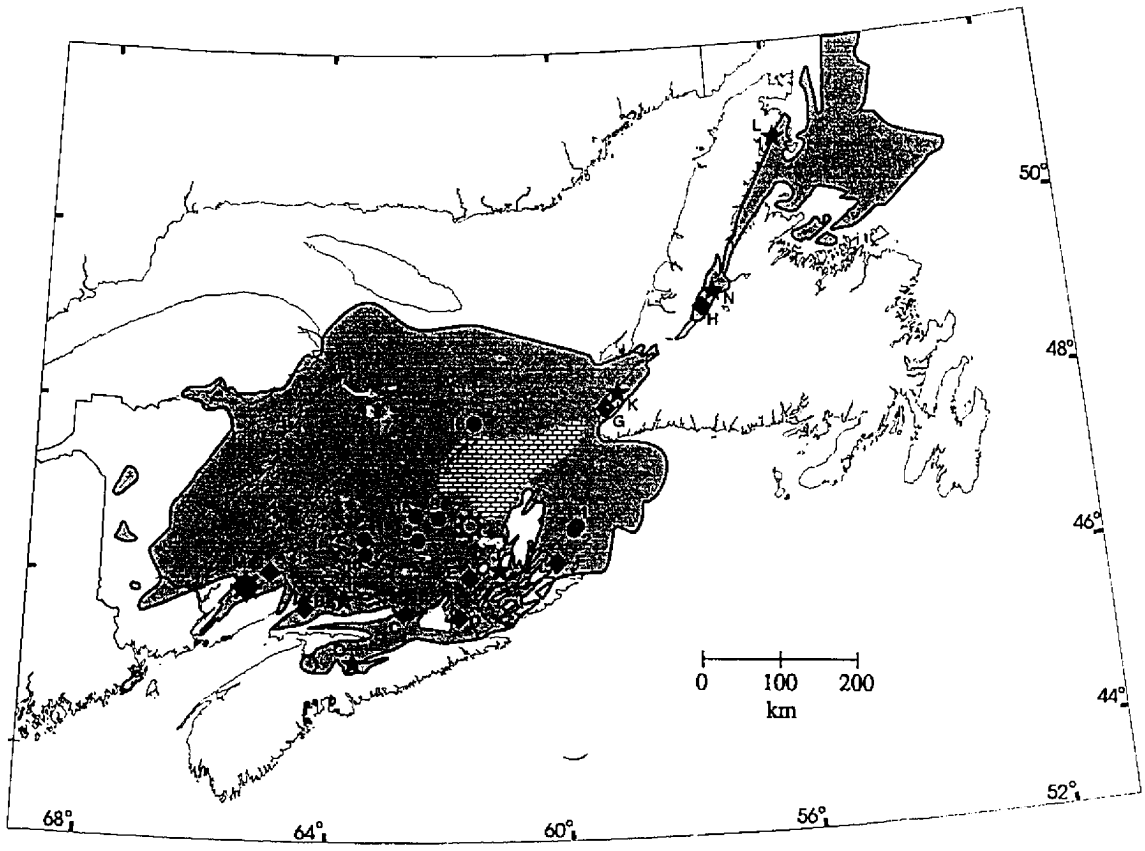
succession (Table 5.1) contains the only source rocks which have demonstrated hydrocarbon generation and expulsion capabilities. The Stoney Creek oil and gas field represents the only commercial deposit of hydrocarbons in the Maritimes Basin discovered thus far (Fig. 5.1), and has been linked, using biomarkers, to the lacustrine Albert Formation of the Horton Group (Chowdhury *et al.*, 1991). The Albert Formation has excellent source rock potential and high Total Organic Carbon, (TOC) values both comparable to source rocks identified in the United Kingdom (Fig. 5.2) (Mossman, 1992). In other areas such as the Lake Ainslie region of Nova Scotia and the Conche region of Newfoundland (Fig. 5.1), numerous oil seeps have been attributed to Tournaisian lacustrine source rocks stratigraphically equivalent to the Albert Formation (Hamblin *et al.*, 1995; Fowler *et al.*, 1993).

The Visean and Namurian portions of the early basin fill succession contain several potential source rocks but a direct tie between hydrocarbons and source has yet to be identified. Fowler *et al.* (1993) analyzed oil samples collected from seeps in the Pugwash Salt Mine in central Nova Scotia (Fig. 5.1) and favours a Visean source, possibly the Macumber Formation (base of Windsor Group). Similarly, Visean hydrocarbon source rocks have been proposed by Hyde *et al.* (1988) and Mossman (1992) in Newfoundland and Nova Scotia. The Mabou Group on the other hand, has not been the focus of many source rock studies; however, the Rocky Brook Formation in the Deer Lake subbasin (Fig. 5.1) has been identified as a potential hydrocarbon source rock (Hamblin, A., 1996, pers. comm.).

Until recently, the source rock potential of the thick, post Namurian-Westphalian event strata onshore was virtually untested (Mossman, 1992). Two studies (Kalkreuth and Macauley, 1987; Mukhopadhyay *et al.*, 1991) have now identified several organic-rich oil shale, coal and coaly shale intervals in the Stellarton and Cumberland subbasins that are potential hydrocarbon source rocks. Similarly, Gibling and Kalkreuth (1991) suggested that several Late Carboniferous black shales and limestones from the

Table 5.1 Some occurrences of potential/proven Carboniferous petroleum source rocks in the Maritimes Basin.

| Group | Formation | Environments of Deposition / Lithology | Kerogen Type | TOC (%) | $T_{MAX}$ $\%R_o$ | Comments/references |
|---|---|---|---|---|---|---|
| Horton | Albert | alluvial-fluvial, lacustrine & minor evaporites | I, III | avg. 1-2<br>up to 12 | 450-460°C<br>0.66-0.87 | Moncton subbasin (Chowdhury *et al.*, 1991) |
| | Big Marsh Mbr. | oil shales | I, III | | 439-443°C<br>0.50-1.40 | Antigonish subbasin (Kalkreuth and Macauley, 1987) |
| | Strathlorne (inferred from seeps) | lacustrine carbonate | N/A | some >1.0 | N/A | Lake Ainslie area biodegradated (Fowler *et al.*,1993) |
| | Crouse Harbour & Cape Rouge (seeps) | alluvial-fluvial, lacustrine | I | avg. 1-2<br>up to 5 | 439-484°C<br>1.07-1.27 | Conche area, Nfld. (Hamblin *et al.*, 1995) |
| Windsor | Macumber (Gays River) | deep water, organic rich shale | | avg. 4.0 | | up to 25m thick (Mossman, 1992) (Fowler *et al.*, 1993) |
| | Ships Cove Woody Cape | | | 1.24-1.27 | 389°C | Bay St. George (Langdon and Hall, 1994; Sinclair, 1992) |
| | Pugwash oil seep | high salinity conditions | N/A | N/A | N/A | inferred source rock (Fowler *et al.*, 1993) |
| Mabou | Rocky Brook | lacustrine | I, III | avg. 1-2<br>up to 15 | avg. 444°C | Deer Lake subbasin (Fowler, M., 1996, pers. comm.; Hyde *et al.*, 1988) |
| Cumberland | Joggins<br>Sydney Mines<br>upper Inverness | carbonaceous limestone<br>black shale/limestone<br>black shales (all marine influenced) | II, III<br>II, III<br>II, III | 1.7-43.3<br>.05-40.2<br>2.2-13.2 | 425-443°C<br>443-454°C<br>436-441°C | Late Carboniferous (Gibling and Kalkreuth, 1991) |
| | Stellarton | continental | III | 1.08-2.09 | gas prone | (Hacquebard, 1984) |
| | Colindale Mbr. (Port Hood) | braidplain/lacustrine | II, III | avg. 2 | 435-445°C | (Crawford, T., 1996, pers. comm) |
| | upper Barachois Grp. | oil shales | III, I/II | 0.8-31.9 | | (Solomon, 1986) |
| | Bird Rock | alluvial plain | III, I? | avg. 1.-1.5 | 300-484°C<br>avg. 454°C | *this study* |
| | Green Gables | alluvial/coastal plain | III, I? | avg. 1.0 | 300-508°C<br>avg. 469°C | *this study* |
| Pictou | none identified? | | | | | |




Well Indications ●

1. NORTH SYDNEY P-05
2. NORTH SYDNEY F-24
7. EAST POINT E-49
8. BEATON POINT F-70
9. NAUFRAGE #1
10. TYRONE #1
11. GREEN GABLES #1
15. CABLE HEAD E-95
16. BRION ISLAND #1
17. BRADELLE E-49

Oil Shales/Source Rocks ◆

A. ALBERT FM.
B. JOGGINS FM.
C. STELLARTON FM.
D. BIG MARSH MBR.
E. COLINDALE MBR/INVERNESS FM.
F. SYDNEY MINES FM.
G. BARACHOIS GROUP
H. ROCKY BROOK

Seeps/Shows/Discoveries ★ ✸

I. PUGWASH SALT MINE
J. LAKE AINSLIE (& wells)
K. FLAT BAY OIL AND GAS SHOWS
L. CONCHE
M. STONEY CREEK OIL AND GAS FIELD
N. CLAYBAR HOLE #1 - GAS BLOWOUT
O. ALTON WELL - GAS BLOWOUT

Figure 5.1 Map showing the locations of oil shale/hydrocarbon source rocks, oil seeps/shows, wells indicating hydrocarbons, and the Stoney Creek oil and gas field.

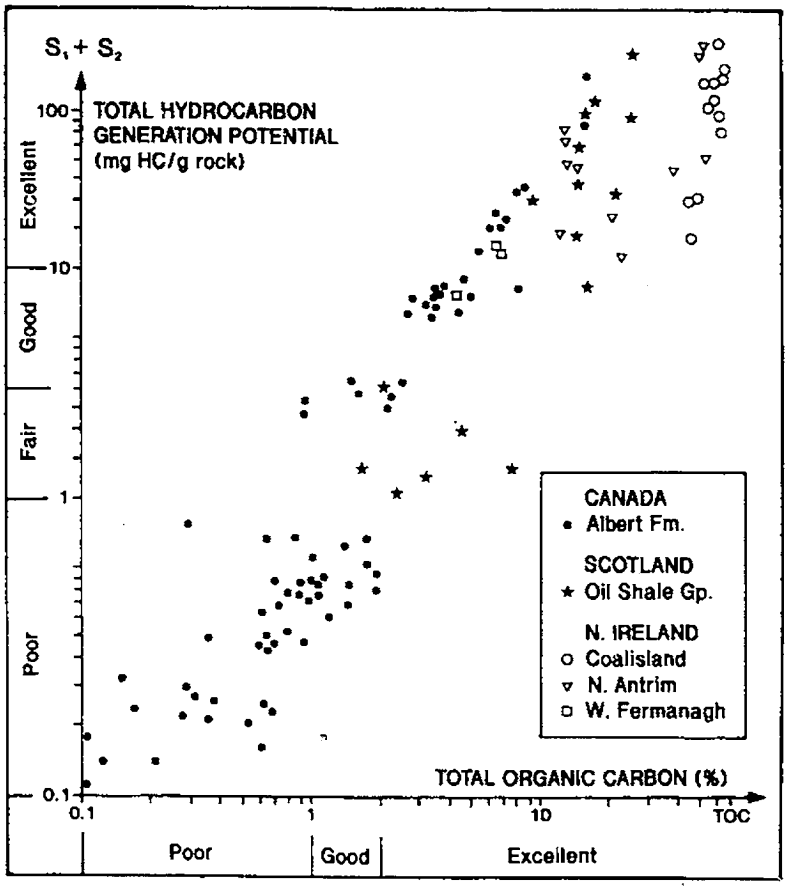



Figure 5.2 Oil and gas potentials of Albert Formation source rocks (Cumberland subbasin, New Brunswick) and several United Kingdom source rocks in relation to total organic carbon (TOC) contents (from Mossman, 1992).

Cumberland, Western Cape Breton and Sydney subbasins have good to very good source rock and hydrocarbon recovery potentials (Fig. 5.3) comparable to other known Maritimes Basin organic-rich rocks. However, the sampled intervals onshore are too thin to be of economic interest (Gibling and Kalkreuth, 1991). Rock-Eval analysis indicates potential source rocks within the Colindale Mbr. (upper Port Hood Fm.) on the western coast of Cape Breton Island (Crawford, T., 1996, pers. comm.).

#### 5.2.1.1 CMB Source Rock Analysis

Prior to this study, subsurface source rock potential in the CMB was essentially untested with only sparse data existing for a few well locations (Naufrage No.1, Beaton Point F-70, North Sydney F-24 and St. Paul P-91). For this study, a total of 1030 samples were collected from the Bradelle L-49 (456 samples), Cable Head E-95 (251 samples), Beaton Point F-70 (28 samples) and East Point E-49 (295 samples) well locations to complement the existing dataset (Table 5.2) (APPENDIX V). All samples were obtained from ditch cuttings and were sent to the Geological Survey of Canada (Calgary) for Rock-Eval pyrolysis and Total Organic Carbon (TOC) content analysis.

Rock-Eval/Total Organic Carbon Analysis involves heating a sample under controlled conditions in the absence of oxygen until thermal decomposition of the dispersed organic mater occurs (Tissot and Welte, 1984). The technique gives analytical results (Table 5.3) which can be used to interpret the quantity of organic matter (TOC), type or quality of organic matter (combinations of S1, S2, and S3) and level of thermal maturity ($T_{max}$). For a more detailed account of the Rock-Eval pyrolysis procedures see Tissot and Welte (1984).

##### 5.2.1.1.1 Results

Standard Rock-Eval pyrolysis geochemical profiles (Fig. 5.4) were examined to help identify potential hydrocarbon source rock intervals within the basin fill. Rock-Eval data, in conjunction with the proposed stratigraphic framework, identified organic-rich intervals within the Green Gables Formation (Fig. 5.4). Organic-rich intervals have also

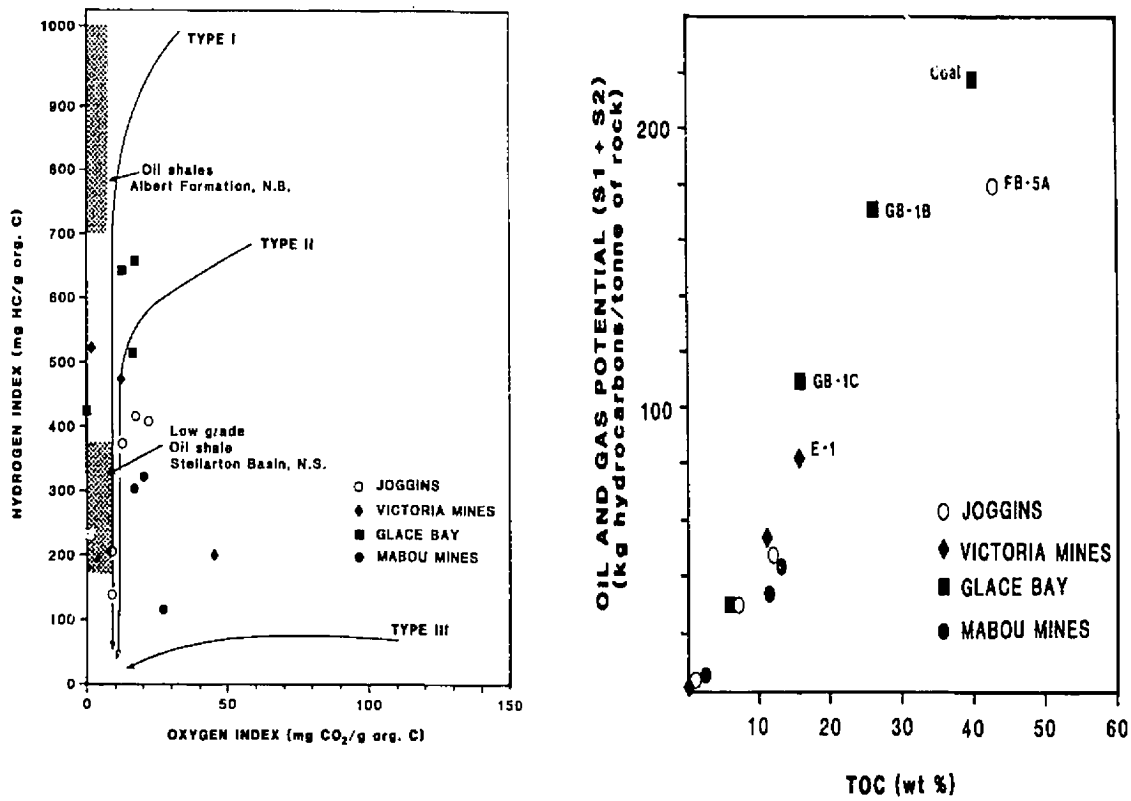



Figure 5.3 (Left) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for several Late Carboniferous black shales and limestones from various Maritimes Basin locations (from Gibling and Kalkreuth, 1991). (Right) Oil and gas potentials of Late Carboniferous black shales and limestones from various Maritimes Basin locations, in relation to total organic carbon (TOC) contents (from Gibling and Kalkreuth, 1991).

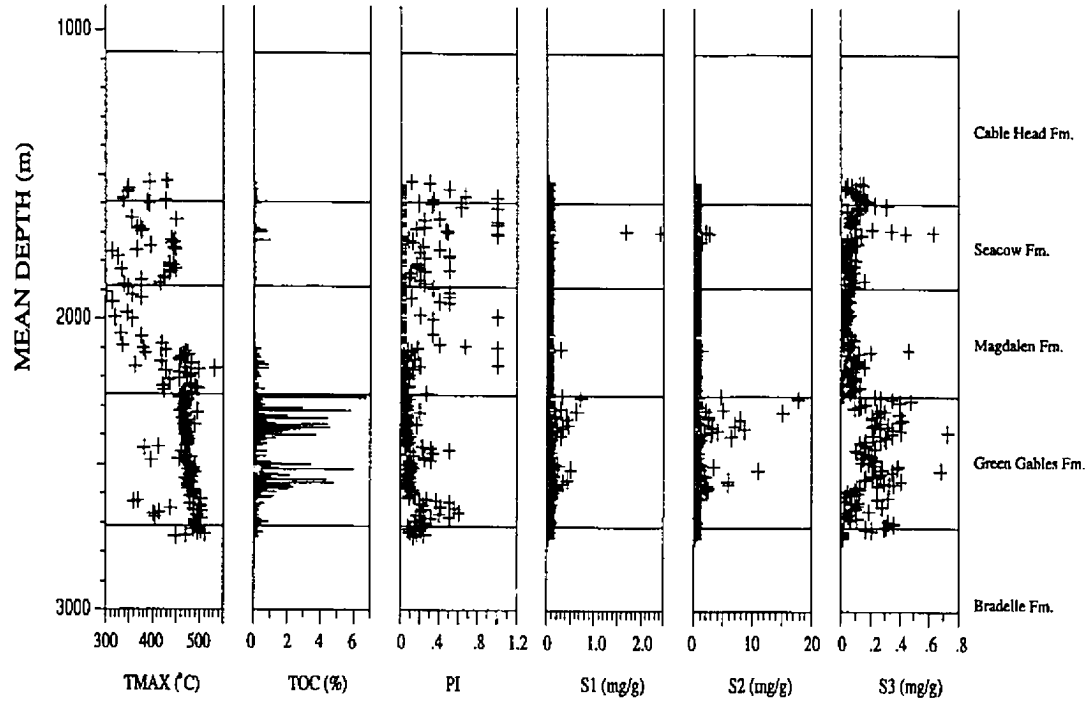
Table 5.2 List of study locations and the types of maturity data provided by each location. Multiple "X's" indicate multiple data sets. The data is located at the GSC (Atlantic).

| Well # | Well Name | Maturation Data (Ro/TAI) | Rock-Eval Data |
|---|---|---|---|
| 1 | Murphy *et al.* North Sydney P-05 | X | |
| 2 | Shell *et al.* North Sydney F-24 | X | X |
| 3 | Mabou Coastal Section | | |
| 4 | NSDME Borehole M-1 | X | |
| 5 | NSDME Borehole M-2A | X | |
| 6 | Hudson's Bay *et al.* East Point E-47 | | |
| 7 | Hudson's Bay-Fina East Point E-49 | X | X |
| 8 | Hudson's Bay *et al.* Beaton Point F-70 | X | X |
| 9 | Soquip *et al.* Naufrage No.1 | XX | X |
| 10 | Soquip *et al.* Tyrone No.1 | XX | |
| 11 | Hudson's Bay-Fina Green Gables No.1 | | |
| 12 | Hudson's Bay-Fina Irishtown No.1 | | |
| 13 | Imperial Wellington Station No.1 | | |
| 14 | Cumberland Coastal Section | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | X | X |
| 16 | Sarep H.Q. Brion Island No.1 | X | |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | X | X |
| 18 | Petro-Canada *et al.* St. Paul P-91 | X | X |
| 19 | NSDME PH-3 | | |
| 20 | Gulf *et al.* Hastings No.1 | | |
| 21 | Irving Chevron *et al.* Middlesex #1 | X | |
| 22 | Hudson's Bay Bartibog No.1 | | |
| 23 | Hudson's Bay St. Isidore No.1 | | |
| 24 | Hudson's Bay St. Isidore No.2 | | |
| 25 | Hudson's Bay Blanchard No.1 | | |
| 26 | Island Development Company Hillsborough No.1 | | |
| 27 | Murphy *et al.* Birch Grove No.1 | X | |
| 28 | Hudson's Bay *et al.* Northumberland Strait F-25 | | |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | | |
| 30 | NSDME P-58 | | |

Table 5.3 List of Rock-Eval geochemical parameters used for source rock analysis (from Bateman, 1995; Tissot and Welte, 1984).

| |
|---|
| **S1** - quantity of indigenous or migrated free hydrocarbons that are expelled from the organic matter during thermal conversion. |
| **S2** - quantity of hydrocarbons expelled by thermal conversion of the organic matter. |
| **S3** - quantity of carbon dioxide expelled by thermal conversion of the organic matter. |
| **Total Organic Carbon (TOC)** - (wt %) of organic carbon calculated from S1, S2, S3. |
| $T_{max}$ ($^0$C) - temperature of maximum hydrocarbon generation during pyrolysis, indicative of thermal maturity. Immature (<435), Early Mature (435-445), Mid Mature (445-450), Late Mature (450-470), Overmature (>470) |
| **Hydrogen Index (HI)** - is the ratio of S2(mg HC/g)/TOC., used for kerogen type. |
| **Oxygen Index (OI)** - is the ratio of S3(mg $CO_2$/g)/TOC, used for kerogen type. |
| **Genetic Potential (S1 + S2)** - total quantity of hydrocarbons released from sample |
| **Production Index (PI)** - ration of S1/(S1+S2), indicates amount of hydrocarbon produced relative to the amount the sample can produce. |

Cable Head E-95




East Point E-49

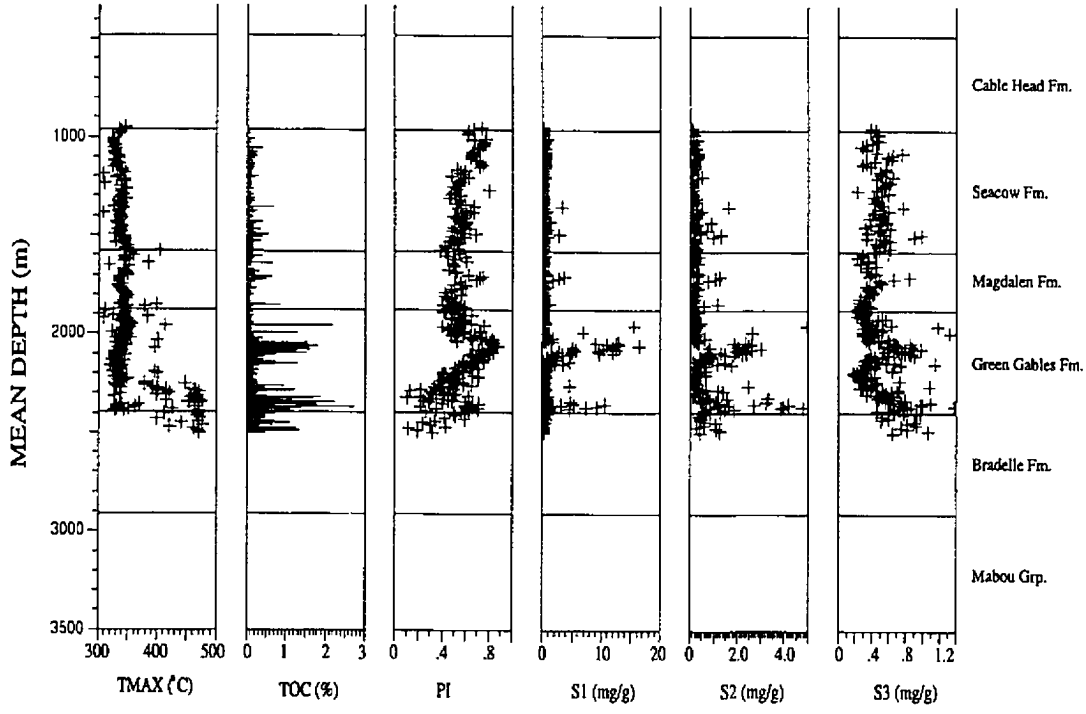



Figure 5.4 Rock-Eval pyrolysis data and stratigraphic framework for Cable Head E-95 (top) and East Point E-49 (bottom) wells (Fig. 2.3). (see Table 5.3 for data definitions)

been identified in the Bird Rock Formation, which is considered to be another potential hydrocarbon source rock interval in the CMB based on Rock-Eval and lithologic data. This interval, however, was sampled at only two well locations (Bradelle L-49 and St. Paul P-91).

A traditional van Krevelen diagram (Fig. 5.5) shows atomic O/C versus atomic H/C and indicates the types of organic matter and level of thermal maturation (Brooks *et al.*, 1987). Rock-Eval derived OI versus HI plots have been shown to correlate closely with van Krevelen plots (Tissot and Welte, 1984). Pseudo-van Krevelen crossplots of hydrogen index (HI) and oxygen index (OI) were constructed for each of the study wells that had Rock-Eval data (APPENDIX V). Anomalous data were filtered from the large datasets using the BasinMod REESA (Rock Eval Expert System Analysis) program which is designed to help interpret large quantities of Rock-Eval pyrolysis and TOC data (APPENDIX V). Overall, the predominant kerogen type in all the examined wells appears to be Type III (vitrinite) which suggests that generated hydrocarbons are likely to be gas (Tissot and Welte, 1984). This observation is consistent with onshore investigations of Upper Carboniferous organic matter (Gibling and Kalkreuth, 1991; Crawford, T., 1996, pers. comm.). The Bradelle L-49 and St. Paul P-91 wells (Figs. V.2, V.7) show some indications of Type II material which may indicate local oil prone source rocks. HI values are typically less than 200 mg hydrocarbons/g TOC, and the apparent thermal maturity for the majority of samples is well within the gas generation zone (Fig. 5.4).

Closer examination of the organic-rich Bird Rock Formation intervals (Fig. 5.6) suggests a predominance of Type III (vitrinite) and Type III/I (vitrinite/liptinite) kerogens with hydrogen index values typically less than 200 mg hydrocarbons/g TOC. The clustering of samples near the Type III domain indicates that the organic matter within the Bird Rock Formation is composed predominantly of terrestrial plant material, implying a gas prone source rock (Tissot and Welte, 1984).

Focusing on the Green Gables Formation (Fig. 5.7), HI values are typically less than 300 mg hydrocarbons/g TOC with the majority of samples clustering near the 100

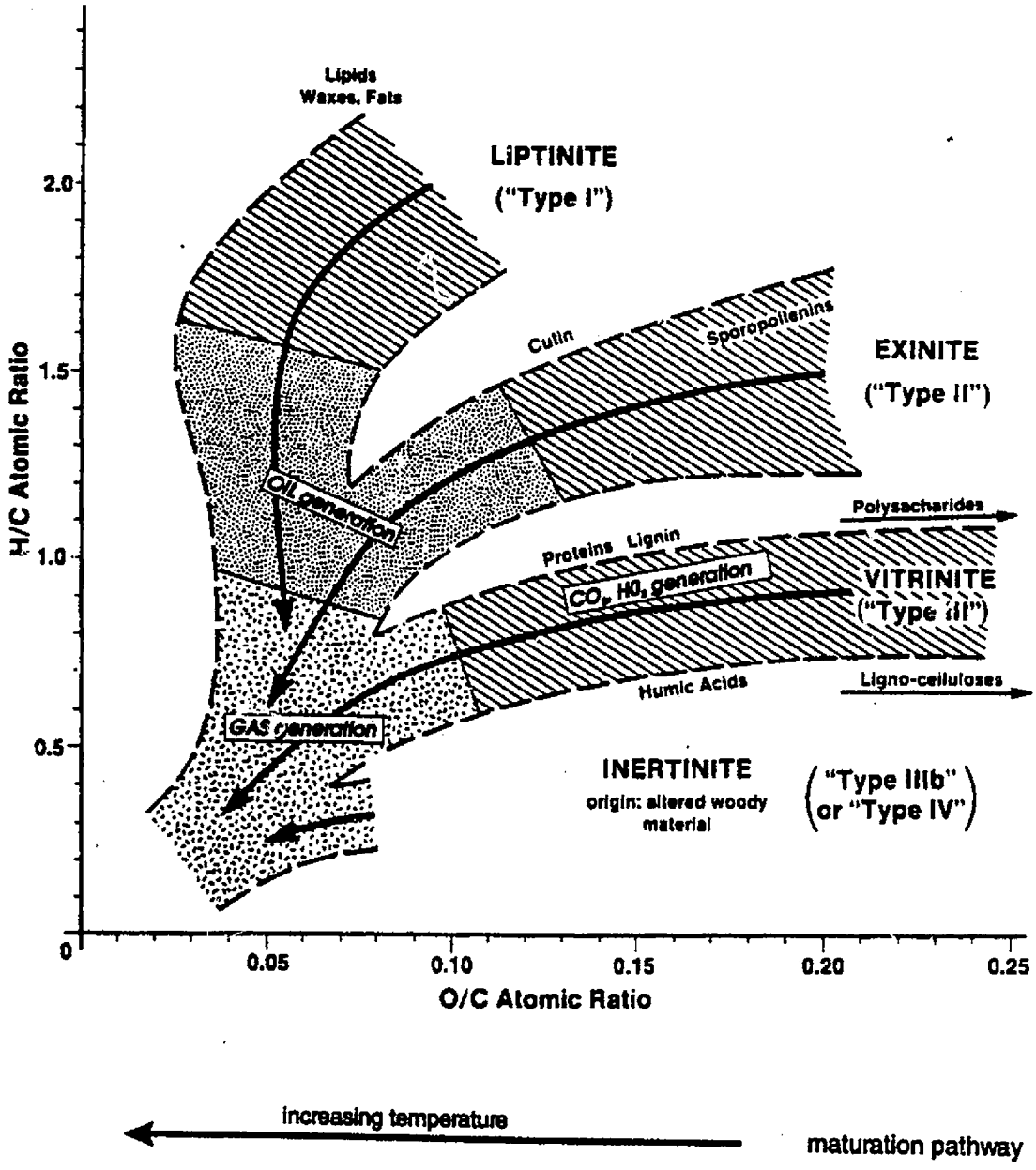



Figure 5.5 van Krevelen diagram showing kerogen-type, composition and organic maturation relationships (from Bateman. 1995; modified from Brooks et al., 1987).

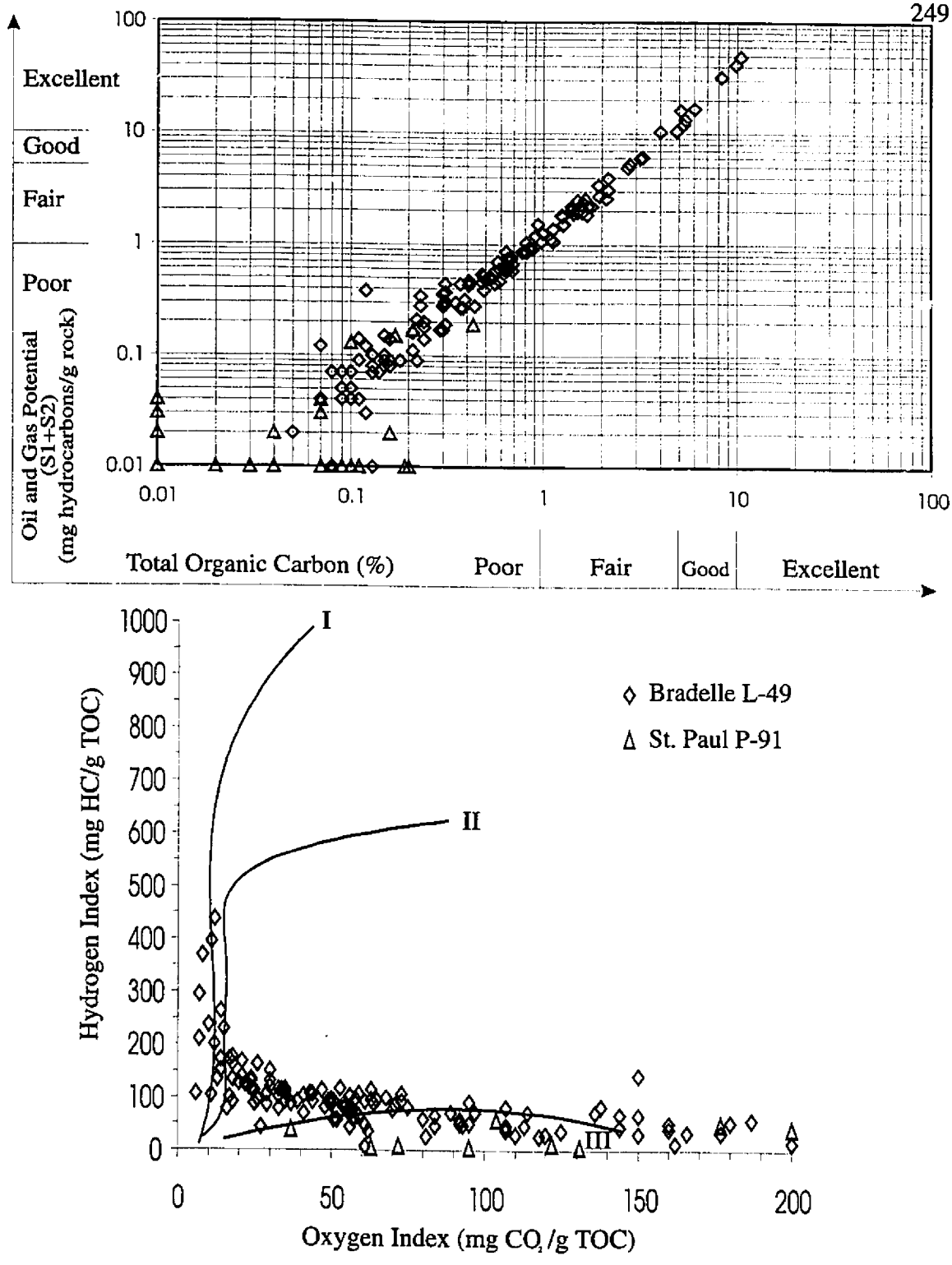



Figure 5.6 (Top) Oil and gas potentials of samples from the Bird Rock Formation in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from the Bird Rock Formation. Analysis based on 165 samples from the Bradelle L-49 (132 samples) and St. Paul P-91 (33 samples) wells (Fig. 2.3).

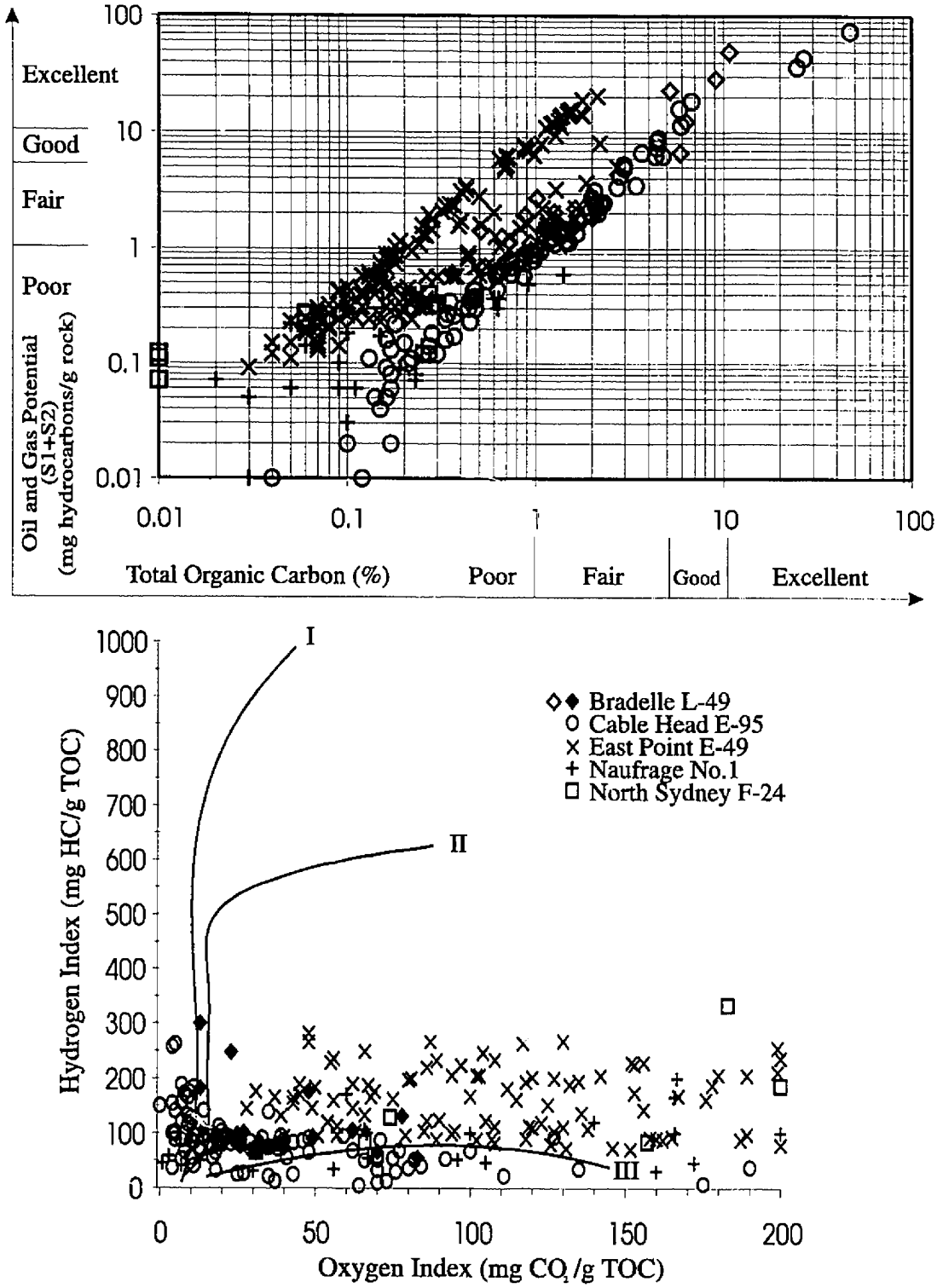



Figure 5.7 (Top) Oil and gas potentials of samples from the Green Gables Formation in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from the Green Gables Formation. Analysis based on 341 samples from the Bradelle L-49 (28 samples), Cable Head E-95 (95 samples), East Point E-49 (165 samples), Naufrage No. 1 (43 samples), and North Sydney F-24 (10 samples) wells (Fig. 2.3).

mg hydrocarbons/g TOC mark. The majority of samples plot near the Type III kerogen domain; however, there are some samples that plot near the Type I/II domain. Similar to the Bird Rock Formation samples, samples from the Green Gables Formation indicate significant terrestrial plant content, suggesting a gas prone source rock.

Crossplots of TOC (wt%) versus total hydrocarbon generation potential (S1+S2), or genetic potential, were constructed for each of the examined CMB wells (APPENDIX V) to indicate the organic-richness of the basin fill in relation to ultimate oil and gas potential. In general, the plots display a linear trend of increasing genetic potential with increasing TOC. The total hydrocarbon generation potential ranges between poor and excellent in samples that are organic-poor (<0.1 % TOC) to organic-rich (>10% TOC), respectively. Although it appears that the majority of samples are clustered in the poor domain, there is a significant number of samples that plot within the fair to good domain with some samples plotting in the excellent domain (Bradelle L-49 and Cable Head E-95, Figs. V.2, V.3). The samples for the Naufrage No.1 and St. Paul P-91 wells (Figs. V.5, V.7) display a wide scatter which probably reflects widely spaced sample intervals. The samples for East Point E-49 seem to plot in two linear trends (Fig. V.4); the upper trend coincides with Green Gables Formation and older strata whereas the lower trend is associated with Magdalen Formation and younger strata. The two trends probably reflect the change from a predominantly grey-bed associated succession (Green Gables Formation) to an increasingly red-bed dominated succession (Magdalen Formation), which suggests a generally lower total hydrocarbon generation potential for the red-bed dominated succession.

The Bird Rock Formation intervals examined (Fig. 5.6) indicate that the genetic potential of the Bradelle L-49 well samples ranges from poor to excellent, whereas all the St. Paul P-91 samples plot within the poor domain. As mentioned above, this could simply reflect the widely spaced sample intervals for the St. Paul P-91 location (33 samples/314 metre interval). TOC values for Bradelle L-49 samples range between poor and excellent, with a significant number of samples plotting above 1% TOC (Fig 5.6).

A similar plot for the organic-rich Green Gables Formation shows two linear

trends of increasing genetic potential and increasing TOC (Fig. 5.7). The upper trend is derived from the Green Gables Formation in East Point E-49, whereas the lower trend is the result of the remainder of the examined wells. The vertical shift in trends indicates a slight increase in total hydrocarbon generation potential for the source rock interval in East Point E-49, however, the TOC contents do not appear to be higher than in other wells. This variation could reflect different maceral contents of the source interval as was suggested by Gibling and Kalkreuth (1991) for a similar shift in genetic potential in samples of similar TOC values. Some samples of the Green Gables Formation in the Bradelle L-49 and Cable Head E-95 wells plot within the excellent source rock quality domain. TOC values vary between poor and excellent with a significant number plotting above 1% TOC (Fig 5.7).

In accord with previous onshore investigations (Fig. 5.3 vs. Figs. 5.6, 5.7), the Bird Rock and Green Gables formations in the CMB contain indications of similar quality hydrocarbon source rocks. Assuming sufficient quantities and adequate thermal conditions, these intervals could represent good to very good source rocks. In addition, the recognition of agglutinated foraminifera within sections of the Late Carboniferous basin fill suggests some deposition in restricted-marine conditions (Wightman *et al.*, 1994a). Such conditions may have resulted in the local accumulations of Type II (oil prone) organic matter (Tissot and Welte, 1984) enhancing the possibility of both liquid and gaseous hydrocarbon generation in the CMB.

It is recognized that the Bird Rock and Green Gables formations contain numerous coal seams and stringers that could result in anomalous Rock-Eval results leading to a biased source rock interpretation (cf. Peters, 1986). However, it is not within the scope of this study to conduct a detailed, metre scale source rock geochemical study but to demonstrate potential zones in the CMB fill that could contain hydrocarbon source rocks. Ideally, this approach, similar to that of McAlpine (1990), would be followed up by a detailed investigation of the source intervals, much like the study by Bateman (1995), who hand picked source material from ditch cuttings for Rock-Eval pyrolysis or a quantitative log analysis study similar to that of Huang and Williamson (1996).

### 5.2.2 Reservoir Rocks

Potential reservoir rocks in the Tournaisian to Late Namurian early basin fill in the CMB are basically untested with only five wells penetrating the Windsor Group into the underlying Horton Group. These wells had typically low (<10%) porosities and permeabilities. Onshore, however, the Horton Group displays good reservoir potential with porosity and permeabilities of outcrop samples reaching as high as 39% and 505 millidarcys, respectively (Hamblin, A., 1996, pers. comm). In the subsurface, sandstones from the Stoney Creek oil and gas field (Fig. 5.1) have measured porosities as high as 25% with permeabilities of 102 millidarcys (Soquip, 1987). Onshore reservoir potential within the overlying Windsor Group was demonstrated in 1987 by a natural gas blowout at the Alton 87-1 well (Fig 5.1), which remained uncontrollable for a period of six days (MacDonald, 1989). The onshore Windsor Group shows signs of both primary and secondary porosity with values locally exceeding 22% (Soquip, 1987). Offshore, in the Hillsborough No.1 well (Fig. 2.3), siliciclastics in upper Windsor Group strata display porosities of 11.6% and permeabilities of 300 millidarcys (West, 1946). Based on available subsurface data and the stratigraphic analysis, described in Chapter 2, the Mabou Group sandstones have low porosity and permeability values that both contribute to poor reservoir potential.

The post Namurian-Westphalian event strata offshore contain four predominantly coarse-grained siliciclastic successions, each corresponding to a forestepping systems set, all of which may contain potential reservoir rocks (Chapter 3). Besides the basic lithological data contained in the well history reports, little has been done regarding the detailed sedimentologic and diagenetic evolution of potential reservoir rocks within the CMB.

Porosities of the coarse-grained successions, as described in Chapter 2, typically range between 5 and 10% with well logs suggesting locally developed porosities of up to 15%. Commercially economic siliciclastic reservoirs typically have average porosities between 15 and 25% (Masters, 1979). Data from sonic logs and core for several locations indicate a direct relationship between depth of burial and reduction of porosity (Soquip,

1987). Figure 5.8 shows good porosity development above the 2000m level but below this level porosities are reduced (<10%). This trend implies that the Horton, Windsor, and Mabou groups, which typically lie deeper than the Cumberland and Pictou groups, would have extremely low porosity development. However, in light of the limited amount of well data available for deeper successions in the CMB and the lack of detailed reservoir analysis it is unwise to dismiss the Horton and Windsor groups as potential reservoirs.

The coarse clastics within the forestepping systems sets represent the most probable reservoirs in the Late Carboniferous CMB fill. The upper portions of each FSS typically consist of amalgamated sandbodies which suggests enhanced connectivity of reservoir sands (cf. Larue *et al.*, 1995). In addition, the development of thicker, more massive, sandstone bodies near the top of the FSSs suggests potential reworking, or cleaning, of sands (cf. Melvin, 1993), which would result in better reservoir development. As well, the cleaner sands near the top of the systems tract would be subject to less compaction, as compared to shalier sandstones, and would therefore, retain more primary porosity (Allen and Allen, 1990). Finally, the regionally extensive, multi-storied, FSS sandstones represent widespread reservoir distribution, a characteristic common in giant and super giant fields (eg. Morse, 1994).

The redbed dominated Pictou Group (Cable Head and Naufrage formations) has porosity and permeability values that tend to be low, however the well history reports for the offshore Sydney subbasin wells (Fig. 5.1) suggest the presence of fractures that would greatly enhance the prospectivity of Pictou Group sandstones in the CMB. Dismissal of the Pictou Group as potential reservoirs based on its redbed characteristic is also unwarranted, as comparable Carboniferous redbed successions in the United Kingdom (UK) have well developed reservoir characteristics. The UK redbeds have diagenetically derived, secondary porosity and permeability development as a result of Carboniferous-Permian uplift and erosion (Wang, 1992). For example, Besly *et al.* (1993) proposed the Westphalian C 'Barren Red Bed' petroleum play that draws on late diagenetically induced porosity and permeability for reservoir development. In light of these examples, the

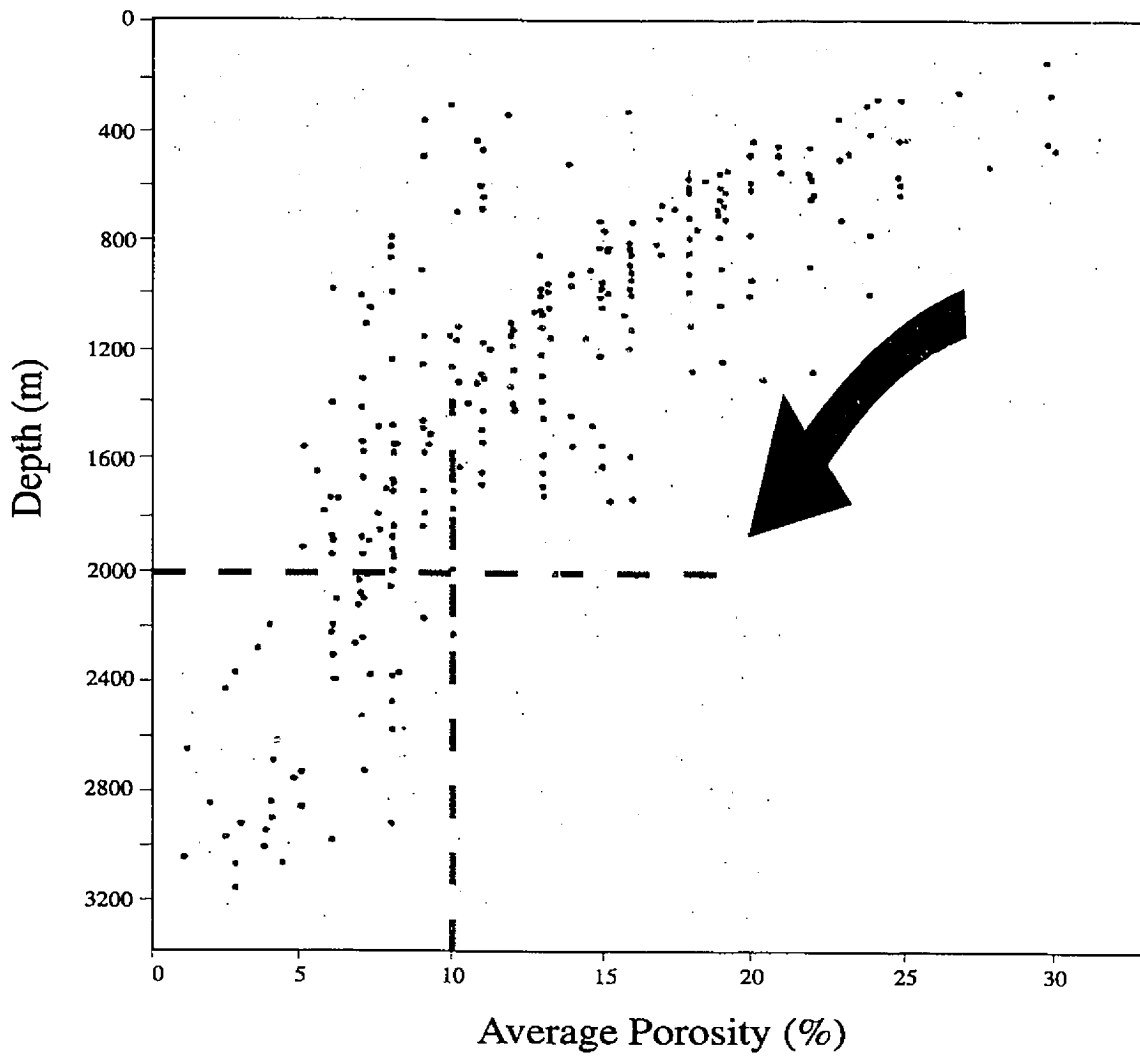



Figure 5.8 Average porosity vs. depth for post Namurian-Westphalian event strata (F-B Sequences 1 to 4) in the CMB (from Soquip, 1987). Porosity is derived from sonic logs and core analyses obtained from Bradelle L-49, Irishtown No.1, Green Gables No.1, Tyrone No.1, East Point E-49, Brion Island No.1 and North Sydney P-05 well locations.

Pictou Group sandstones could have some, as yet unrecognized, reservoir potential; the redbed dominated, early Permian Rotliegend reservoir in the North Sea, sourced from underlying Carboniferous Coal Measures, contains an estimated 145 trillion cubic feet of gas (Tcf) (Glennie, 1984).

The isolated sandbodies in the backstepping systems sets (BSSs) represent smaller, less interconnected, potential reservoirs. The floodplain-lacustrine nature of the sandstones suggests that reservoir development was related to lacustrine deltaic and associated channel processes. Both of which are traditionally good reservoir targets (Morse, 1994). Larger paleovalley fills within the BSSs, as described onshore by Gibling and Bird (1994), have good reservoir characteristics and represent potential reservoir intervals. These reservoirs however, are unresolveable using the current seismic database.

#### 5.2.2.1 Indications of Charged Reservoirs

A problem in assessing hydrocarbon charge in the CMB is that the primary objective during the early exploration activity was oil and not natural gas. As a result, indications of gas could have gone largely unnoticed due, for example, to overpressured muds and lack of drill stem testing. Even so, a compilation of mudlogs for several CMB wells (Fig. 5.9) shows the liberation of gas from the drilling mud and can be interpreted as signs of gas being expelled from subsurface stratum (Grant and Moir, 1992).

A drill stem test (DST) in Green Gables No.1 showed a strong air blow with a high methane content from a Brion Island Formation reservoir (Hudsons Bay Oil and Gas Co. Ltd., 1973). This favourable test has recently resulted in a proposed reentry of the well by a petroleum company with the main objective being natural gas. A generally higher quartz content and favourable porosities suggest that the Brion Island Formation sandstones have the best reservoir potential in the Late Carboniferous CMB fill. Age equivalent Morrowan sandstones, above the Mississippian-Pennsylvanian unconformity in the eastern United States, are prolific gas and oil reservoirs.

Numerous indications of prospective reservoirs and hydrocarbon charge have

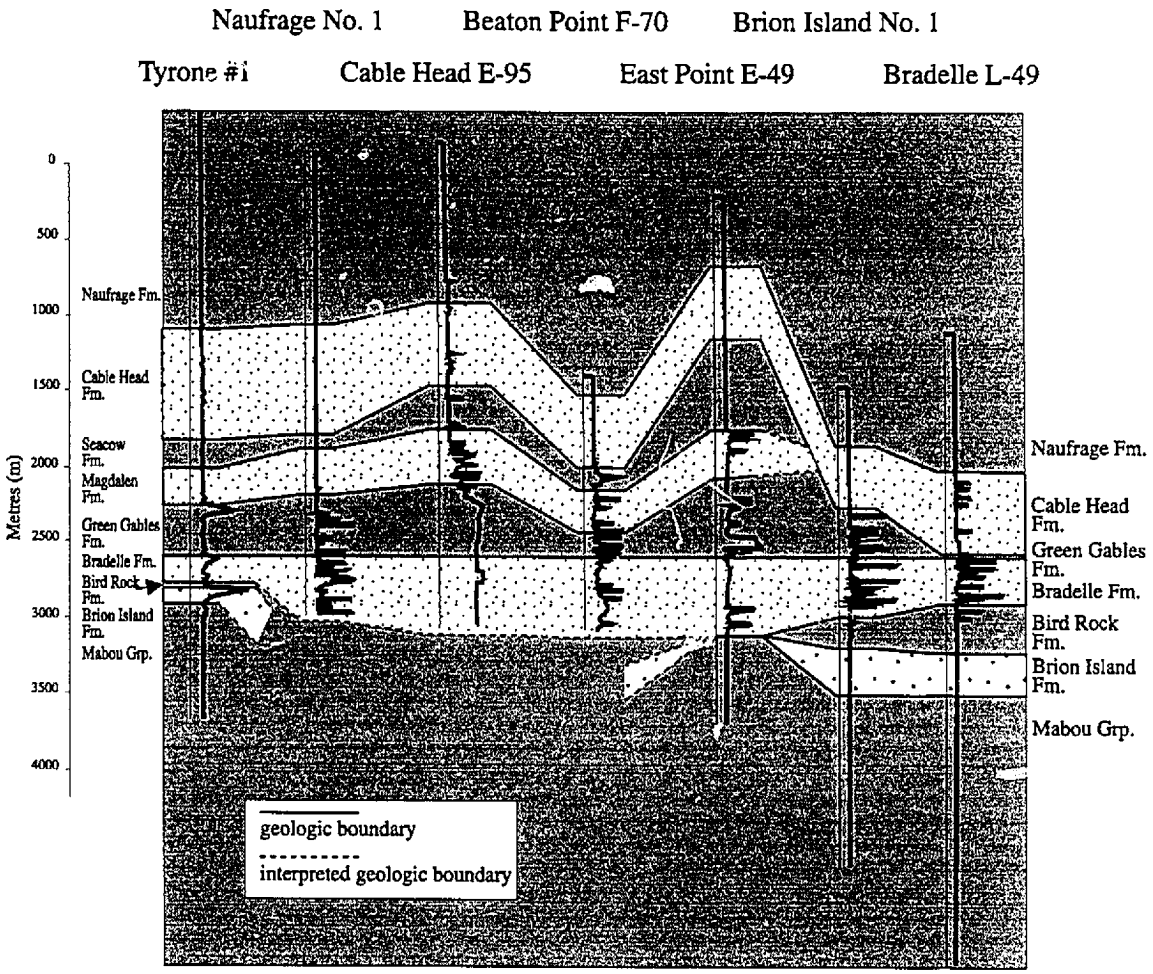



Figure 5.9 Gas kicks recorded in 7 CMB wells (Fig. 5.1), as indicated on mud logs, are superimposed on the stratigraphic framework developed in Chapter 2 (modified from Grant and Moir,1992). Datum is the top of the Bradelle Formation.

been displayed by Bradelle Formation sandstones. The relatively large number of indications may only be due to the fact that this succession has been penetrated more frequently than the underlying Brion Island Formation, or perhaps that the formation is closely associated with the CMB Coal Measures. Grant and Moir (1992) proposed that the Coal Measures seismic facies, coincident with the Bradelle and Green Gables formations, present potential coal bed methane targets with conservative estimates of a 70 Tcf methane resource for the CMB and a 7.6 Tcf methane resource for the area underlying Prince Edward Island. As for more traditional hydrocarbon shows, both North Sydney wells (Fig 5.1) displayed questionable to spotty oil staining within the Bradelle Formation. A core cut from the top of the Bradelle Formation in North Sydney F-24 (1100-1119m) exhibited a strong gas odour, and the gas that bubbled from throughout the interval ignited when lit (Shell Canada Resources, 1976). The Naufrage No.1 well (Fig. 5.1) penetrated 40m (2834-2874m) of gas saturated sandstones with traces of bitumen staining (Soquip *et al.*, 1975a). At the time, six DSTs were unable to flow gas from the reservoir (Soquip *et al.*, 1975a); technological advances in reservoir enhancement over the last 20 years might have succeeded in liberating gas from the sandstones. Northwest of the Naufrage No.1 location, mudlogs showed gas saturated mud below the 2400m level in the Cable Head E-95 well (Figures 5.1, 5.9). The well report does not mention gas shows and no DSTs were performed, however, the rig crew were "convinced" they had hit gas in the lower part of the well (Anger, C., 1995, pers. comm.). Adequate porosity and permeability are demonstrated by DST #1 (1470-1505m) in the Brion Island No.1 well (Fig. 5.1), where 1280m of salt water was recovered from oil stained sandstones of the Bradelle Formation (Sarep Ltd., 1971). McCamis (1973) referred to the Bradelle Formation at this location as one of the best potential reservoirs in the southern Gulf of St. Lawrence.

The Magdalen Formation represents the only proven gas reservoir in the CMB (Fig. 5.1). At the East Point E-49 well location, a DST over a 12m interval of sandstone in the upper part of the formation produced 5.3 MMcf/day (million cubic feet per day) of gas with an associated 480 BWPD (barrels of water per day). The absolute open flow

rate was 8.0 MMcf/d (Hudsons Bay Oil and Gas Co. Limited, 1974) and gas in place is estimated to be 77.3 Bcf (billion cubic feet). Assuming a recovery factor of 80%, recoverable reserves are estimated to be 61.8 Bcf (Agulera, R., 1977, pers. comm.). The East Point gas show was classified as an uneconomic gas discovery due to the offshore nature of the East Point structure.

### 5.2.3 Sealing Rocks

Sealing rocks are typically associated with evaporitic or shale prone intervals that form relatively impermeable barriers to hydrocarbon migration (Allen and Allen, 1990). The evaporitic nature of the Windsor Group succession represents the most favourable seal rock in the CMB, the impermeable nature of which was indirectly demonstrated by the accumulation of gas at the Alton 87-1 well location (Fig 5.1) (MacDonald, 1989) and directly observed in upper Windsor Group strata at the Hillsborough No.1 well location (West, 1946).

The CMB has an abundance of shale-rich intervals located both in the finer grained successions (BSSs) and coarse-grained successions (FSSs). Although typically less dependable than an evaporitic seal, the CMB upper Carboniferous shales have proven seal characteristics as was indicated above by the numerous signs of hydrocarbon charge, and demonstrated by the East Point E-49 gas deposit which is capped by overlying Seacow Formation shales.

### 5.2.4 Overburden Rocks

The overburden rock element in a typical petroleum system is commonly overlooked with only the source, seal and reservoir elements receiving attention. Magoon and Dow (1994) proposed that overburden rocks are critical for the thermal maturation of organic matter within the basin fill. As well, they suggested that overburden rocks have an impact on the development of underlying hydrocarbon migration pathways to the eventual trap.

The overburden rock element is composed of all strata above the main source, seal

and reservoir elements (Deming, 1994). In the CMB this would broadly include, based on the current indicators, all strata lying above the Westphalian-Stephanian hiatus (i.e., Pictou Group). The overburden rock would include also the strata that may have previously existed and were removed subsequently by the post-Permian event. Further discussion on the CMB overburden rock element is found in a following section on thermal history.

### 5.2.5 Potential CMB Plays: Trapping Mechanisms

Several possible trapping mechanisms exist in the CMB that utilize different combinations of source, seal and reservoir elements, six of which are described below. The plausibility of each hydrocarbon trap depends on the presence of a mature source rock that has generated hydrocarbons, reservoir rocks that have adequate porosities and permeabilities to store hydrocarbons, and a seal, or set of seals, to keep the hydrocarbons from migrating out of the trap. The CMB traps can be broadly classified as structural, stratigraphic, or a combination of the two.

**CMB Play Type 1:** Subsalt (Fig. 5.10, A) (APPENDIX VI)

The geometry of the trap is related to the Tournaisian structural development of numerous Horton Group half graben subbasins, identified on and offshore (Durling and Marillier, 1993b; Hamblin and Rust, 1989), which were subsequently covered by the Visean Windsor Group. This play utilizes the well known Horton Group source and reservoir rocks with an associated Windsor Group evaporitic seal.

**CMB Play Type 2:** Diapiric (Fig. 5.10, B; Fig. 2.18)

The most common type of structure in the CMB is inherently associated with Windsor Group salt movement. Post depositional salt flowage has formed pillows, diapirs, salt walls and complete piercement structures. As mentioned previously, most of the wells in the CMB were drilled on some type of salt structure, as a result, the majority of large structures have been tested. However, the wells were drilled typically at the apex

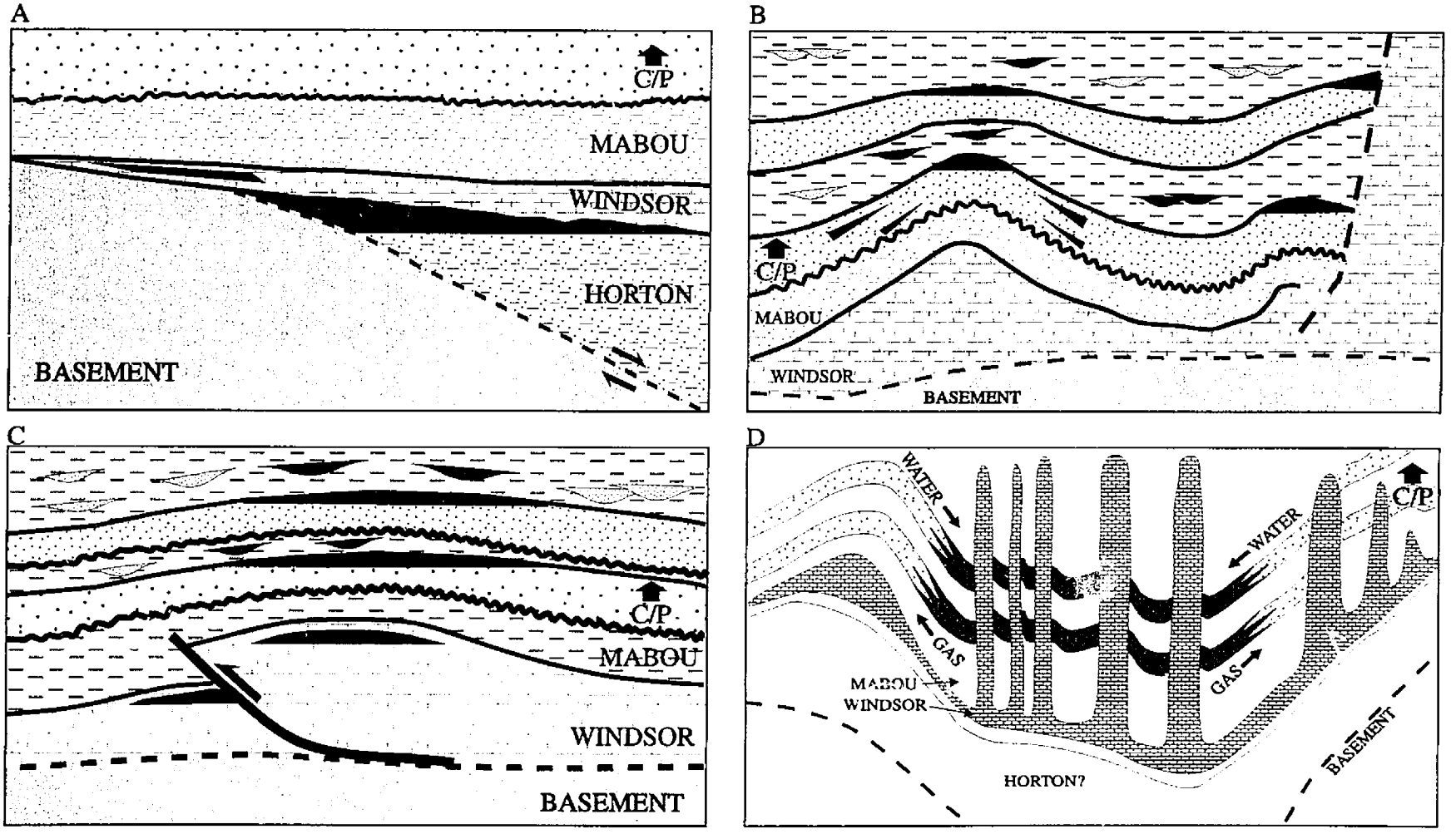



Figure 5.10 Conceptual hydrocarbon play types in the CMB: A) Subsalt and Depostional Pinchout, B) Diapiric (pillows and piercement) with minor facies change plays and paleovalley fills, C) Faulted, D) Basin-Centre Gas concept shown on a cross-section through the basin depocentre, horizontal distance exceeds 120km and vertical depth exceeds 8km. The dark grey area in D represents gas saturated reservoirs (cross-section modified from Bell and Howie, 1990). C/P = Cumberland and Pictou Group strata.

of the structures and a variety of structural and stratigraphic traps overlying and flanking the salt remain untested. In addition, there is one known success (East Point E-49), but most of the wells were drilled for oil and could have missed gas pay. The play utilizes source rocks from above and below the tectonized salt, all the post-Windsor reservoirs, and impermeable shales for seals.

**CMB Play Type 3:** Faulted (Fig. 5.10, C) (APPENDIX VI)

These structural traps are closely associated with locally faulted Windsor Group successions. The fault soles out into the base of Windsor Group and is assumed to be the result of compressional stresses and minor salt tectonism. The fault play utilizes source rocks in the Horton Group and Windsor Group, reservoirs within the Windsor Group and the Windsor Group and associated fault as seals. In addition, the play involves post-Windsor Group strata above the structure in a fault drape anticline. The post-Windsor Group play utilizes all potential source rocks in the CMB stratigraphic column, reservoirs within the Brion Island and Bradelle formations and impermeable seals within the Bird Rock and Green Gables formations.

**CMB Play Type 4:** Basin-Centred Gas (Fig. 5.10, D)

This conceptual play is located in the bottom of the basin (depocentre) and utilizes sandstone reservoirs that have porosities of typically less than 15% and permeabilities less than 0.5 millidarcys (cf. Masters, 1979). The basin-centred gas (BCG) play is technically a stratigraphic trap which has proven to be a successful play in such areas as the Denver and Western Canadian Sedimentary basins (Rose *et al.*, 1986).

The mechanics behind the play are somewhat unclear but Masters (1979) suggested that as downdip reservoir rocks become less porous and permeable than the water saturated rocks on the basin flank, a critical point is reached when the pore size becomes so restricted that gas is trapped. The trap occurs at the gas-water interface where the high water saturation of the low permeable rock reduces gas permeability to near zero, resulting in a "water block" which is further enhanced with a strong hydrostatic or

hydrodynamic head of the updip water column (Masters, 1979).

Play characteristics vary between basin-centred gas (BCG) deposits but a few general criteria have been outlined by Rose *et al.* (1986);

a) BCG reservoirs on the flanks are saturated with fresh to brackish water and porosity/permeability decrease towards the basin centre.

b) BCG reservoirs are associated with argillaceous petroleum source rocks and/or coal beds that are thermally mature.

c) BCG accumulations occur at a variety of depths and subsurface elevations.

d) Subsurface temperatures in the gas saturated zone range between 65°C and 171°C.

e) BCG deposits generally reflect the current distribution of thermally mature source rocks, occurrences of commercial reservoir conditions and tend to be basinward of the meteoric water influence.

The CMB has several characteristics that may indicate BCG deposits;

a) Reservoirs within the post-Mabou strata display porosities that are adequate on the basin flanks but decrease with increasing depth (Fig. 5.8).

b) Well history reports and petrophysical logs suggest that potential reservoir sandstones in Brion Island No. 1, East Point E-49, East Point E-47 wells typically have high water saturations.

c) Evidence of hydrocarbon charge at several well locations suggests thermal maturation of organic matter in the basin.

**CMB Play Type 5:** Stratigraphic (Fig. 5.10, A, B)

The CMB has several limited possibilities for stratigraphic plays; depositional pinchouts and facies changes. The depositional pinchout play occurs on the flanks of the basin and is associated with the successive onlapping of younger stratigraphic successions. This conceptual play utilizes any source rocks from below the potential reservoir; reservoirs occur within the Windsor, Brion Island, Bradelle successions and closure is associated with onlapping finer grained CMB successions. Closure of the trap would rely on regional dip of the system.

The traps associated with facies changes result from the juxtaposition of reservoir and lateral seal. The thick regionally extensive, multi-stacked, coarse-grained FSSs likely lack effective lateral seals unless associated with post depositional Windsor Group salt flowage that may have affected the depositional patterns of the overlying successions, focussing the fluvial systems away from rising salt structures. If this occurred, it is possible that fine-grained lateral seals for the FSSs may occur in proximity to the flanks of the salt structures. The facies change play utilizes source rocks from below the potential reservoir; reservoirs occur in the Brion Island, Bradelle and Magdalen formations; seals are impermeable shales.

**CMB Play Type 6:** Unconformity (Fig. 5.10, B, C)

The presence of both regionally and locally extensive surfaces of discontinuity within the CMB would imply the presence of numerous trapping possibilities below and above the surfaces (Allen and Allen, 1990). However, the regional surfaces associated with the Namurian-Westphalian, Mid-Westphalian and the Westphalian-Stephanian events typically have coarse-grained successions overlying the hiatuses, thus removing the likelihood of a top seal for any potentially underlying reservoir units. On a more local scale, the paleovalley fills discussed by Gibling and Bird (1994) are typically enclosed in impermeable floodplain deposits and represent excellent possibilities for hydrocarbon accumulations.

## 5.3 CMB Timing of Hydrocarbon Generation

The preceding sections demonstrate that the CMB contains the source, reservoir, seal, and overburden rock elements that are required for a viable petroleum system. In addition, trapping mechanisms have been recognized, and some porous zones have been charged with hydrocarbons. The final requirement for the accumulation of commercial quantities of oil and gas is the favourable interaction through time of the source, reservoir and seal systems in conjunction with the correct timing of trap formation relative to hydrocarbon generation/expulsion. The investigation of hydrocarbon charge timing with

respect to petroleum system elements and trapping mechanisms requires the integration of basin burial history profiles with the thermal history of the basin. The objective of this section is to construct an organic maturation framework which will outline the relative timing of hydrocarbon generation with respect to the development of petroleum system elements and processes.

### 5.3.1 Maturation Modelling

The hydrocarbon charge of a sedimentary basin depends upon its maturation, expulsion and migration history, of which maturation history, or hydrocarbon generation, is the most critical component in the petroleum system (Waples *et al.*, 1992). The relative timing of organic matter maturation and the subsequent generation of hydrocarbons is reconstructed by maturation modelling, or charge modelling, techniques. The development of a hydrocarbon generation model requires the reconstruction of a basin's burial and thermal histories, collectively referred to as the time-temperature history, and the subsequent conversion of this history to a maturation model which outlines the generation of oil and gas through time.

The conversion of time-temperature histories to maturation histories can be achieved by two different approaches; the basic empirical modelling approach (Waples, 1980; Lopatin, 1971) and the theoretical, first order, kinetic approximation of individual or collective organic reactions (Tissot *et al.*, 1987; Tissot and Espaitalie, 1975)

Traditionally, the conversion of a time-temperature history to maturity values was empirically derived using methods originally introduced by Lopatin (1971) and further developed by Waples (1980). The approach, commonly referred to as the Lopatin approach, models single organic reactions using the principle that reaction rates during hydrocarbon generation double with every increase of $10^0$C with depth, and increase exponentially with time (Waples, 1980).

It is now recognized that the reaction rates during hydrocarbon generation and degradation double with every 3-$5^0$C rise in temperature and that the Lopatin method, which assumes that maturation is a continuous process with a temperature dependent rate,

generally overestimates thermal maturity (Tissot *et al.*, 1987). In contrast, the kinetic approach incorporates temperature restrictions that, if exceeded, inhibit additional maturation (Cercone and Pollack, 1991). As well, the type of organic matter contained within the source rock is known to influence the total amount of hydrocarbons generated and the depth of hydrocarbon generation (Welte *et al.*, 1988), a parameter not taken into consideration with the Lopatin method.

The chemical first order kinetic reactions outlined by Tissot and Espaitalie (1975) were developed to mathematically model kerogen degradation and hydrocarbon generation based on the first order decomposition reaction, $dx_i/dt = - k_i x_i$ , where $x_i$ is the residual petroleum potential of organic matter involved in reaction i and $k_i$ is the constant reaction rate parameter for temperature (Tissot *et al.*, 1987). The reaction rate parameter is dependent on the temperature as outlined in the Arrhenius equation, $k_i = A\exp(-E_i/RT)$, where T is the absolute temperature, $E_i$ is the activation energy related to reaction i, R is the gas constant and A is the Arrhenius frequency factor related to reaction i (Allen and Allen, 1990). The activation energies and frequency factors used as input for the Arrhenius equation are taken directly from the type of kerogen in the source rock (Welte *et al.*, 1988). Therefore, unlike the empirical approach, the kinetic models are able to adjust for organic matter type and represent the kinetics of parallel and successive reactions of oil and gas formation, interrelating the effects of both time and temperature (Tissot *et al.*, 1987). The integration of first order decomposition reaction kinetics, the Arrhenius equation and computed time-temperature histories, allows for the quantitative calculation of thermal maturity of oil and gas generation as a function of the time and location within a basin (Tissot *et al.*, 1987).

Several commercial basin modelling software programs are available to assist with the reconstruction of burial and thermal histories and the subsequent conversion of these into organic maturation and hydrocarbon generation histories. As mentioned in Chapter 4, this study uses the 1-D version of BasinMod software developed by Platte River Associates (Denver, Colorado), on a UNIX workstation, to aid in the reconstruction of subsidence, compaction, thermal and maturation histories for case study areas of the

CMB. The BasinMod package uses a standard industry approach that is well documented (Williamson *et al.*, 1994; Waples *et al.*, 1992).

The reconstruction of burial, thermal and maturation histories requires the simplification of a very complex interaction between many different and dynamic basin system elements and processes. The key objective of this study is to reconstruct the burial and thermal histories of several case study areas that have (Table 5.2) and to convert these histories into maturation models using the first order reaction kinematic model developed by Lawrence Livermore National Laboratories (LLNL Easy $\%R_0$ model). As a calibration, model predictions of vitrinite reflectance are compared to present day thermal maturation values measured from the wells. The net result of the exercise is a relatively simple, non-unique model which honours the well data and which provides a basic framework for further and more comprehensive modelling.

**Assumptions**

In order to model burial, thermal and maturation histories, numerous assumptions have to be made, each of which is accompanied by different degrees of uncertainty. Standard assumptions used throughout the CMB modelling program are outlined in Table 5.4, with case specific assumptions detailed with each modelling scenario. The majority of burial history assumptions were outlined in Chapter 4 in the subsidence analysis section.

As mentioned in Chapter 4, the fundamental components of each CMB burial history are the age/depth pairs and interval lithologies, both of which are provided from the analysis of welldata (Table 5.4). Given the resolution of the CMB biostratigraphic data (see Chapter 2, for a full discussion), the placement of definitive age/depth pairs with lithologic formation boundaries is at times uncertain. However, the large thickness of basin fill (>10km), accumulated over a relatively short period of time (<25 Ma), is assumed to overwhelm any specific age/depth problems. In any case, all model calculations are computed at 2 million year time steps over 200 metre stratigraphic intervals; this approach is assumed to provide a broad definition of maturation and

Table 5.4 Summary of data and assumptions used in CMB basin modelling.

| | Source | Utility |
|---|---|---|
| Observational data:<br>Age/depth biostratigraphy | CMB biostratigraphic database (APPENDIX I) | Burial history computations |
| Lithology | Digital petrophysical logs<br>Canadian Stratigraphic Services Logs<br>Well history reports | Burial history computations, compaction corrections, thermal histories |
| Bottom hole temperatures | Well History Reports<br>Log Header information | Thermal history |
| Vitrinite reflectance ($\%R_{omax}$)<br>Thermal Alteration Index (TTI)<br>$T_{MAX}$ data ($^0C$) | GSC internal reports<br>Well History reports<br>unpublished Rock-Eval | Not used in calculations, only used to compare model predictions |
| Model Assumptions | | |
| Initial porosities | Sclater and Christie, 1980<br>Sand = 45%<br>Shale = 60%<br>Limestone = 60% | Porosity reduction and decompaction calculations |
| Decompaction porosities | Sclater and Christie, 1980<br>Sand = .27 1/km<br>Shale = .51 1/km<br>Limestone = .22 1/km | Decompaction calculations |
| Thermal Conductivity | Default Basmod values<br>Blackwell and Steele, 1989<br>claystone and siltstone 0.80 to 1.25<br>shales 1.05 to 1.45<br>sands 1.70 to 2.50<br>sandstone 2.50 to 4.20<br>quartzite 4.20 to 6.30<br>lithic sand 1.25 to 2.10<br>greywacke 2.70 to 3.35<br>coal < 0.5 | Thermal history calculations |
| Present Day Heat Flow | (Hyndman *et al.*, 1979; Reiter and Jessop, 1985) best estimate approximately 55 $mWm^{-2}$<br>(Reiter and Jessop, 1985)<br>New Brunswick Platform 64 $mWm^{-2}$<br>Cape Breton 63 $mWm^{-2}$<br>Naufrage 54 $mWm^{-2}$<br>Bradelle L-49 51 $mWm^{-2}$<br>East Point E-49 34(57) $mWm^{-2}$ | Thermal history calculations |
| Paleosurface temperatures<br>(Illinois Basin region) | Cluff and Byrnes, 1990<br>Devonian 27°C<br>Carboniferous 27°C<br>Permian 22°C<br>Jurassic/Triassic 22°C<br>Cenomanian 19°C<br>Santonian 24°C<br>Middle Eocene 24°C<br>Late Oligocene 20°C<br>Holocene/Pleistocene 0°C | Thermal history calculations |
| Lithology of removed overburden | Dunkard Group equivalent predominantly sandstones | Burial and thermal history calculations |

generation events well within the resolution of the biostratigraphic data.

The nature and magnitude of the Namurian-Westphalian, Mid-Westphalian and Westphalian-Stephanian events in the CMB are not well understood. The Namurian-Westphalian event represents a major change in basin character so it has been modelled as a hiatus from 317 to 315 Ma based on similarities to the Mississippian-Pennsylvanian unconformity in the eastern United States. No major changes in the present day maturation profiles across either the Mid-Westphalian or Westphalian-Stephanian events are apparent so it is assumed that these events had a negligible affect on the maturation of the present basin fill (cf. Cluff and Byrnes, 1990; Cercone and Pollack, 1991).

BasinMod calculates thermal histories using only vertical conduction methods assuming that all heat comes from sources below the strata being modelled. Heat transfer by fluid flow and convection are recognized to be important to the overall thermal history of the basin, however, the one dimensional analysis does not presently have the capability to handle the complexity of non-conductive heating. The next phase of CMB model development could include the use of 2-D BasinMod modelling software which does address some of these concerns.

The lithology of any succession of strata removed by the post-Permian unconformity is an unknown parameter. The characteristics of the postulated overburden rocks are important to subsidence and compaction calculations which are in turn important for thermal and maturation calculations. The lithology of any additional overburden used in the following burial and thermal models is assumed to be similar to the coarse-grained Dunkard Group redbed succession in the eastern United States based on observations outlined in Chapter 4 and APPENDIX IV. Similarly, surface paleotemperatures for the CMB were taken from Illinois Basin estimates, outlined by Cluff and Byrnes (1990), based on the broadly similar equatorial positions of each basin (Fig. 4.4).

#### 5.3.1.1 CMB Burial Histories

The CMB burial history reconstructions (Fig. 5.11) are primarily based on the

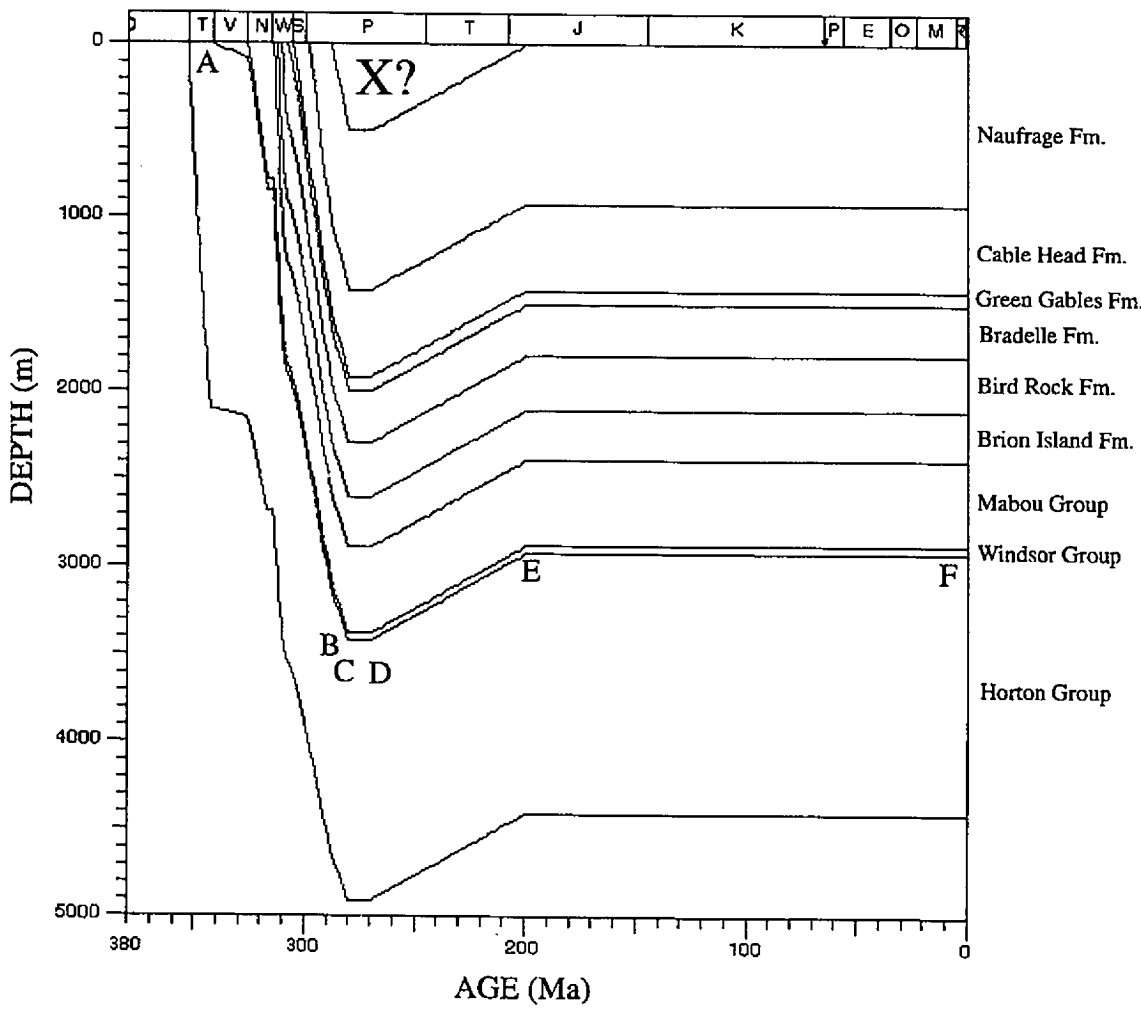



Figure 5.11 Standardized burial history curve for CMB wells based conceptually on previous Apatite Fission Track Analysis work by Ryan (1993), Hendricks et al. (1993) and Grist et al. (1995). (see text for discussion of letters along the burial path, A to F)

present basin fill which provides age/depth pairs and interval lithologies directly from the subsurface stratigraphic column (Fig. 5.11, A to B). Burial histories for the CMB wells were constructed for the subsidence analysis portion of Chapter 4 and were constrained by the age of the present day basin fill. Complicating the CMB stratigraphic history is the post-Permian unconformity which has removed an unknown amount of strata (Fig. 5.11, X). Onshore Nova Scotia, however, minor Mesozoic (Triassic, Jurassic and Cretaceous) strata unconformably overlie structurally tilted Carboniferous strata (Ryan, 1993). The presence of this relatively thin veneer of Mesozoic rocks, overlain by Quaternary deposits, constrains portions of the CMB burial history, but to develop a CMB maturation history all the events following deposition of the youngest strata preserved (Early Permian) until the present day must be constrained (Fig. 5.11, B to F). The events between the Early Permian and present day are somewhat speculative, however, several studies have applied modern reconstruction techniques to help constrain the post-burial and thermal histories of the CMB (cf. Grist *et al.*, 1995; Ryan, 1993).

The framework for CMB burial history plots is conceptually reconstructed from apatite fission track analysis (AFTA) data reported by Ryan *et al.*, (1990), Hendricks *et al.* (1993), Ryan (1993) and Grist *et al.* (1995). The AFTA results indicate that the Maritimes Basin received the majority of basin fill between 320 Ma and 290 Ma with maximum burial of the CMB fill occurring approximately at 280 Ma. Following maximum burial, the Maritimes Basin underwent rapid exhumation from 280 Ma to 190 Ma, slower exhumation from 190 Ma to 100 Ma, and even slower exhumation from 100 Ma to present (Ryan, 1993). Preliminary organic maturation model results (Rehill, 1993) suggest that the different stages of exhumation do not affect overall maturity values; as a result the CMB burial histories in this study are characterized by a single, relatively rapid, erosional event from 270 to 200Ma. It is further assumed that the CMB experienced no uplift or subsidence from 200Ma to the present day as post-Triassic events are assumed to have had little effect on the deposition and erosional history of the basin. The assumed single erosional event and post-Jurassic hiatus are analogous to the assumptions made by Cercone and Pollack (1991) for a Michigan Basin Late Paleozoic burial history model.

### 5.3.1.2 CMB Thermal History

#### 5.3.1.2.1 Source Rock Maturity

Vitrinite reflectance ($\%R_{omax}$) is a measure of optical reflectivity from a polished vitrinite coal maceral surface (Allen and Allen, 1990). $\%R_{omax}$ data are direct indicators of a basin's thermal history and are key to calibrating the generation and expulsion history of hydrocarbons. Several studies outline both the advantages and disadvantages of using $\%R_{omax}$ data (Allen and Allen, 1990; Tissot and Welte, 1984), however, it is the most broadly accepted and standardized method of quantifying organic maturation in sedimentary basins (Waples *et al.*, 1992; Waples, 1980).

A compilation of approximately 850 near surface vitrinite reflectance values for the Maritimes Basin is summarized in Figure 5.12 (Ryan, 1993). Values decrease towards the north-northwest with the highest values occurring around the southeast-south-southwest periphery of the present Maritimes Basin. Note that an onland zone of high $\%R_{omax}$ values extends from near the New Brunswick - Nova Scotia border east and northeast to the Sydney subbasin, and is coincident with the most tectonized region in the Maritimes Basin. The lowest values (approximately 0.5) suggest that the organic matter near surface has undergone some type of thermal heating (Dow, 1977).

Vertical subsurface profiles of vitrinite reflectance have been constructed for several CMB wells (Fig. 5.13). Assuming a constant present day geothermal gradient of $25^0$C/km (cf. Ryan *et al.*, 1990), a simple organic maturation profile can be reconstructed which reflects current basin thermal conditions. A comparison of CMB model predictions with present day thermal maturation values measured from the wells suggests that, similar to the near surface vitrinite values, the subsurface strata have undergone some type of additional heating since burial and deposition.

As demonstrated, near surface and subsurface vitrinite reflectance values are too high to be accounted for with present basin conditions, suggesting that thermal conditions within the basin have changed since deposition. The two primary variables in a basin's thermal history are the amount of removed overburden and paleo heat flow/geothermal gradients (Deming, 1994; Cercone and Pollack, 1991; Cluff and Byrnes, 1990).

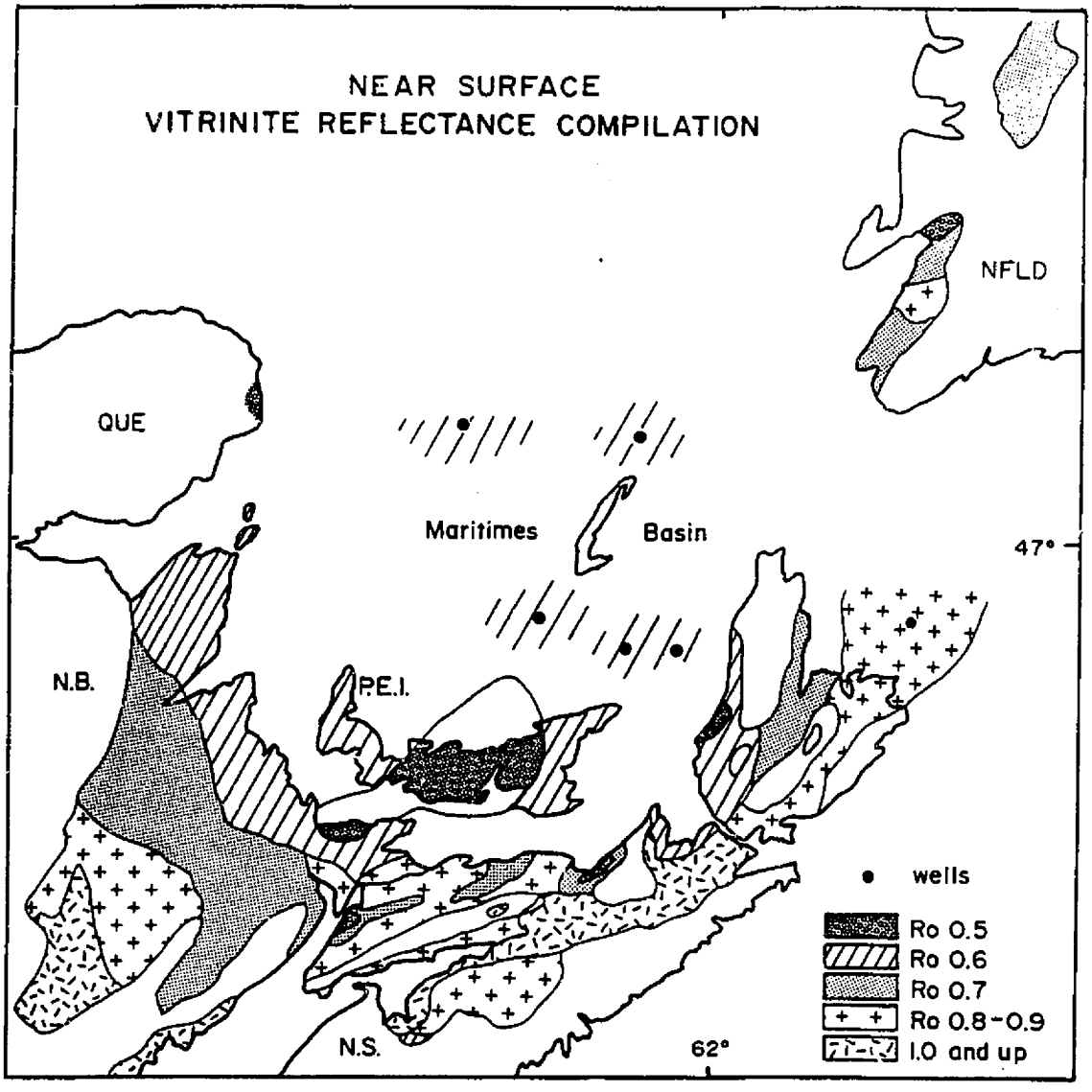



Figure 5.12 Near surface vitrinite reflectance (%Romax) values from throughout the Maritimes Basin (from Ryan, 1993).

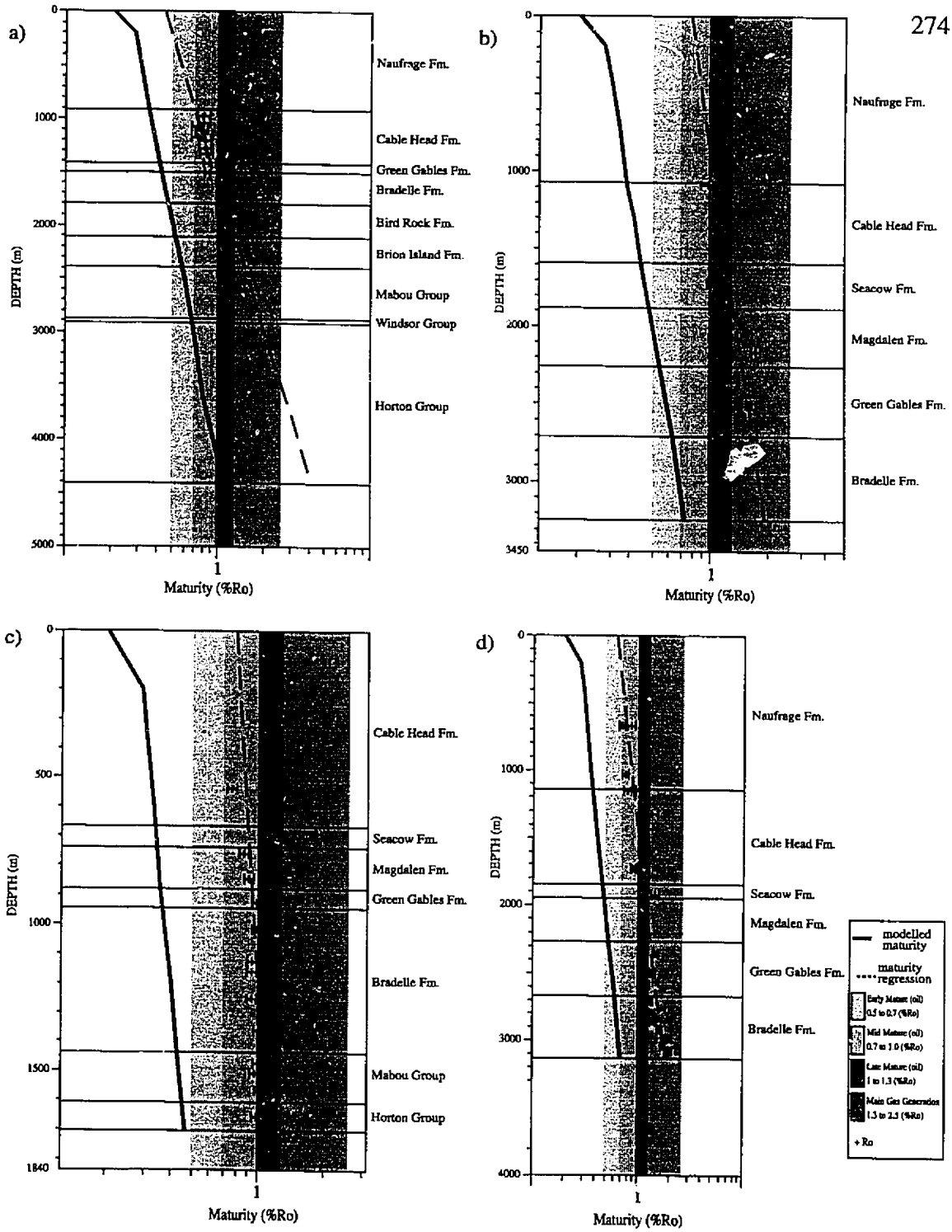



Figure. 5.13 Observed present day maturity values ( ⊢—⊣ ) for several wells in the CMB database. Each well profile consists of a regressed maturation curve (right), or best fit maturation gradient, for present day data and a modelled maturation profile (left) assuming present day geothermal gradients (25°C/km) and stratigraphic thicknesses. a) Bradell L-49 b) Cable Head E-95 c) North Sydney F-24 d) Naufrage No.1 (see Fig. 5.1 for locations).

Increased organic maturity can be caused by:

1) Deposition and subsequent removal of significant amounts of overburden rock.
2) Increased heat flow causing a basinal shift in isorank lines upsection.
3) A combination of the above two scenarios (increased heat flow and overburden removal).

Each of these different thermal options with respect to CMB evolution are examined for each study well location containing measured thermal maturity data in order to determine the impact on the timing of trapping mechanisms and the generation-expulsion of hydrocarbons.

In the following section, a preferred CMB burial, thermal, and maturation model is presented with a discussion of key variables. In succeeding sections, the sensitivity of timing events in the basin are examined with respect to some of these key assumptions.

#### 5.3.1.2.2 CMB Thermal Model

The preferred CMB thermal model generally follows the modelling methods of Williamson (1992) and uses steady-state thermal heating to reconstruct the thermal history of the CMB. The CMB burial history described above (Fig. 5.11) is used and compaction/decompaction calculations apply the methods proposed by Sclater and Christie (1980). The three main unknowns when reconstructing thermal histories using steady-state heat flow are the paleo heat flow, thermal conductivities of the basin fill, and, in the case of the CMB, the amount of missing overburden.

In models which incorporate steady-state heat flow it is essential to have estimates of basal heat flow and the thermal conductivity of the rocks in the sedimentary package (Williamson, 1992; Lerche, 1990). The heat flow model used in BasinMod software uses the direct relationship, $Q_z=K\ dT/dz$, where $Q_z$ is the vertical heat flow, K is the thermal conductivity, and dT/dz is the temperature gradient. The models calculate the heat flows of each time interval independently of the prior time interval (Gallagher and Sambridge, 1992; Allen and Allen, 1990).

Basal heat flow consists of a subcrustal component and the radiogenic component, of which subcrustal heat flow energy is the predominant energy source for the basin system (Ungerer *et al.*, 1990). The distribution and transfer of heat occurs by conduction and convection, but as mentioned previously, convection and non-vertical heat flow, although important, are not considered in the 1-D CMB models. Blackwell and Steele (1989) suggested, however, that it is the internal events such as intrusion and diapirism, radiogenic decay, large/small scale flow of fluids and both vertical and horizontal thermal conductivity that are responsible for the heating and generation of hydrocarbons. The heat flow of a basin is clearly complex, however, to keep the CMB models as simple as possible, the heat flow values used here represent the total of all heat sources at the surface. Regardless of the complexities, it is the conduction of heat which largely controls the variations in the geothermal gradients, which are in turn directly related to the thermal conductivity of the basin fill (Lerche, 1990).

Thermal conductivity values depend on both the porosity and lithology of the rock (Gallagher and Sambridge, 1992), which in turn are important in the reconstruction of burial histories. Typically, in most thermal modelling exercises there is not enough information available to measure the thermal conductivities for a sedimentary column (Blackwell and Steele, 1989; Lerche, 1990) and thermal conductivity values must be estimated from the literature. An inherent problem is that from locality to locality, thermal conductivity values vary, and it is debatable as to what values are representative of typical lithologies (Williamson, 1992).

The thermal conductivity of a basin is particularly sensitive to the effects of salt tectonism (Keen and Beaumont, 1990). Anhydrite and salt have very high thermal conductivity values and when associated with diapirs or piercement structures tend to funnel heat upward into the overlying sediments (Keen, 1983). However, the increased heat flow associated with the salt flowage does not appear to affect the generation or degradation of kerogen in the sediments overlying the salt structure; instead, hot fluids which migrate up the flanks of salt diapirs may affect the occurrence and accumulation of hydrocarbons (Keen, 1983).

Coals have the lowest matrix conductivity values of rocks in the basinal fill (Table 5.4) and may affect local and regional geothermal gradients. Thick coal packages increase the geothermal gradients resulting in a non-linear temperature vs. depth curve (Blackwell and Steele, 1989). In light of this, the CMB Coal Measures require special attention with regard to thermal conductivity value estimates.

Lithologic compositions for each CMB succession were initially assigned default thermal conductivity values from the BasinMod modelling package. The Cumberland Group within the CMB contains significant quantities of coal which will affect the overall thermal conductivity profile of the basin fill. The thermal conductivities (TC) for the basin fill were slightly adjusted from the BasinMod default values. The TC values were adjusted no more than 10% and were kept within the limits suggested by Blackwell and Steele (1989) for similar, Late Paleozoic rocks. It is assumed that the resulting TC profile (Pictou Group-relatively high, Cumberland Group-relatively low (coal bearing), Mabou Group-relatively medium, Windsor Group-relatively higher, and Horton Group-relatively high) for the CMB better reflects the lithologic contrasts of the CMB stratigraphic column.

**Scenario A: Increased Heat Flow and Additional Overburden Model**

The CMB thermal model (Scenario A) includes three major events that were probably associated with heating (Fig. 5.14); the event that initiated basin subsidence, a tectonic event identified by the subsidence analysis of present fill, and the Triassic rifting event that created the Fundy Basin and the Orpheus Graben on the southern margin of the Maritimes Basin. Heat flows for these events are estimated from modern analogues and the effect of varying the amounts of missing overburden is examined.

The first heating event assumes an extensional origin for the Maritimes Basin (Belt, 1968b). The event was initiated during the Middle Devonian and lasted until the Late Namurian (370 to 317 Ma) with an associated decrease in heat flow over that period to equilibrium conditions. Extensional basins evolving from the active rift to passive margin phase have present day heat flow values that range between 63-110 $mWm^{-2}$, with

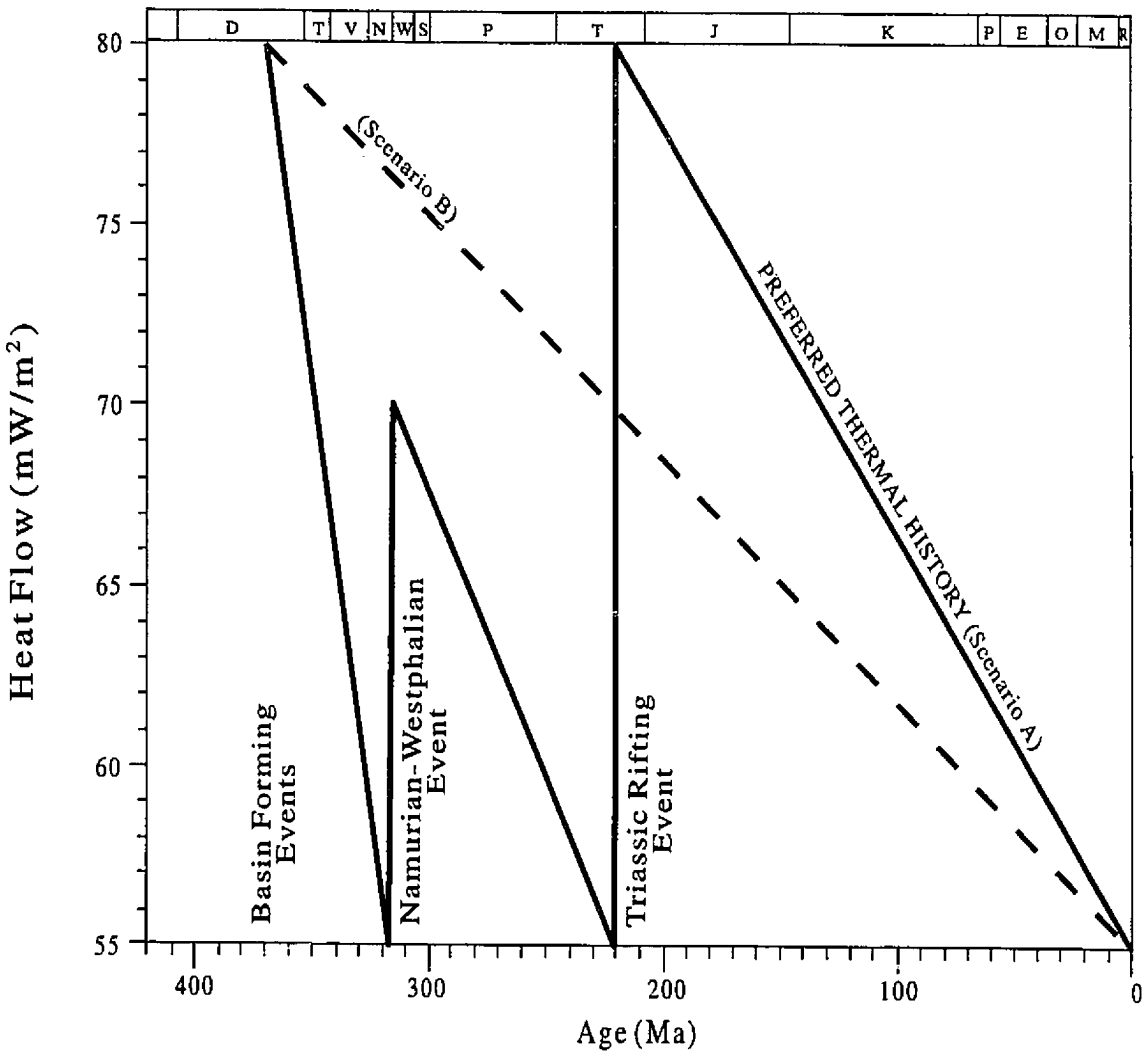



Figure 5.14 Time vs. heat flow plot for CMB thermal models scenario A and B. The scenario A thermal history includes three major events which were probably associated with heating whereas the scenario B thermal model only includes the initial basin forming events.

the most common value typically 80 $mWm^{-2}$, whereas basins evolving from the syn-rift to post-rift stage have heat flow values between 37-66 $mWm^{-2}$, typically 50 $mWm^{-2}$ (Allen and Allen, 1990; Gretener, 1981). By comparison, active strike slip basins have present day heat flow values of between 80 and 120 $mWm^{-2}$ (Allen and Allen, 1990; Gretener, 1981). Heat flow for the first event in the Maritimes basin is assumed to be analogous to actively extending basins, so a value of 80 $mWm^{-2}$ was chosen as the initial heat flow value at 370 Ma. It is assumed that the heat flow decreased from this value to near equilibrium levels, much like a typical rifted margin (cf. Keen and Beaumont, 1990). It is assumed that the present day state of the Maritimes Basin closely approximates equilibrium conditions, so the present day heat flow of 55 $mWm^{-2}$ (Table 5.4) was used for the heat flow value at the end of the first event.

Based on observations described in Chapter 4, the second event assumes a wrenched/compressional phase of tectonic development for the period after the early extensional phase. The duration of the second event is from the Late Namurian-Westphalian to the Middle Triassic (315 to 220 Ma) (Fig. 5.14). Compressional wrenched tectonic regimes have present day heat values between 40 and 96 $mWm^{-2}$, typically 70 $mWm^{-2}$ (Allen and Allen, 1990; Teichmuller and Teichmuller, 1986). The common value of 70 $mWm^{-2}$ was used as the initial heat flow of the second event (315Ma) and it is assumed that the heat flow decreased from this time to equilibrium conditions (221 Ma), which were assumed to be similar to the present day value of heat flow for the Maritimes Basin (55 $mWm^{-2}$).

The third and final heating event (220 to 0 Ma) (Fig. 5.14) is associated with Triassic rifting along the southeastern-eastern-northeastern side of the Maritimes Basin. The rifting, which resulted in the formation of the Fundy Basin and Orpheus Graben occurred between 220 and 180 Ma (Dehler and Keen, 1993) and is assumed to have thermally affected Maritimes Basin strata. Keen and Beaumont (1990) suggested that the rifting of a continental margin affects strata more than 100km inland from the active rift. The Triassic rifting initially generated heat flows in excess of 80 $mWm^{-2}$ decreasing to equilibrium values (Keen and Beaumont 1990), assumed to be a present day value of 55

$mWm^{-2}$.

Using the heating events outlined above in conjunction with the CMB fill thermal conductivity profile described previously, the amount of overburden deposited from 288 to 280 Ma in the CMB burial history (Fig. 5.15) was varied to match the predicted maturity values with the measured maturity values.

The use of three heating events with associated overburden estimates resulted in acceptable matches between present day measured maturity values and the predicted maturity values at all case study areas (cf. Fig. 5.15, Table VII.1). The amount of overburden ranged from 0m at the East Point E-49 location, which required no additional overburden to match maturity values, to a maximum of 2400m of overburden at the Middlesex No.1 case study location (Table VII.1). Modelled overburden estimates are lower than those suggested by previous studies (Table 5.5).

#### 5.3.1.3 CMB Maturation History: Timing of Hydrocarbon Generation

The conversion of the CMB thermal model to an organic maturation and hydrocarbon generation model was accomplished using the first order reaction kinetic method (LLNL Easy $\%R_0$ model) as outlined at the start of the modelling section. Table VII.2 details the timing of organic maturation as calculated using the preferred CMB thermal model (three phases of steady-state heat flow with additional overburden, Table VII.1)

The model suggests that maturation of CMB source rocks occurred early in the basin history, from approximately 310 to 280 Ma, essentially right after burial (cf. Fig 5.16, 5.17). The maturation histories imply that the offshore Horton Group source rocks became overmature relatively early, with some strata reaching the top of the main gas generation zone by 294 Ma (cf. Fig. 5.16, Table VII.2). The level of maturation for the Bird Rock and Green Gables formation varies between wells with most organic maturation occurring during the time of maximum burial (290-270 Ma) (Table VII.2). The Bird Rock Formation went through the main gas generation zone in several of the deeper wells (eg., Bradelle E-49, Fig. 5.16, Table VII.2) but has remained within the Mid

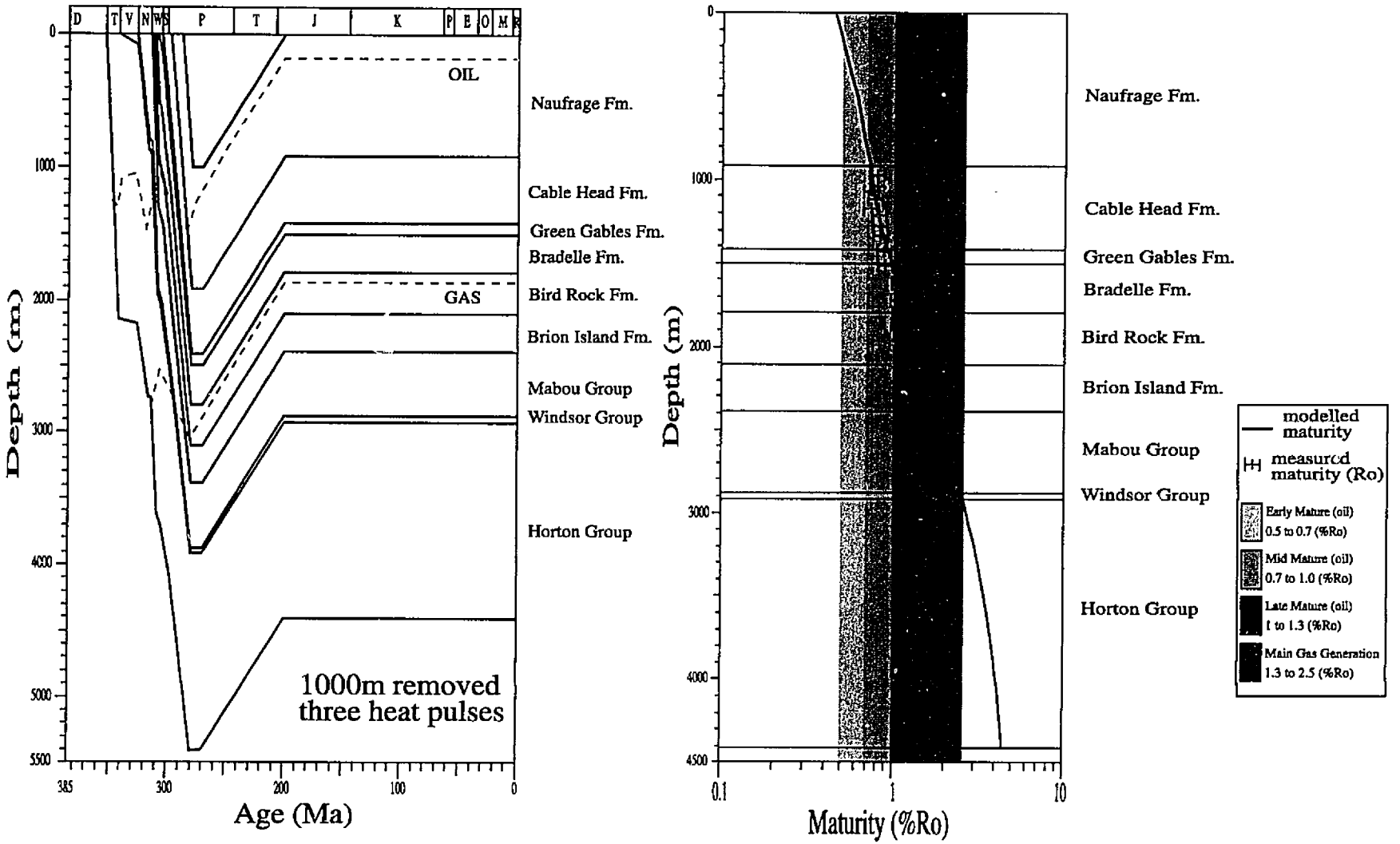



Figure 5.15 Scenario A CMB thermal model results for the Bradelle L-49 case study area. (left) Burial history plot and (right) maturation profile for Scenario A, the preferred CMB thermal model, which uses three steady-state thermal events. A good match is observed between modelled and measured thermal values.

Table 5.5 List of previous studies that suggested additional overburden rock in the Maritimes Basin. AFTA = Apatite Fission Track Analysis

| Author/estimates based on: | amount of eroded material | location | timing |
|---|---|---|---|
| Poole, 1903<br>**stratigraphic observation** | >762m | Gulf of St. Lawrence | Pre-Carboniferous |
| Hacquebard and Donaldson, 1970<br>**coal rank analysis/vitrinite** | 2070m | onshore Sydney subbasin | Post-Carboniferous? |
| van de Poll (1973)<br>**stratigraphic observation** | 450m | western & southwestern margin of the basin | Post-Carboniferous? |
| Hacquebard and Cameron (1989)<br>**coal rank analysis/vitrinite** | 3700 to 4200m | from east to west onshore Sydney subbasin | Post-Carboniferous? |
| | 2200m | onshore New Brunswick | Post-Carboniferous? |
| | 750m | onshore Nova Scotia | Post-Early Cretaceous? |
| | 2286m | Mabou Mines (NSDME Boreholes M1 and M2A) | Post-Permian |
| | 1530m | Bradelle L-49 | |
| | 2240m | Brion Island No. I | Post-Permian? |
| Ryan *et al.* (1990)<br>**AFTA**[1] | 1000-3000m | Maritimes Basin | Early Permian to Early Jurassic |
| Hendricks *et al.* (1993)<br>**AFTA** | 3000 - 6000m[2] | Deer Lake subbasin | Pre-Jurassic? |
| Ryan (1993)<br>**AFTA**[3] | 2000-4000m | Maritimes Basin | 270-200Ma |
| | 2000m (min) | Cable Head E-95 | |
| | 2500m (min) | Bradelle L-49 | |
| | 2000m (min) | East Point E-49 | |
| | 4000m (min) | North Sydney (offshore wells) F-24 and P-05 | |
| Grist *et al.* (1995)<br>**AFTA**[4] | up to 4000m | CMB | Post-Permian? |

[1]Calculated paleogeothermal gradients of 22°-27°C/km.
[2]Depending on geothermal gradient.
[3]Calculated present geothermal gradient of 25°C/km.
[4]Calculated recent geothermal gradients of less than 40°C/km

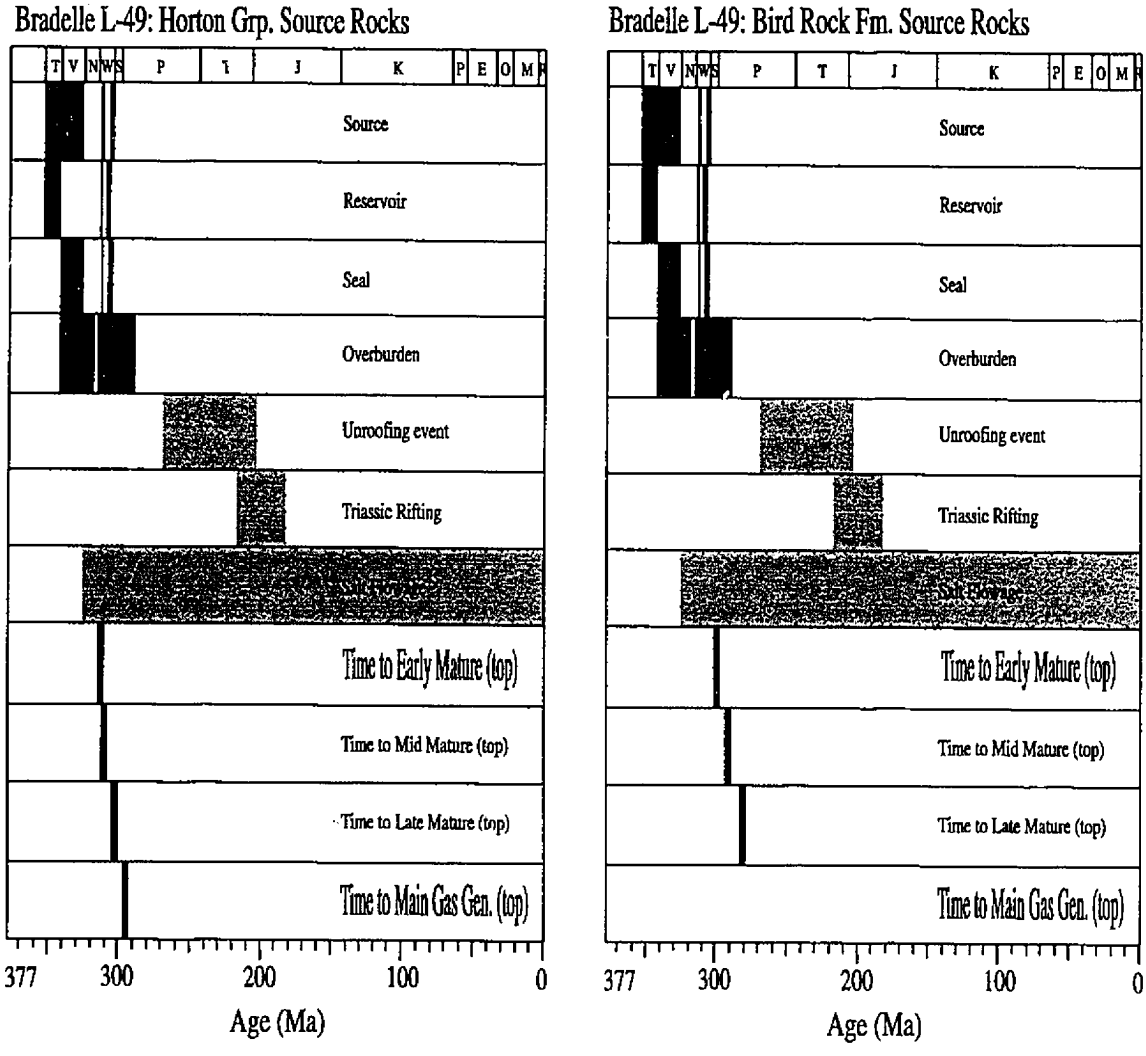



Figure 5.16 Plot of Bradelle L-49 petroleum system elements and processes for the Horton Group and Bird Rock Formation source rock intervals. The relative timing using the preferred CMB thermal model (Scenario A) is plotted (when the top of each succession reached the top of a particular maturation zone).

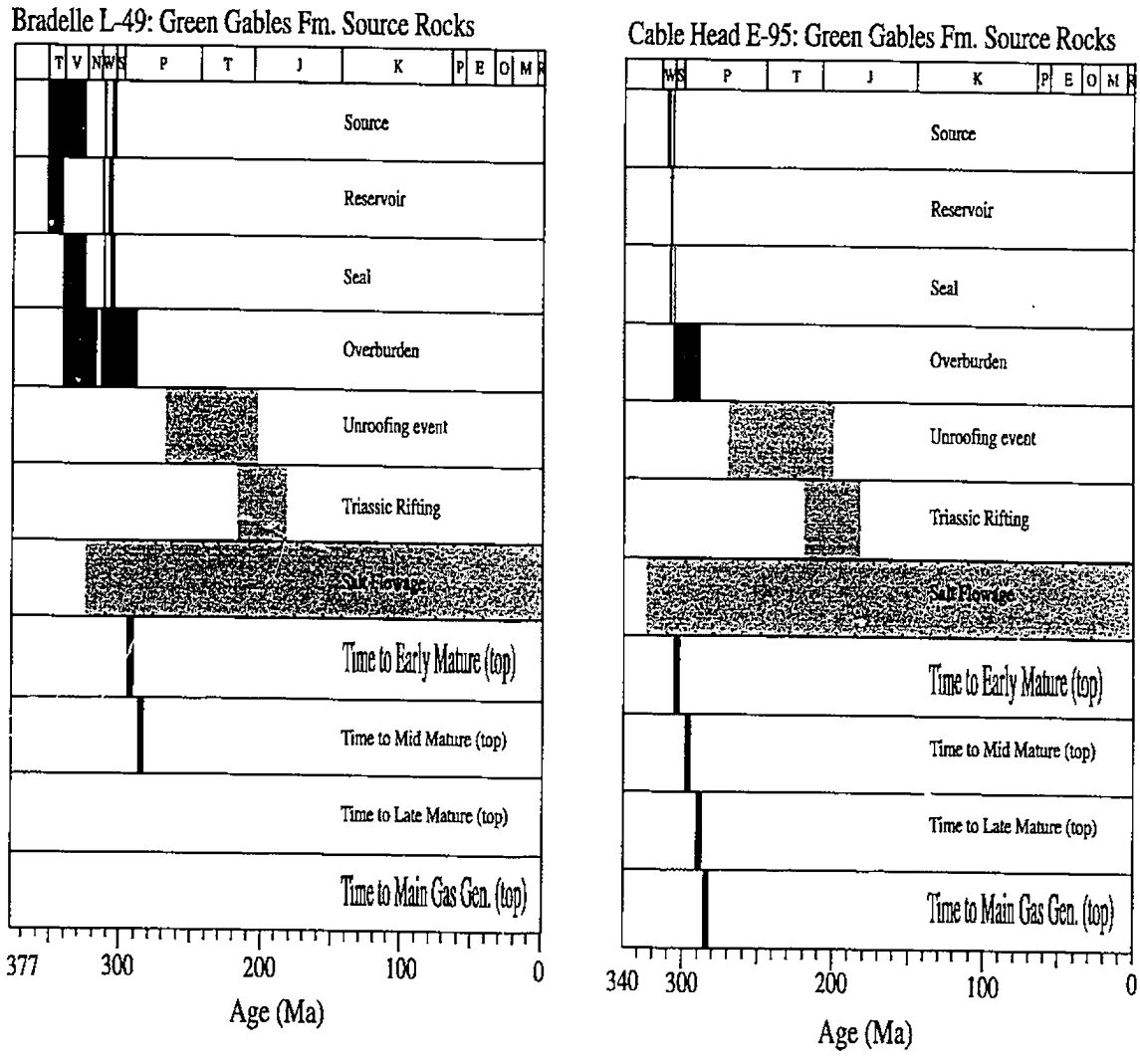



Figure 5.17 Plot of Bradelle L-49 and Cable Head E-95 petroleum system elements and processes for the Green Gables Formation source rock intervals. The relative timing using the preferred CMB thermal model (Scenario A) is plotted (when the top of each succession reached the top of a particular maturation zone).

Mature level for the shallower wells (eg.,NSDME M-1, Table VII.2). The Green Gables source interval appears to follow a similar relationship, with intervals deeper in the basin (eg., Cable Head E-95, Fig. 5.17) reaching the main gas generation zone, but with intervals on the basin flanks reaching the Mid Mature zone of organic maturation (eg., Bradelle L-49, Fig 5.17).

In the context of the CMB petroleum system, the deposition of source, reservoir, seal and overburden rocks in relation to the timing of trap formation and hydrocarbon generation-expulsion, appears to be favourable for the accumulation of hydrocarbons. The main elements were broadly in place prior to, or during the early stages of, organic maturation (Figs. 5.16, 5.17, Table VII.2, ). As well, most trapping mechanisms (CMB play types) were formed during, or shortly after, deposition of the elements and prior to the main phase of maturation. The most significant CMB play type, salt related trapping mechanisms, closely associated to post-depositional Windsor group salt flowage, was initiated prior to any advanced organic maturation (Figs. 5.16; 5.17), suggesting large traps were available for hydrocarbon accumulation. The relatively rapid organic maturation, generation, and accumulation of hydrocarbons in the CMB generally occurred prior to the main unroofing (270-200 Ma) and Triassic rifting (220-180 Ma) events (Figs. 5.16; 5.17).

### 5.3.2 CMB Model Sensitivity

Given a number of key geologic observations and assumptions, the CMB thermal model is able to generate vitrinite values consistent with measured vitrinite from the wells. However, the preferred CMB thermal model is non-unique and other interpretations likely exist. To examine the sensitivity of some of the geological assumptions used in the CMB model with respect to organic maturation, three different geological scenarios are proposed; Scenario B, Scenario C and Scenario D.

#### 5.3.2.1 Scenario B: One Phase of Increased Heat Flow

The preferred CMB thermal model assumes that three major heating events

occurred during the evolution of the CMB (Fig. 5.14). Scenario B is essentially the same as preferred scenario (A) except that only one heating event, associated with the initial basin formation, is used in each study area model (Fig. 5.14). For each study area, the magnitude of the heating event is held constant, whereas the amount of overburden deposited from 288 to 280 Ma (Fig. 5.18) is varied to match the predicted maturity values with the measured maturity values. The magnitude of the heating event is initially 80 $mWm^{-2}$ at 370 Ma, and is allowed to decrease to a present day value of 55 $mWm^{-2}$, which is consistent with measured values from a typical extensional basin evolving from an active state to a post-rift phase (Allen and Allen, 1990; Gretener, 1981). The general assumptions are the same as Scenario A; a CMB burial history is used, compaction/decompaction calculations use the methods proposed by Sclater and Christie (1980), and the same CMB fill thermal conductivity profile described previously is applied.

Using only one steady-state heating event in Scenario B and varying the amount of overburden resulted in satisfactory matches between predicted and measured thermal maturity data at all case study areas (cf. Fig 5.18). The fits between maturity values were comparable in quality to those resulting from the preferred CMB thermal model, however, the quantity of overburden required to match the two maturation data sets was slightly less than the amount required in Scenario A (Table VII.1). The general timing of organic maturation using this model did not differ substantially from the Scenario A model (Table VII.2).

#### 5.3.2.2 Scenario C: Minimal Overburden Model

The CMB burial and thermal histories assume that additional overburden was necessary to thermally mature organic matter to present day values. However, several studies (Deming, 1994; Cercone and Pollack, 1991; Cluff and Byrnes, 1990) have proposed that increased organic maturity can be caused by increased heat flow causing the observed basinal shift in isorank lines upsection. The Scenario C minimal overburden model assumes that the amount of overburden deposited between the Early Permian and

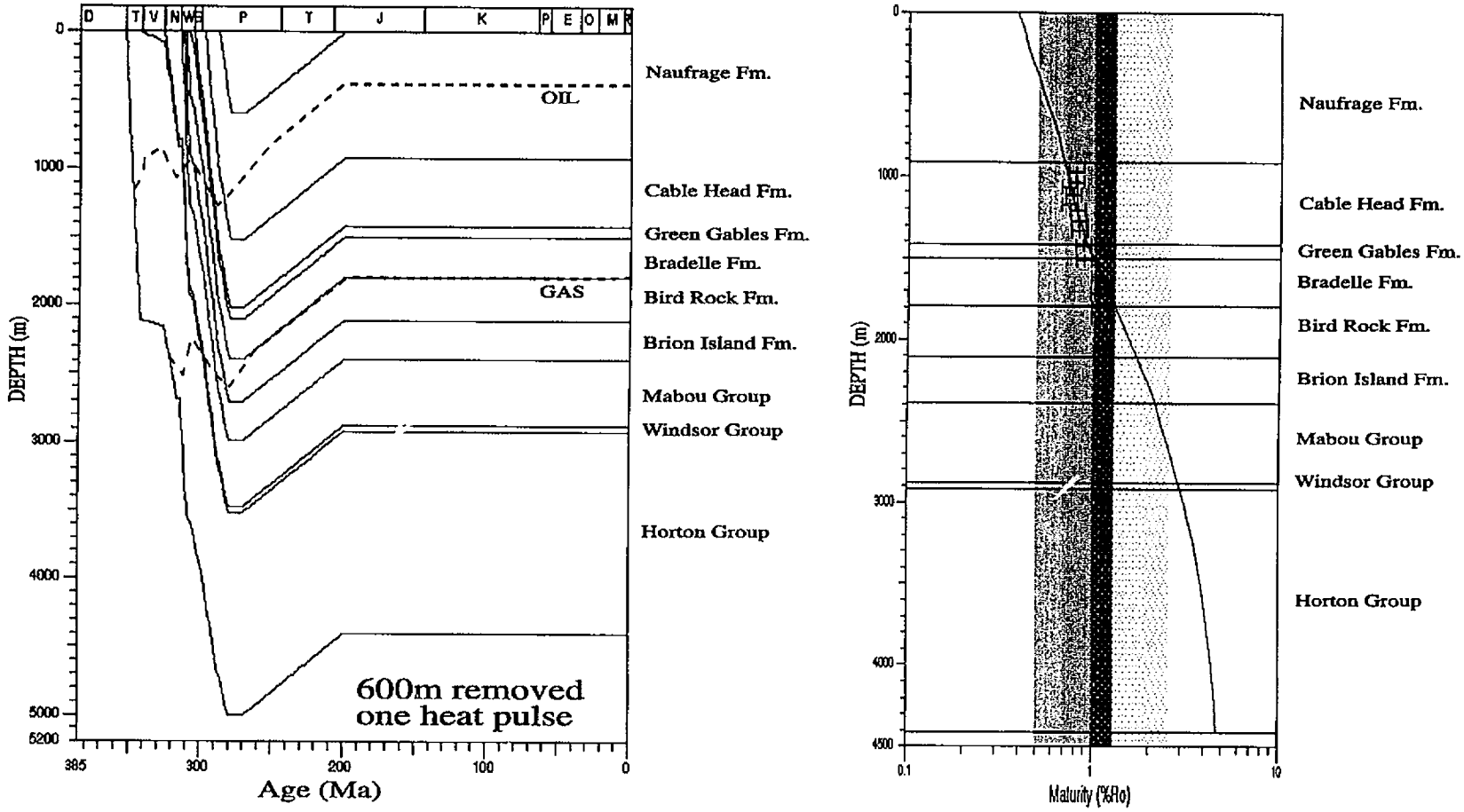



Figure 5.18 Scenario B CMB thermal model results for the Bradelle L-49 case study area. (left) Burial history plot and (right) maturation profile for Scenario B which uses only one steady-state thermal event. A good match is observed between modelled and measured thermal values. See Figure 5.15 for organic maturation legend.

Triassic (<100m) was negligible. Instead, an increased steady-state heating event was responsible for increasing the organic maturation of the Maritimes Basin samples. Scenario C examines two types of thermal histories; increased paleogeothermal gradient and increased heat flow.

**Scenario C1: Constant Geothermal Gradients**

The amount of overburden deposited at 288 Ma in the CMB burial history is kept at a constant value of 100m for each case study location. To match modelled maturity values with measured maturity values paleogeothermal gradients were varied to get the best possible fit between model results and measured maturity data from the wells. This is a common preliminary thermal modelling approach (cf. Cercone and Pollack, 1991; Cluff and Byrnes, 1990; Cercone, 1984), however, this method, using constant geothermal gradients, does not consider the effects of compaction through time or changes in lithologic characteristics of the basin fill and any overburden succession and so is a geologically unreasonable model.

Varying the magnitude of paleogeothermal gradients with minimal overburden resulted in satisfactory fits between measured and predicted organic maturity values. Half of the modelled paleogeothermal gradients were within the previously suggested range of acceptable geothermal gradients (25$^{0}$C/km to 67$^{0}$C/km) (Ryan, 1993; Hacquebard, 1984) (Table VII.3), however, the remaining model results exceeded this range. The Sydney and Moncton subbasin wells (Birch Grove No.1, North Sydney F-24, North Sydney P-05, and Middlesex No.1) required higher paleogeothermal gradients, however, substantial sections of recognized CMB stratigraphy have been removed from the Sydney Subbasin well locations (i.e., Birch Grove No.1 spudded in Green Gables Formation, inferring the erosion of the upper Cumberland Group and complete Pictou Group). The higher temperature for the Moncton Subbasin well may be due to the poor quality of maturity data available for this location, making a match between predictions and measurements rather difficult. Overall, the matches between predicted and measured maturity values were acceptable but not as good as the matches resulting from Scenario A modelling.

The general timing of organic maturation using this model did not differ substantially from values obtained using the preferred CMB thermal model (Scenario A).

**Scenario C2: Steady-state Heat Flow**

This model assumes an increased heat flow regime associated with the events that initiated basin subsidence. The heat from this event is subsequently allowed to decrease to the estimated present day heat flow of 55 $mWm^{-2}$ (Reiter and Jessop, 1985). The CMB Scenario C2 models for each case study area vary basal heat flow estimates, keep overburden negligible but constant (100m) and assume a common thermal conductivity profile based on the relative lithologic contrasts in the CMB fill. To match modelled maturity values with measured maturity values different heat flow regimes were modelled to get the best possible fit between model results and measured maturity data from the wells. Contrary to the previous scenario (Scenario C1) compaction was taken into account using the methods of Sclater and Christie (1980) and the lithology of the CMB fill played a role in model generation.

Varying the heating event responsible for the initial basin formation with a steady-state decrease to the present day value resulted in several satisfactory fits between predicted and measured thermal maturity data (Table VII.3). The models generated matches roughly of the same quality as Scenario C1 with the preferred CMB thermal model typically resulting in overall better fits than Scenario C1 models. The overall timing of organic maturation using this model did not differ substantially from values obtained using the preferred CMB thermal model (Scenario A) (Table VII.2).

Heat flows for active rift to passive stages of rift type basins range between 63-110 $mWm^{-2}$ with a mode of 80 $mWm^{-2}$ (Allen and Allen, 1990; Gretener, 1981). In light of these values, the heat flow values required to match maturity data in the CMB (Table VII.3) are not geologically unreasonable if it is assumed that a similar mechanism formed the Maritimes Basin (cf. Belt 1968b). Again, high values in the Sydney and Moncton subbasins may be explained by the arguments outlined in the previous section.

### 5.3.2.3 Scenario D: Additional Overburden Model

The thermal scenarios proposed so far in this chapter have assumed increased thermal heating in the past associated with greater levels of overburden in the Permo-Triassic resulting in the elevated present day vitrinite reflectance values. However, increased organic maturity can also be caused by the deposition and subsequent removal of significant amounts of overburden rock without assuming increased thermal heating in the past (Deming, 1994; Cercone and Pollack, 1991; Cluff and Byrnes, 1990).

Previous models have been proposed that suggest that the Maritimes Basin has been covered by substantial amounts of overburden that has since been removed (Table 5.5). Early estimates of erosion by Poole (1903) and van de Poll (1973) were based on geologic observations of stratigraphy and structural orientation. The first Maritimes Basin thermal model used measured coal ranks and calculated the amount of overburden necessary to heat the coal to its present rank (Hacquebard and Donaldson, 1970). The recognition of vitrinite as an organic maturity indicator led to several studies in which the amount of overburden was based on the projection of present near surface vitrinite values back to the assumed zero maturity value of 0.2 $\%R_{omax}$ (Hacquebard and Cameron, 1989). The more recent estimates of eroded overburden have integrated apatite fission track analysis with vitrinite reflectance and coalification curves to backcalculate present day thermal data to estimate erosion (Ryan *et al.*, 1990; Hendricks *et al.*, 1993; Ryan, 1993; Grist *et al.*, 1995). A common feature of the models using coal rank, vitrinite reflectance, and AFTA is that the amount of eroded overburden is based on a projection which uses present day heat flow/geothermal gradients and assumes that these present day conditions were constant back through time.

The thermal models in CMB Scenario D take the assumptions of the prior models one step further and examine a series (D1 to D4) of different paleogeothermal gradients and their affect on the amount of overburden necessary to mature organic matter to present day levels. A modelling strategy similar to that proposed by Cercone (1984) was adopted for Scenario D and four different paleogeothermal gradients were examined (25, 35, 45, 55 $^0$C/km), all of which are within previously suggested ranges for

paleogeothermal gradients; 25°C/km (Ryan *et al.*, 1990) to 67°C/km (Hacquebard, 1984).

Each paleogeothermal gradient was kept constant through time at each case study location using the CMB burial history. To match modelled maturity values with measured maturity values, overburden was deposited, or "added", to the present CMB stratigraphic column at 288 Ma, with deposition ending at 280 Ma. Following a short hiatus from 280 to 270 Ma, the overburden was removed from the CMB succession between 270 and 200 Ma. Modelling of each paleogeothermal gradient consisted of adding or removing overburden strata to get the best possible fit between model results and measured maturity data from the wells.

At each case study location, the application of four different paleogeothermal gradients associated with varying amounts of overburden, resulted in acceptable matches between present day measured maturity values and the predicted maturity values (cf. Fig 5.19). As expected, increasing the constant geothermal gradients required decreasing amounts of overburden rock to match present maturity values with predicted maturity values (Fig. 5.19). Typically, the amount of overburden is decreased by roughly 50% with every 10°C increase in paleogeothermal gradient. Locally, scenarios D3 and D4 suggest that at the Beaton Point F-70, East Point E-49, Naufrage No.1, and Tyrone No.1 well locations, no additional overburden is necessary to elevate the maturity values in the CMB (Table VII.4)

The highest quality matches between predicted and measured values were yielded by scenarios D1, D2 and D3. Scenario D4 resulted in a good fit between maturity values, however, overall, the higher the paleogeothermal gradient, the poorer the comparison between predicted and measured values. The modelled erosional estimates from Scenario D are generally consistent with previous estimates of erosion in the Maritimes Basin (Table 5.5). In general there were no significant changes in the timing of organic maturation or hydrocarbon generation with different paleogeothermal gradients. The general timing of organic maturation using this model did not differ substantially from values obtained using the preferred CMB thermal model (Scenario A) (Table VII.2).

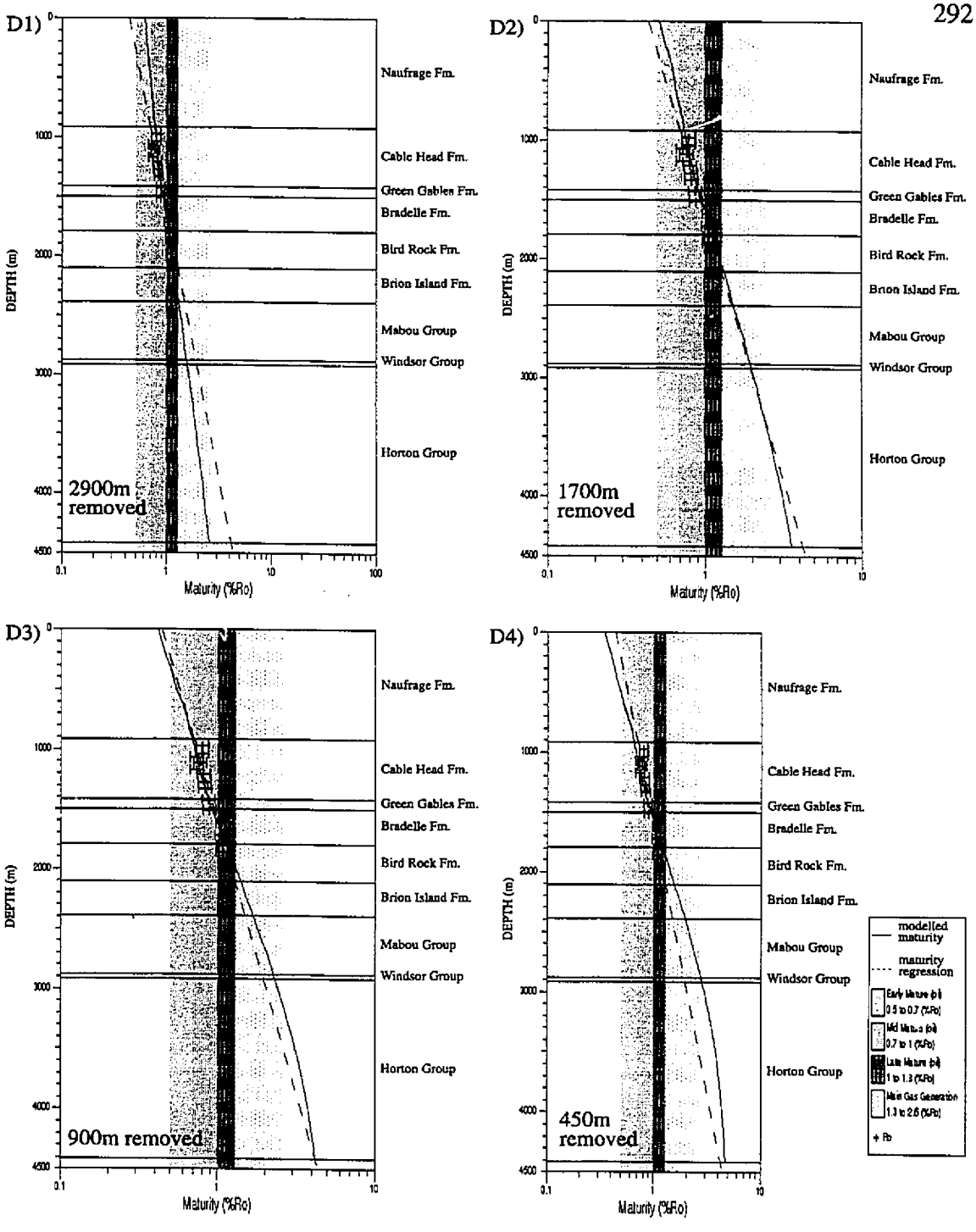



Figure 5.19 Scenario D maturation profiles from the Bradelle L-49 case study location showing the good fit between predicted maturity values and measured maturity values from the well data. D1) A constant 25°C/km geothermal gradient required the addition and removal of 2900m of Permian strata to match the present maturation profile. D2) A constant 35°C/km geothermal gradient required the addition and removal of 1700m of Permian strata to match the present maturation profile. D3) A constant 45°C/km geothermal gradient required the addition and removal of 900m of Permian strata to match the present maturation profile. D4) A constant 55°C/km geothermal gradient required the addition and removal of 450m of Permian strata to match the present maturation profile.

#### 5.3.2.4 Impact on Timing of Hydrocarbon Generation

The most significant feature of the maturation histories is that, regardless of which thermal model is used, the relative timing of organic maturation is essentially the same (cf. Fig. 5.20, Table VII.2) suggesting that the modelled timing of major hydrocarbon generation and expulsion events in the CMB is largely parameter insensitive due to a very rapid burial history. The maturation models suggest that the maturation of CMB source rocks occurred early in the basin history, soon after burial (~310 to 280 Ma).

## 5.4 Discussion

The main objective of this chapter was to describe the CMB petroleum system and to outline the interaction through time of the source, reservoir, seal and overburden rock elements with respect to hydrocarbon generation. A preferred thermal model has been presented that investigates the effects of three phases of increased steady-state heat flows in association with additional Permo-Triassic overburden. The model is internally consistent with the observed data and used a standardized set of general assumptions (Table 5.4), all of which led to the consistent matching of predicted thermal maturity values with measured maturity values from the well data. Several key assumptions were examined with respect to the sensitivity on the timing of organic maturation in the CMB. Each of the thermal scenarios examined in this chapter, with their associated maturation histories, are only an interpretation and collectively they are to be considered as only several possible, non-unique solutions to the question of organic maturation and hydrocarbon charge history in the CMB.

### 5.4.1 Thermal Modelling

From the models examined, there is no significant difference in the timing of organic maturation (Fig. 5.20). The model used in Scenario A is the most geologically reasonable because it utilizes three phases of steady-state heat flow instead of applying a constant geothermal gradient, accounts for compactional and lithological effects, and resulted in more reasonable erosional estimates.

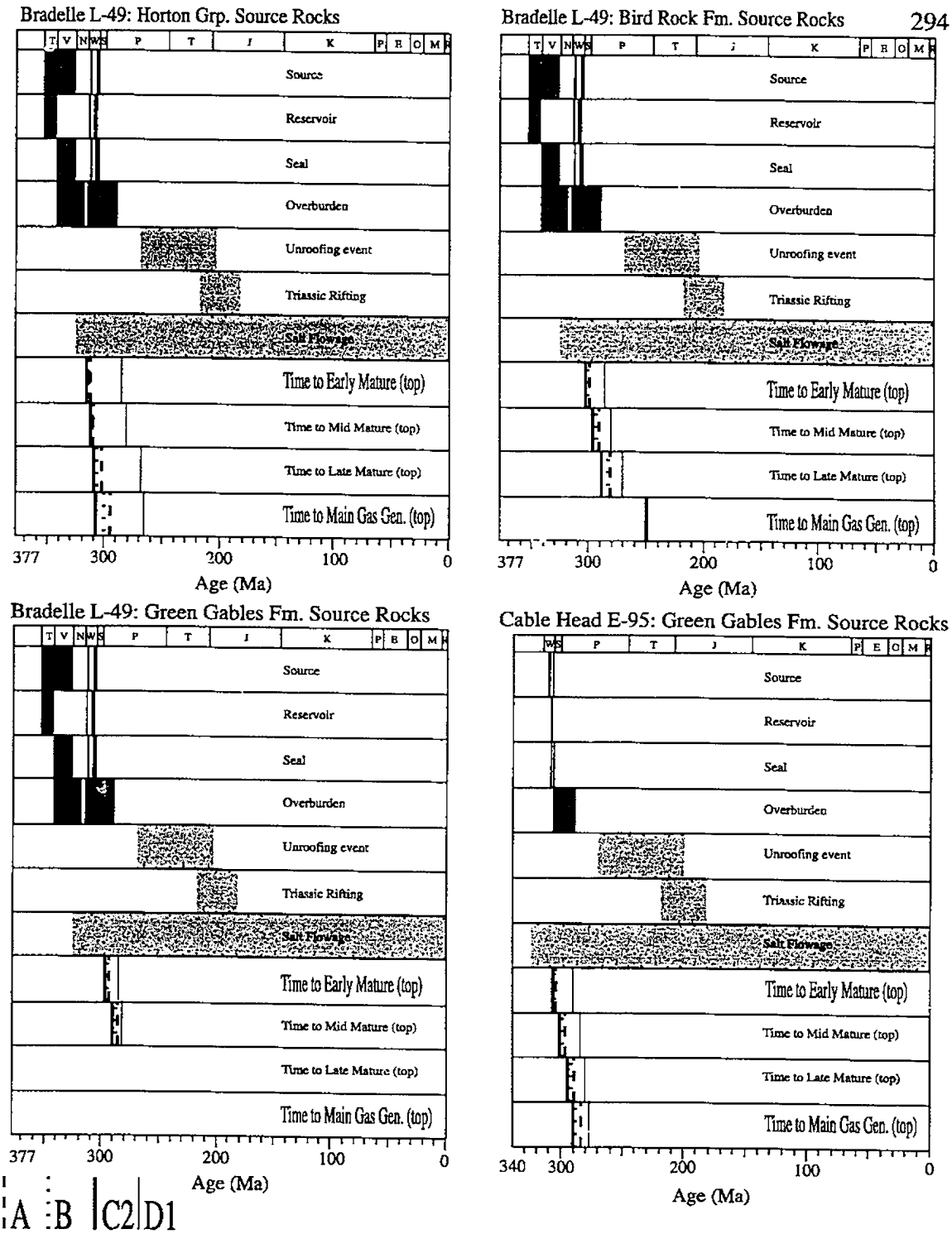



Figure 5.20 (top) Plot of Bradelle L-49 petroleum system elements and processes for the Horton Group and Bird Rock Formation source rock intervals. (bottom) Plot of Bradelle L-49 and Cable head E-95 petroleum system elements and processes for the Green Gables Formation source rock interval. The relative timing of organic maturation for each CMB thermal history scenario is plotted (A, B, C2, D1) and indicates little difference between the four modelling scenarios. Legend for models in bottom left corner.

Besides the initial heating event associated with basin formation, there is abundant evidence to support temporal and spatial variations in geothermal gradient in the Maritimes Basin. A thermal event is implied by the presence of Windsor Group volcanics on the Magdalen Islands (Barr *et al.*, 1985) and mid Carboniferous (339 Ma) gabbroic plutons on Cape Breton Island, Nova Scotia (Barr *et al.*, 1996). The regional extent of these thermal events is uncertain, however, the events may reflect only localized thermal heating which would be insignificant in the regional thermal history (cf. Thrasher, 1992).

In addition to the increased Late Carboniferous tectonism indicated by the CMB subsidence analysis, a Mid-Carboniferous event involving higher heat flows, uplift and deformation was proposed by Gibling *et al.* (1987). The event is associated with a widespread thermal anomaly within the Meguma Zone that occurred approximately between 300 and 320 Ma (Reynolds *et al.*, 1987), and a hot brine expulsion event that occurred during the Late Carboniferous (300 Ma) (Ravenhurst and Zentilli, 1987). In addition to the thermal indicators, as mentioned in Chapter 4, compressional/wrench tectonism occurred during the Late Carboniferous (Waldron *et al.*, 1989).

Mesozoic activity in close proximity to the Maritimes Basin involved minor structural deformation, rifting, dyke intrusion, and volcanic eruptions (Gibling, 1995). At the Northumberland Strait F-25 well location, Pe-Piper and Jansa (1986) documented that the well penetrated several Late Triassic intrusive successions. The most significant Mesozoic activity in the Maritimes Basin region is the rifting associated with the formation of the Fundy Basin and Orpheus Graben (Dehler and Keen, 1993).

There is no reason to assume that the above mentioned events did not affect the thermal maturation of the Maritimes Basin strata. Scenario C1 and D models do not account for any of the observed thermal events in the Maritimes Basin, whereas, the preferred CMB thermal model does attempt to account for the recognized episodes of magmatic activity, volcanism, deformation, uplift and heat in the Maritimes Basin.

Scenarios C1 and D are considered plausible thermal modelling alternatives given that there are negligible differences in organic maturation between these models and the

steady-state heat flow models (Scenarios A, B, C2). However, Scenario C2 and D models do not address the effects of compaction and basin fill lithology on CMB subsidence and compaction histories. Lithology and the evolution of porosity are both intricately related to the thermal conductivity of the basin fill, which is known to be a critical component of thermal and organic maturation calculations (Williamson, 1992; Blackwell and Steele, 1989). It is therefore not geologically reasonable to assume that compaction and lithology have no affect on thermal history.

Large estimates of previous overburden have been made in the past using the methods described in Scenario D (cf. Ryan 1993; Hacquebard and Cameron, 1989). As has been shown, methods employing a constant geothermal gradient do not take into account the effects of compaction, lithology or changing heat flow regimes through time. The favoured steady-state heat flow models suggest that significantly less overburden is needed to increase the CMB maturation values to their present levels. It has been suggested that the unroofing event which resulted in the subsequent removal of any overburden was related to the mechanisms responsible for the opening of the Atlantic (Hendricks *et al.*, 1993). Keen and Beaumont (1990) suggested that the shoulders of an actively rifting continental margin are typically uplifted 1 to 2 km, which would be broadly consistent with the amount of erosion modelled at each of the case study areas in scenario C1.

## 5.5 Concluding Statement

A viable petroleum system has been defined for the CMB that includes all the necessary elements of source, reservoir, seal and overburden. Source rocks are provided by the Horton, Bird Rock and Green Gables successions which contain organic rich intervals that are presently mid to overmature. Rock-Eval data suggest that the total organic carbon content for the Bird Rock and Green Gables formations averages 1-2 wt%, and that the organic matter is generally terrestrial in origin indicative of gas prone source rocks. Primary reservoirs, some of which have been charged with hydrocarbons, are found within the Horton, Windsor, Brion Island, Bradelle and Magdalen intervals.

Reservoir porosity and permeability appear to be good to excellent above subsurface depths of 2000m. Below 2000m, reservoir quality quickly deteriorates. The main sealing elements are provided by Windsor Group evaporites and shale-prone intervals located throughout the Maritimes Basin stratigraphic column. Ample overburden material is provided by the Pictou Group and any Permo-Triassic strata that has subsequently been removed. Different configurations of source, seal and reservoir elements helped define numerous potential trapping mechanisms in the CMB.

Subsidence, compaction, thermal and maturation histories have been reconstructed for 14 case study well locations in the CMB. Using the CMB burial history, the preferred model of CMB thermal history incorporated three phases of steady-state heat flow with deposition of additional overburden in the Early Permian. Using this thermal model, the source rock intervals within the CMB fill underwent organic maturation and expulsion very early (~310-280 Ma) in the basin's history. The modelled organic maturation framework indicates favourable timing between the development of petroleum system elements and processes, i.e. traps were available at the time of hydrocarbon charge.

Three thermal scenarios were proposed to determine the sensitivity of the timing of organic maturation. The resulting organic maturation frameworks did not differ significantly from the preferred CMB thermal model, suggesting that the modelled timing of major hydrocarbon generation and expulsion events in the CMB are largely parameter insensitive.

# CHAPTER 6 - CONCLUDING REMARKS

## 6.1 General Conclusions

Previous geological studies of the Maritimes Basin have tended to focus on its preserved onshore portions within individual subbasins and platform areas, which collectively represent a very small portion of the total area of the basin. This has contributed to the development of a complex stratigraphic nomenclature and tectonic history that has hampered understanding of the regional Maritimes Basin petroleum system.

The integrated analysis of the offshore Maritimes Basin presented in this thesis incorporates biostratigraphic, lithostratigraphic and seismic data. This has enabled a synthesis of the stratigraphy and petroleum geology of the Maritimes Basin region. The major conclusions and contributions of this thesis are:

1) A thick (>10km) succession of Late Carboniferous strata, broadly equivalent at the group level to the strata that crop out onshore, underlies the southern Gulf of St. Lawrence. The post-Windsor Group basin fill consists of a thick, essentially undeformed, Early Namurian to Early Permian succession which can be subdivided into three major lithostratigraphic units separated by regionally extensive, chronostratigraphically significant surfaces.

2) A detailed stratigraphic framework has been developed that recognizes the Mabou, Cumberland, and Pictou Groups within the post-Windsor Group basin fill. A regionally identifiable, formation level stratigraphic nomenclature is proposed for the Cumberland and Pictou Groups. The CMB Cumberland Group can be subdivided into six formations consisting of (in ascending order) the Brion Island, Bird Rock, Bradelle, Green Gables, Magdalen and Seacow formations. The CMB Pictou Group can be subdivided into the lower Cable Head and upper Naufrage Formations.

3) A Forestepping-Backstepping (F-B), nonmarine sequence stratigraphic model is proposed to better understand the development of the post-Namurian CMB fill. These F-B sequences are bounded by regionally identifiable conformable to unconformable sequence boundaries and consist of a basal, coarse-grained facies overlain by a

finer-grained facies. The basal facies are interpreted to be forestepping systems tracts, that developed when the rate of sediment supply exceeded the rate of accommodation increase causing the progradation of braided fluvial systems basinward. Backstepping systems tracts overlie both the basal unit and a transgressive surface. These tracts developed when the rate of sediment supply to the braided fluvial systems was exceeded by the rate of accommodation increase. This resulted in a relative rise in stratigraphic baselevel which forced the retreat of the fluvial systems back to the basin margin and initiated the backstepping deposits.

**4)** Application of the F-B sequence analysis method identified two 2nd order and two 3rd order composite depositional sequences in the post-Namurian CMB fill. Each composite F-B sequence is composed of a basal forestepping system set and an upper backstepping system set which are in turn composed of smaller 4th and 5th order sequences. Each 2nd-3rd order composite sequence is bounded at the top and bottom by regionally identifiable sequence boundaries with an equally extensive transgressive surface recognized within each sequence.

**5)** The regionally extensive 2nd-3rd order composite CMB F-B sequences developed in response to a series of episodic allocyclic tectonic events that controlled the relative rates of change of accommodation and sediment supply. Sediment supply was controlled by renewed Alleghanian thrusting in the Carboniferous Appalachians that occurred as a series of discrete pulses attributed to three periods of tectonic activity. Accommodation in the CMB depositional system was controlled by increased tectonic subsidence during the Westphalian, primarily due to the onset of Alleghanian thrusting to the south, combined with related local activity. It is probable that several episodes of differential tectonic subsidence of the Maritimes Basin, in association with several episodes of sediment influx due to renewed uplift of the Carboniferous Appalachians, interacted to develop the cyclic F-B sequences in the basin fill.

**6)** Climatic and eustatic controls were superimposed on the regionally dominant tectonic mechanisms and fulfilled important roles in the development of the smaller scale 4th and 5th order sequences. Evidence for restricted-marine conditions within the

Maritimes Basin and open-marine conditions in close proximity to the Maritimes Basin suggests that eustasy exerted a strong secondary control on smaller scale sequence development within F-B Sequence 2 and potentially F-B Sequence 3.

**7)** Based on evidence recorded by post Namurian Maritimes Basin fill it is postulated that the post Namurian Maritimes Basin developed as a Continental Wrenched Foldbelt Basin, analogous to a hypothetical wrenched Appalachian Foreland Basin caused by Variscan Foldbelt oblique collision.

**8)** A viable petroleum system has been defined for the CMB that includes all the necessary elements of source, reservoir, seal and overburden. Source rock potential is evident in the Horton (Type I/II), Bird Rock (Type III/I) and Green Gables (Type III/I) successions. Reservoir rocks include the Horton, Windsor, Orion Island, Bradelle and Magdalen intervals. Windsor Group evaporites and shale-prone intervals comprise possible seals. Finally, overburden is provided by the Pictou Group and any Permo-Triassic strata that may have been subsequently removed. Different structural and stratigraphic configurations of source, seal and reservoir elements define numerous potential trapping mechanisms in the CMB.

**9)** Subsidence, compaction, thermal and maturation histories have been reconstructed for 14 case study well locations in the CMB. The preferred CMB model incorporates an AFTA modified burial history and a three phase steady-state heat flow model, which suggests that removal of between 1-2 km of Permo-Triassic overburden has occurred. The CMB maturation model indicates that source rocks in the CMB underwent organic maturation and expulsion very early (~310-280 Ma) in the basin's history, and that the timing is favourable between the development of petroleum system elements and processes, i.e., traps were available at the time of hydrocarbon charge.

**10)** Three thermal scenarios were proposed to determine the sensitivity of the timing of organic maturation. The resulting organic maturation frameworks did not differ significantly from the preferred CMB thermal model, suggesting that the modelled timing of major hydrocarbon generation and expulsion events in the CMB is largely parameter insensitive.

## 6.2 Recommendations for Future Work

The following are suggestions for future work that have come out of this study:

1) Detailed CMB seismic sequence analysis with special emphasis on the seismic facies analysis of the Coal Measures seismic sequence (e.g. mapping seismic facies, progradation vs. retrogradation features of basin fill)

2) Provenance study of the sandstones contained in the forestepping systems sets to further investigate the eastern United States stratigraphic and sedimentologic link.

3) Detailed study of physical and chemical characteristics of the Bird Rock and Green Gables source rock intervals.

4) Detailed evaluation (e.g. XRD, SEM, whole-rock inorganic) of the regionally extensive discontinuities (Namurian-Westphalian, Mid-Westphalian, and Westphalian-Stephanian events) present within the Late Carboniferous CMB fill.

5) Employ the F-B sequence analysis model on smaller scale CMB fill events (e.g. Boss Point megacycles) to test the validity of the method for 4th and 5th order sequence analysis. On a more regional scale, apply the model to other predominantly nonmarine basins, specifically in the eastern United States, to strengthen links between 2nd-3rd order stratigraphic events within different Carboniferous depocentres.

6) Perform detailed mapping of the specific CMB play types recognized.

7) Construct site specific organic maturation and expulsion models for recognized CMB hydrocarbon play types using 1-D and 2-D versions of BasinMod.

8) Further integrate the CMB sedimentary fill succession with geodynamic models of basin evolution.

# APPENDIX I: CMB BIOSTRATIGRAPHIC DATABASE

Table I.1 List of biostratigraphic data currently available for the CMB study wells. (wells in alphabetical order, questions marks indicate questionable data)

| WELL NAME | AGE | DEPTH (m) (start) | DEPTH (m) (end) |
|---|---|---|---|
| BEATON POINT F-70 | Stephanian - Westphalian D | 700 | |
| | Mid Westphalian D | 840 | |
| | Mid Late Westphalian C | 1160 | |
| | Late Westphalian B - Early Westphalian C | 1441 | |
| | HACQUEBARD, 1986 | | |
| | | | |
| | Westphalian D? | 720 | 980 |
| | Mid to Late Westphalian C? | 980 | 1430 |
| | Early Westphalian C | 1430 | 1720 |
| | DOLBY, 1994 | | |
| | | | |
| BIRCH GROVE NO.1 | Late Westphalian C | 145 | |
| | Late Westphalian B/Early Westphalian C | 259 | 551 |
| | BARSS, 1968 | | |
| | | | |
| BLANCHARD NO.1 | Westphalian C | 669 | |
| | BARSS, 1967b | | |
| | | | |
| BRADELLE L-49 | Permian? | 86 | 319 |
| | Stephanian | 319 | 1093 |
| | Late Westphalian C - Early Westphalian D | 1114 | 1696 |
| | Late Westphalian B - Early Westphalian C | 1717 | 2087 |
| | Late Visean - Early Namurian | 2108 | 4367 |
| | BARSS ET AL., 1979 | | |
| | | | |
| | Lower Permian - Stephanian | 0 | 566 |
| | Westphalian D | 566 | 883 |
| | Westphalian C | 883 | 1762 |
| | Early Westphalian C? | 1762 | 1867 |
| | Westphalian A | 1867 | 2503 |
| | Namurian | 2503 | 2726 |
| | Namurian A | 2726 | 2852 |
| | Visean | 2852 | 3310 |
| | Tournaisian | 3310 | 4202 |
| | SHELL CANADA RESOURCES LTD., 1973 | | |
| | | | |
| | Stephanian | 1054 | 1130 |
| | Westphalian | 1130 | 1280 |
| | Westphalian D | 1280 | 1554 |
| | Westphalian C | 1554 | 1883 |
| | Westphalian B | 1883 | 2114 |
| | Westphalian A | 2114 | 2590 |
| | Namurian | 2590 | 3373 |
| | Visean | 3373 | 3991 |
| | Tournaisian | 3991 | |
| | INRS-PETROLE, 1975b | | |
| | | | |
| | Stephanian A - Early B | 331 | 1030 |
| | Westphalian D | 1030 | 1455 |
| | Mid to Late Westphalian C | 1455 | 1636 |
| | Early Westphalian C | 1636 | 1786 |
| | Westphalian B | 1786 | 2027 |
| | Namurian C? | 2027 | 2117 |
| | Visean | 2117 | 2720 |
| | DOLBY, 1994 | | |

| | | | |
|---|---|---|---|
| | | | |
| | Stephanian/Westphalian D | 1063 | 1093 |
| | Westphalian D/WestphalianC | 1575 | 1605 |
| | Westphalian C/Westphalian B | 1877 | 1907 |
| | DOLBY, G., 1993, PERS. COMM. | | |
| | | | |
| **BRION ISLAND NO.1** | Permian | 0 | 518 |
| | Stephanian to Westphalian C | 518 | 1425 |
| | Westphalian B | 1425 | 1500 |
| | Westphalian A | 1500 | 2232 |
| | Namurian A | 2232 | 2458 |
| | Visean | 2458 | 2719 |
| | Visean | 2719 | |
| | SAREP LTD., 1971 | | |
| | | | |
| | Stephanian | 699 | 837 |
| | Stephanian/Westphalian | 837 | 873 |
| | Westphalian D | 873 | 1355 |
| | Westphalian C | 1389 | 1434 |
| | Westphalian B/C | 1440 | 152[illegible] |
| | Westphalian A | 1563 | 1994 |
| | Westphalian A? | 2048 | 2199 |
| | Namurian A | 2244 | 2410 |
| | Namurian? | 2470 | 2590 |
| | Visean? | 2648 | |
| | INRS-PETROLE, 1975b | | |
| | | | |
| | Namurian and younger | above | 2139 |
| | Latest Visean | 2139 | 2458 |
| | "should correspond to Lower Mabou" | | |
| | GILES, P., 1995, PERS. COMM. | | |
| | | | |
| | Stephanian | 584 | 840 |
| | Westphalian D | 864 | 1352 |
| | Westphalian C | 1380 | 1413 |
| | Westphalian B/C | 1437 | 1494 |
| | Westphalian A | 1527 | 2036 |
| | Westphalian A? | 2063 | 2217 |
| | Namurian A | 2244 | 2708 |
| | INRS-PETROLE, 1973 | | |
| | | | |
| | | | |
| **CABLE HEAD E-95** | Westphalian D | 1700 | 2075 |
| | Late Westphalian C | 2075 | 2300 |
| | Late Westphalian B/ Early Westphalian C | 2300 | 2750 |
| | Westphalian B? | 2750 | 3235 |
| | HACQUEBARD, 1986 | | |
| | | | |
| | Westphalian D? | 1970 | 2900 |
| | Late to Mid Westphalian C | 2900 | 3200 |
| | Early Westphalian C | 3200 | 3235 |
| | DOLBY, 1994 | | |
| | | | |
| **EAST POINT E-49** | Westphalian | 1530 | 1681 |
| | Westphalian ? | 2283 | 2584 |
| | Westphalian B | 2855 | 2886 |
| | Namurian | 2976 | 3307 |
| | INRS-PETROLE, 1975c | | |
| | | | |
| | Sakmarian | 1039 | 1042 |
| | Stephanian | 1560 | 1720 |
| | Westphalian D? - Stephanian | 2229 | 2822 |
| | Late Visean - Early Namurian? | 2873 | 2880 |

| | | | |
|---|---|---|---|
| | Late Visean - Early Namurian | 2964 | 3268 |
| | BARSS ET AL., 1979 | | |
| | | | |
| **EAST PONT E-47** | L. Stephanian D/B | 1020 | 2120 |
| | Stephanian B/Late Westphalian D | 2120 | 2440 |
| | Westphalian D/Late Westphalian C | 2440 | 2660 |
| | DOLBY, 1994 | | |
| | | | |
| **FREDERICTON NO.2** | Late Namurian - Early Westphalian | 1045 | |
| | LEGALLAIS, 1983 | | |
| | | | |
| **GREEN GABLES NO.1** | Stephanian | 843 | 1367 |
| | Westphalian D | 1636 | 1645 |
| | Westphalian | 1696 | 1961 |
| | Late Namurian | 2277 | 2331 |
| | Late Visean - Early Namurian? | 3075 | 3343 |
| | BARSS ET AL., 1979 | | |
| | | | |
| | Stephanian | 1229 | 1566 |
| | Westphalian | 1566 | 1717 |
| | Westphalian D | 1717 | 1867 |
| | Westphalian | 1867 | 2428 |
| | Namurian? | 2428 | 2536 |
| | INRS-PETROLE, 1975c | | |
| | | | |
| | Permian? | 967 | 1262 |
| | Stephanian | 1361 | 1367 |
| | Westphalian D | 1636 | 1645 |
| | Westphalian D? | 1696 | 1898 |
| | Late Namurian | 2277 | 2413 |
| | Visean - Early Namurian | 3075 | 3343 |
| | BARSS ET AL., 1979 (P. Giles Modified) | | |
| | | | |
| **HASTINGS NO.1** | Westphalian A to C | 579 | 1112 |
| | Westphalian A | 1112 | 2182 |
| | Late Namurian | 2219 | 2237 |
| | Namurian | 2237 | 2658 |
| | Namurian A and B | 2658 | 2676 |
| | SOUAYA, 1975 | | |
| | | | |
| | Westphalian B and C | 1359 | 1460 |
| | Westphalian A | 1588 | 1704 |
| | Late Namurian to Westphalian A | 1893 | 2182 |
| | Late Namurian | 2222 | 2237 |
| | GULF OIL CANADA, 1975 | | |
| | | | |
| **HILLSBOROUGH NO.1** | Permian | spud | 1864 |
| | Pennsylvanian | 1864 | 3137 |
| | Mississippian | 3137 | 3575 |
| | ISLAND DEVELOPMENT COMPANY, 1944 | | |
| | | | |
| | Linopteris Obliqua Pictou Grp | | 1229 |
| | Linopteris Obliqua Morien Series (13) | | 1611 |
| | Westphalian D? | | |
| | BARSS, 1960 | | |
| | | | |
| **IRISHTOWN NO.1** | Sakmarian? | 810 | 816 |
| | Westphalian to Stephanian | 855 | 1503 |
| | Late Westphalian B Early Westphalian C | 1557 | 1566 |
| | Late Visean to Early Namurian | 1584 | 1880 |
| | BARSS ET AL., 1979 | | |
| | | | |
| | Westphalian | 1048 | 1078 |

| | | | |
|---|---|---|---|
| | Westphalian | 1380 | 1383 |
| | Westphalian C | 1500 | 1560 |
| | Westphalian B - Westphalian C | 1560 | 1620 |
| | Westphalian | 1620 | 1623 |
| | Namurian - Visean | 1895 | 1922 |
| | INRS-PETROLE, 1975c | | |
| | | | |
| | Sakmarian? | 810 | 816 |
| | Stephanian | 855 | 1069 |
| | Westphalian | 1334 | 1503 |
| | Late Westphalian B to Early Westphalian C | 1557 | 1566 |
| | Early Namurian | 1584 | 1590 |
| | Visean | 1870 | 1880 |
| | BARSS ET AL., 1979 (P. Giles Modified) | | |
| | | | |
| **MIDDLESEX NO.1** | Late Visean | 1288 | 1293 |
| | VAN HELDEN, B.G., 1995, PERS. COMM. | | |
| | | | |
| **NAUFRAGE NO.1** | Stephanian to Lower Permian | 663 | 783 |
| | Westphalian D? | 1024 | |
| | Westphalian | 1145 | |
| | Westphalian | 1205 | 3057 |
| | SOQUIP ET AL., 1975a | | |
| | | | |
| | Early Permian | 648 | 792 |
| | Stephanian | 1136 | 1765 |
| | Westphalian D? | 2151 | 2160 |
| | Late Westphalian D | 2277 | 2512 |
| | Mid to Early Westphalian D? | 2512 | 2798 |
| | Late Early Middle Westphalian C? | 2798 | 3066 |
| | DOLBY, G., 1995, PERS. COMM. | | |
| | | | |
| **NORTH SYDNEY F-24** | Permo-Carboniferous | 283 | 494 |
| | Stephanian | 494 | 693 |
| | Westphalian D | 693 | 959 |
| | Westphalian C | 959 | 1262 |
| | Westphalian | 1262 | 1322 |
| | Late Namurian? | 1322 | 1413 |
| | Namurian B-C | 1413 | 1586 |
| | Late Visean? - Early Namurian | 1586 | 1687 |
| | ROBERTSON RESEARCH, 1976 | | |
| | | | |
| | Stephanian | 280 | 750 |
| | Westphalian D | 750 | 1090 |
| | Westphalian C | 1090 | 1289 |
| | Early Westphalian C | 1289 | 1367 |
| | Namurian A | 1367 | 1503 |
| | Late Visean - Namurian A | 1503 | |
| | SHELL CANADA RESOURCES LTD., 1976 | | |
| | | | |
| **NORTH SYDNEY P-05** | Westphalian C | 286 | 756 |
| | Late Westphalian B - Early Westphalian C | 756 | 1372 |
| | Middle Devonian - Namurian | 1372 | 1641 |
| | ROBERTSON RESEARCH, 1974 | | |
| | | | |
| | Stephanian | 515 | 696 |
| | Westphalian D | 720 | 1027 |
| | Late Westphalian C | 1054 | 1208 |
| | Late Westphalian B- Early Westphalian C | 1259 | 1328 |
| | Late Visean - Early Namurian | 1358 | 1497 |
| | BARSS ET AL., 1979 | | |
| | | | |
| **NORTHUMBERLAND STRAIT F-25** | Early Namurian? | 111 | 346 |

| | | | |
|---|---|---|---|
| | Late Visean | 401 | 1241 |
| | Visean | 2000 | 2003 |
| | BARSS ET AL., 1979 | | |
| | | | |
| | Namurian | 295 | 747 |
| | INRS-PETROLE, 1975c | | |
| | | | |
| **NSDME BOREHOLE M-1** | Stephanian? | 437 | |
| | Westphalian D | 535 | 993 |
| | DOLBY, 1994 | | |
| | | | |
| **NSDME BOREHOLE M-2A** | Stephanian A | 96 | 316 |
| | Westphalian D | 316 | 919 |
| | Late to Mid Westphalian C | 919 | 1214 |
| | DOLBY, 1994 | | |
| | | | |
| **NSDME DDH P58** | Westphalian D? | 3 | |
| | Westphalian C - Westphalian D | 34 | 134 |
| | Mid to Late Westphalian C | 134 | 454 |
| | Early Westphalian A | 656 | 710 |
| | Late Namurian? - Early Westphalian A | 710 | 835 |
| | DOLBY, 1994 | | |
| | | | |
| **NSDME PH-3** | Mid Westphalian C? | 8.8 | |
| | Westphalian B - Westphalian C | 42.3 | |
| | Early Westphalian C? | 86.9 | 594.5 |
| | Westphalian A | 6 foot seam equivalent | 590 |
| | Mid Westphalian C | Top Hole equivalent | |
| | DOLBY, 1989a,b/GILES, P., 1995, PERS. COMM. | | |
| | | | |
| **ST. PAUL P-91** | Namurian A | 795 | 1985 |
| | Late Visean - Early Namurian | 2150 | 2165 |
| | Middle Visean | 2195 | 2205 |
| | Visean | 2590 | 2725 |
| | UTTING, 1984 | | |
| | | | |
| **TYRONE NO.1** | Stephanian | 1295 | 1747 |
| | Westphalian C | 2892 | 2952 |
| | Westphalian | 3012 | 3102 |
| | Namurian ? | 3102 | 3133 |
| | Namurian | 3133 | 4042 |
| | SOQUIP ET AL., 1975b | | |
| | | | |
| | Permian? | 0 | 1292 |
| | Stephanian | 1292 | 1795 |
| | Westphalian C? | 2482 | 2877 |
| | Late Westphalian B - Early Westphalian C | 2961 | 3087 |
| | Late Visean - Early Namurian | 3111 | 3798 |
| | BARSS ET AL., 1979 | | |
| | | | |
| | Stephanian | 1292 | 1795 |
| | Westphalian C? | 2482 | 2877 |
| | Late Westphalian B - Early Westphalian C | 2961 | 3087 |
| | Namurian | 3111 | 3798 |
| | BARSS ET AL., 1979 (P. Giles modified) | | |
| | | | |
| **WELLINGTON STATION NO.1** | Westphalian D | 581 | 946 |
| | Namurian C? | 1343 | 1506 |
| | Late Tournaisian | 2100 | 2735 |
| | Late Tournaisian | core | 2793 |
| | DOLBY, 1994 | | |

Wightman, W.G. 1994. Cable Head E-95 and Brion Island No.1 wells: Agglutinated foraminifera and thecamoebian assemblages. Paleotec Geological Consulting, unpublished report, 3p.

**Cable Head E-95 and Brion Island No.1 wells: Agglutinated foraminifera and thecamoebian assemblages**

Agglutinated foraminifera were identified at all intervals in both wells, with the exception of the 1435-1470 m interval in the Cable Head E-95 well. Thecamoebian assemblages were observed in all 19 samples from the Brion Island No. 1 well, but were absent from the 1395-1920 m, 2250-2285 m and 2340-2375 m intervals in the Cable Head E-95 well. Percentage diagrams showing the relative abundance of the agglutinated foraminiferal and thecamoebian components in the studied intervals, together with lithology (clast) types based on grain counts, are shown in the accompanying figures for each well.

Representatives of *Trochammina* comprise the dominant agglutinated foraminifera in both wells. *Ammobaculites* and *Ammotium* are also common in these wells. Other foraminifera include biserial agglutinated forms (possibly *Textularia*), and possibly also *Haplophragmoides*. Preservation of the faunas is variable; most were poorly preserved, and compressed. Relatively well-preserved assemblages occur in the 2830-2865 m and 2550-2585 m intervals in the Cable Head E-95 well, and in the 1314-1402 m and 1463-1524 m intervals in the Brion Island No. 1 well. The thecamoebians are of the same spherical morphotypes (similar to modern *Difflugia* and *Centropyxis*) observed in the Bradelle L-49 and East Point E-49 wells and outcrop samples from the Sydney Basin.

**Brion Island No. 1 well**

In the Brion Island No. 1 well, the proportion of thecamoebians in the samples fluctuated, comprising between 20% and 80% of the fauna. The highest abundances of thecamoebians occur in the 884-972 m, 1006-1094 m and 1372-1402 m intervals. *Trochammina* is the dominant agglutinated foraminifera, comprising 50-70% of the assemblage through most studied intervals. *Ammobaculites* occurs in most samples and generally dominates over the *Ammotium* and "other" groups, comprising <20% of the assemblages. Biserial and other rare foraminifera occur in the 823-881 m, 1036-1064 m, 1097-1125 m, 1417-1448 m and 1493-1524 m intervals. Fragments of smooth ostracod valves (probably *Carbonita*) occur in the 975-1003 m interval.

Lithologically, there is a general decrease in the abundance of red siltstone clasts downhole through the study interval, from approximately 70% of the clast type in the

823-881 m interval to between 10 and 40% at greater depths. Grey siltstone comprises 20-50% of the clasts in samples above 1250 m, and 50-80% of the clasts in samples below 1250 m. Sandstone clasts (generally calcareous) occur sporadically in all samples and is the dominant clast type in the 945-1033 m and 1219-1247 m intervals. Coal clasts were observed in all samples at abundances of <20%. Limestone occurs sporadically in the studied intervals.

**Cable Head E-95 well**

In the Cable Head E-95 well, thecamoebians have their greatest abundance in samples below 2550 m where they comprise up to 70% of the fauna. At shallower intervals the thecamoebians occur sporadically and comprise <15% of the fauna. *Trochammina* is the dominant agglutinated foraminiferal genus, typically comprising 60-90% of the assemblage in most samples. *Ammobaculites* and *Ammotium* are generally more abundant in the samples from the Cable Head E-95 well than in those from the Brion Island No. 1 well. Together, these two groups may locally comprise up to 50% of the fauna. As with the Brion Island No. 1 well, *Ammotium is* subordinate to *Ammobaculites.* Other rare types of foraminifera occur in low abundances in many of the samples.

Lithologically, there is a general decline in the abundance of red siltstone clasts downhole. Grey siltstone is more abundant at depths below 2505 m, and comprises 70-80% of the clasts in some cases. Sandstone is present in various proportions in all sampled intervals except 2465-2500 m. In a number of samples it comprises 50-70% of the clasts. Coal clasts are absent in intervals above 2250 m, but makes up 75% of the clasts in the 2465-2500 m interval. In other samples, coal comprises <25% of the clasts. Limestone clasts are rare, occurring in low abundances (<3%) in samples above 2375 m.

**Discussion**

No obvious faunal patterns show up in the distribution of foraminifera and thecamoebian assemblages in the Brion Island No. 1 well that would suggest an overall change in depositional settings up- or downhole. The persistence of thecamoebians in all samples studied in the Brion Island No. 1 well, however, indicates freshwater paleoenvironments existed at some time during each sample interval. Brackish water deposition also played a part during the time periods represented by the sample intervals, as indicated by the occurrence of *Trochammina* dominated foraminiferal faunas. Maximum abundances of *Ammobaculites* with "other" foraminiferal groups suggest middle (?) estuarine conditions during such intervals.

The general increase in thecamoebians downhole in the Cable Head E-95 well suggests a greater freshwater influence in the deeper sample intervals. Depths greater than 2400 m are, according to Hacquebard's (1986) work, biostratigraphically placed within Spore Zone A, (containing the Tracey Coal Seam). Assuming the spore biostratigraphy

presented in Hacquebard (1986) to be correct, a similar paleoenvironmental trend *(i.e.* an overall increase in freshwater settings downhole) is observed for the transition from Spore Zone B to Spore Zone A in the Bradelle L-49 well (see Wightman *et al.*, paper in GSC *Current Research* 1994-D).

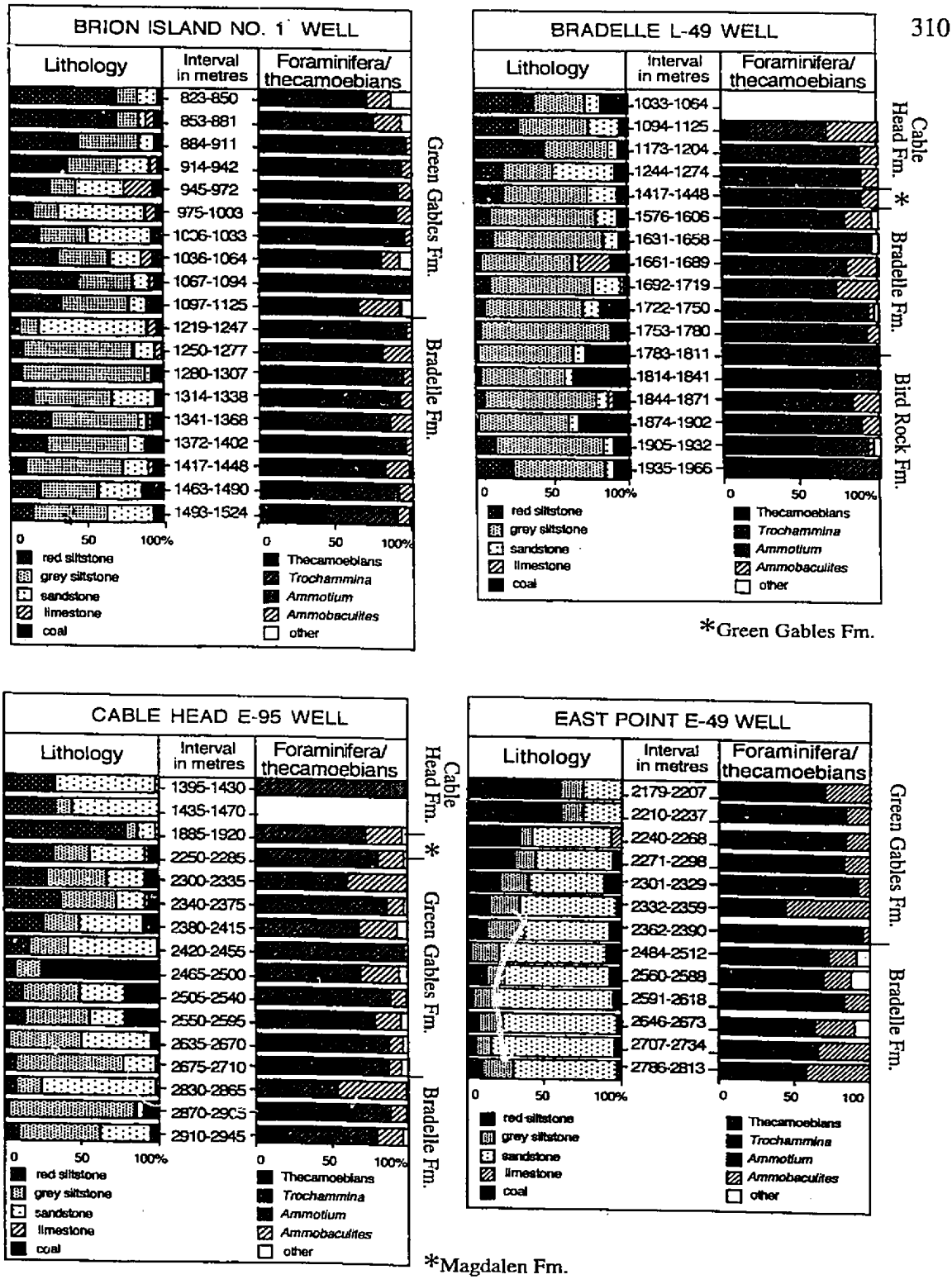



Figure II.1 Percentage diagrams of lithological clasts, agglutinated foraminifera and thecamoebians in the intervals examined in several Central Maritimes Basin (CMB) wells. Approximate locations of stratigraphic intervals are indicated on the right side of each plot.

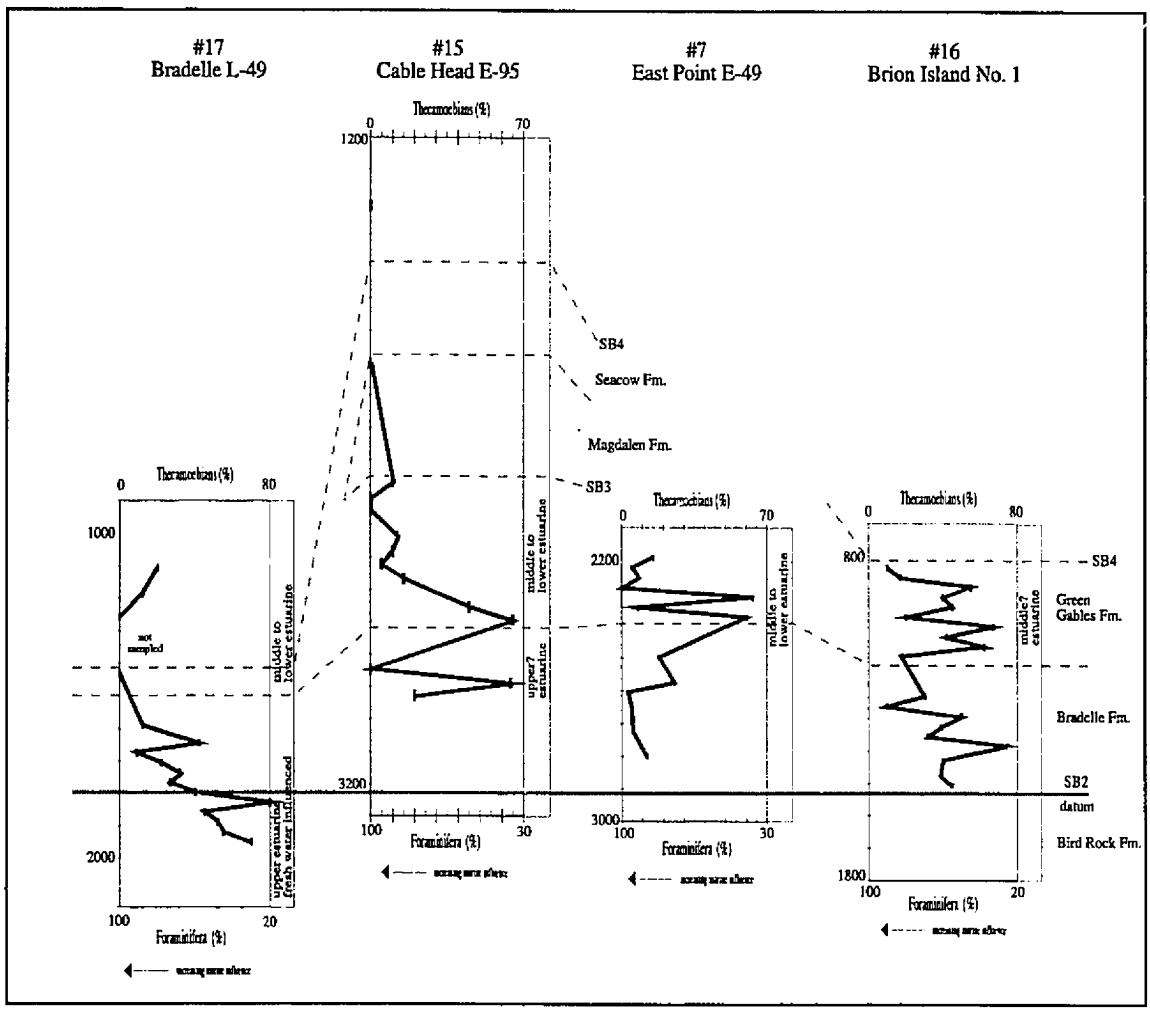



Figure II.2 Relative proportions of agglutinated foraminifera to thecamoebians plotted against depth for several CMB wells. CMB stratigraphic successions are indicated and all depths are in metres.

# Paleontological evidence for marine influence during deposition of the Westphalian Coal Measures in the Gulf of St. Lawrence-Sydney Basin region, Atlantic Canada

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*Wightman, W.G., Grant, A.C., and Rehill, T.A., 1994: Paleontological evidence for marine influence during deposition of the Westphalian Coal Measures in the Gulf of St. Lawrence-Sydney Basin region, Atlantic Canada; in Current Research 1994-D; Geological Survey of Canada, p. 41-50.*

**Abstract:** Coal Measures penetrated by oil and gas exploration wells in Gulf of St. Lawrence – Sydney Basin are a regionally mappable seismic facies. The broad extent of this seismic facies has prompted the speculation that it reflects cyclothem deposition, analogous to cyclothem deposits of the Illinois Basin and Mid-Continent Basin region of the United States. This implies that the depositional cycles included periods of marine incursion. Evidence for such incursions, in the form of agglutinated foraminifera assemblages, has been reported from coal-bearing strata of the Sydney Basin, Cape Breton Island. Similar assemblages have now been found in two offshore wells in the Gulf of St. Lawrence. This discovery supports arguments for cyclothymic deposition, enhances the possibility of marine source rocks for hydrocarbon generation, and underlines the need for review of the paleogeographic and depositional history of the Central Maritimes Basin.

**Résumé :** Les couches de charbon traversées par des puits d'exploration du pétrole et du gaz, dans le golfe du Saint-Laurent et le bassin de Sydney, représentent un faciès sismique cartographiable à l'échelle régionale. En raison de la vaste étendue de ce faciès sismique, on a formulé l'hypothèse selon laquelle il représenterait le dépôt de cyclothèmes analogues à ceux du bassin de l'Illinois et de la région du bassin médio-continental des États-Unis. Ceci signifie que les cycles de sédimentation comprenaient des périodes d'incursion des eaux marines. Les preuves de ces incursions, soit la présence d'associations de foraminifères à test agglutiné, ont été signalées dans les strates houillères du bassin de Sydney, dans l'île du Cap-Breton. Des associations semblables ont été observées dans deux puits extracôtiers du golfe du Saint-Laurent. Cette découverte appuie l'hypothèse du dépôt de cyclothèmes, augmente la possibilité de la présence de roches mères marines capables de former des hydrocarbures, et souligne le besoin de réviser l'évolution paléogéographique et sédimentaire de la partie centrale du bassin des Maritimes.

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## INTRODUCTION

The Gulf of St. Lawrence – Sydney Basin region includes Prince Edward Island and the offshore part of the Permo-Carboniferous Maritimes Basin of Atlantic Canada (Fig. 1). In assessing the offshore extent of the late Westphalian to Stephanian (Fig. 2) coal seams formerly mined in the Mabou and Inverness coalfields, western Cape Breton island, Hacquebard (1986) examined five oil and gas exploratory wells in the Gulf of St. Lawrence (Fig. 3). Four distinctive coal-bearing zones were recognized that could be traced over distances of up to 240 km and correlated with onshore sections. The coal zones were named after intervals of coal seams found in the Sydney Mines Formation of the Sydney coalfield (Fig. 3), and dated by Barss and Hacquebard's (1967) spore zones of the Pictou Group (Fig. 2). Hacquebard (1986) and Hacquebard et al. (1989) interpreted the Mabou and Inverness coalfields to be part of a much larger basin, and defined the Gulf of St. Lawrence Carboniferous Coal Basin as the largest coal basin in eastern Canada.

Based on interpretation of industry seismic data (Fig. 4), Grant and Moir (1992) showed that the coal occurrences in the exploratory wells coincide with a "Coal Measures" seismic facies mappable over a large portion of the Gulf of St. Lawrence – Sydney Basin region (Fig. 5). They inferred the original extent of Coal Measures deposition to be over 100 000 km$^2$. Grant (in press) compared the depositional extent of this seismic facies to that of cyclothem deposition in the Illinois Basin and Mid-Continent Basin region of the United States.

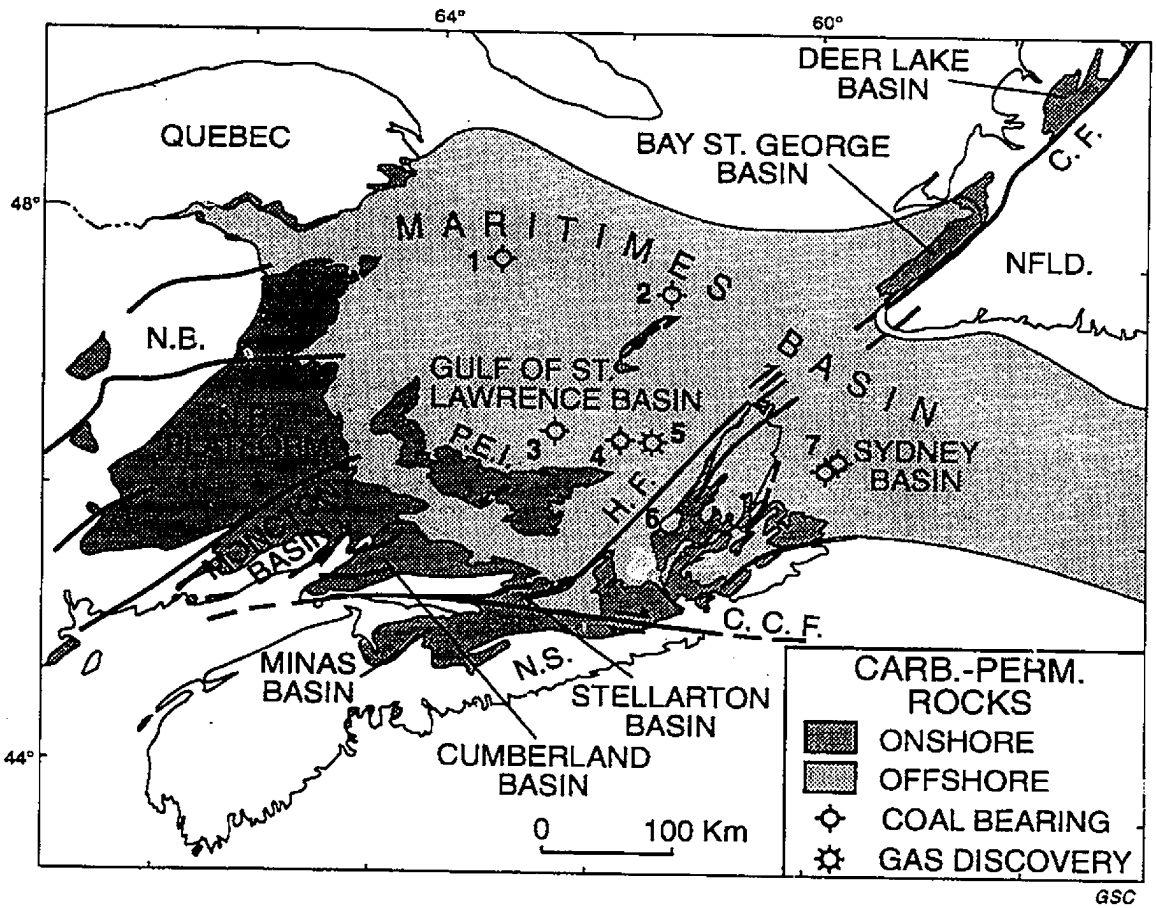


*Figure 1. Distribution of Carboniferous and Permian rocks (shaded) in the Maritimes Basin of Atlantic Canada. Major faults: C.F. – Cabot Fault; C.C.F. – Cobequid-Chedabucto Fault; H.F. – Hollow Fault. Numbers denote well locations offshore and coalfields on land referred to in text: 1 – Bradelle L-49 well; 2 – Brion Island No. 1 well; 3 – Cable Head E-95 well; 4 – Beaton Point F-70 well; 5 – East Point E-49 well; 6 – Mabou-Inverness coalfield; 7 – Sydney coalfield on land to south-southwest. After Gibling et al. (1992).*

The Sydney Mines Formation of the Sydney Basin coalfield has traditionally been thought to have been deposited in a freshwater setting. However, documentation of cyclothymic stratal patterns (Bird, 1987), and preliminary identification of agglutinated foraminifera (Thibideau and Medioli, 1986), suggested a marine influence during deposition. Gibling and Bird (1990) and Gibling (1992) subsequently documented eleven complete cyclothems within the Sydney Mines Formation. Wightman et al. (1992, 1993, in press) have reported on the agglutinated foraminifera and thecamoebian assemblages within these cyclothems, and identified various levels of marine influence during deposition.

The presence of marine strata in the Upper Carboniferous of the Maritimes Basin would have implications for marine source rock distribution and reservoir depositional models. Therefore, the Geological Survey of Canada issued a contract (Wightman, 1993, No. 23420-3-Co69/01-OSC) to examine cuttings from exploratory wells in the Gulf of St. Lawrence region for the presence of similar agglutinated foraminifera and thecamoebian assemblages. Although this work is still in progress, preliminary results indicate the occurrence of such assemblages in the Bradelle L-49 and East Point E-49 wells (Fig. 1, 3, 5). This paper documents the distribution of the assemblages in these wells, and comments on their significance.

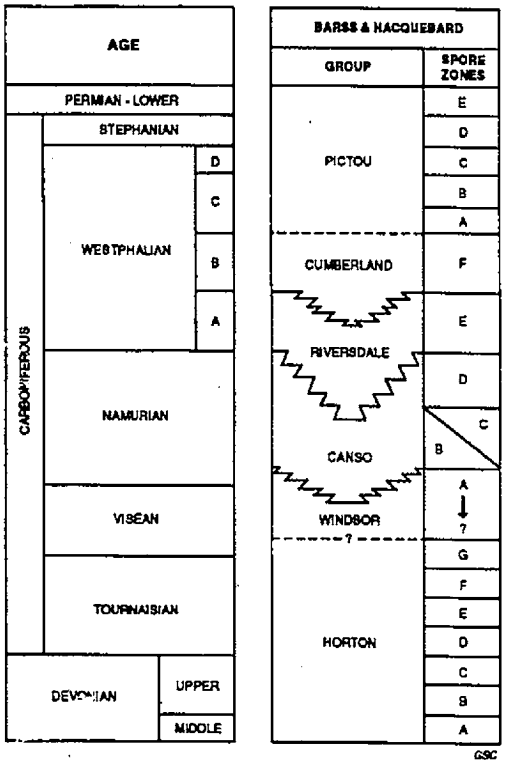


*Figure 2. Stratigraphic subdivisions and age of Upper Paleozoic rocks in eastern Canada, after Hacquebard et al. (1989).*

## MATERIALS AND METHODS

Rotary cuttings from the Gulf of St. Lawrence wells are stored in the Nova Scotia Offshore Petroleum Board facilities, Dartmouth, Nova Scotia. Samples of approximately 20 g were collected every 3 m, and combined every 30 m, resulting in a 200 g sample for each 30 m interval. Allowing for intervals for which no samples were available, this resulted in a total of 17 samples for the 1033-1966 m interval in the Bradelle L-49 well, and 13 samples for the 2179-2813 m interval in the East Point E-49 well. These intervals correspond to the approximate position of the coal-bearing strata identified in the wells by Hacquebard (1986), and the Coal Measures seismic facies mapped by Grant and Moir (1992). The advantage of our sampling strategy is that it allows for a rapid appraisal of the microfossil characteristics of each well. The main drawback is that if nine of the ten samples collected for each 30 m interval are barren of microfossils, any microfossils in the tenth sample will be diluted by a factor of ten.

Samples from the Bradelle L-49 well were washed through a 63 µm wet sieve to remove the clay, and then oven dried. A portion of each washed sample was put aside for immediate examination, while the remainder of the sample was processed using the industrial detergent method described by Wightman et al. (in press). Comparison of the portions of the samples that had been washed only with water to the portions treated with industrial detergent showed that no significant advantage was to be gained from use of the latter method. This is probably because drilling had ground the strata sufficiently to release the microfossils through mechanical breakdown of the rock. The samples from the East Point E-49 well were consequently not treated with industrial detergent. A small (approximately 10 g) portion of the coarse (>1.0 mm) fraction of the water-washed samples from both wells was also treated with sodium hypochlorite, using the method described by Wightman et al. (in press). This method of treatment is the most effective way of releasing agglutinated foraminifera from carbonaceous shales and siltstones, and gave good results in this study.

Washed residues were sieved into >63 µm, >125 µm, >250 µm and >500 µm size fractions, and each of these was systematically examined by sprinkling an even, light coating of the residue over a 5 cm x 10 cm picking tray. All foraminifera and thecamoebians were picked from two such picking tray spreads for each size fraction. Because of poor preservation, specimens were examined under both reflected light, and transmitted light with glycerin. Photomicrographs of the best specimens were taken with the environmental scanning electron microscope unit at the Atlantic Geoscience Centre.

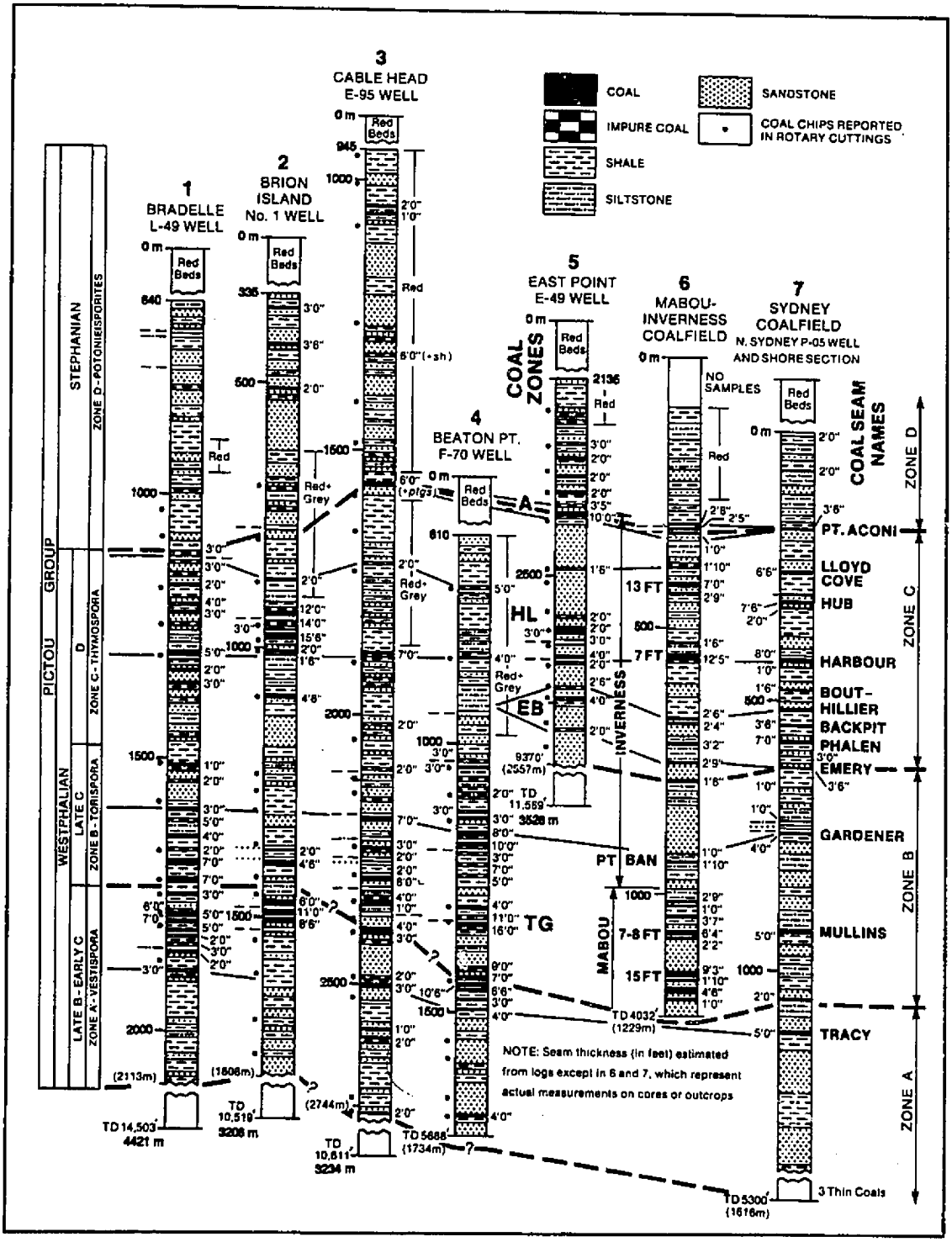


*Figure 3. Logs of wells in the Gulf of St. Lawrence region with correlations of coal-bearing strata to coalfields on Cape Breton Island (locations in Fig. 1). After Hacquebard (1986).*

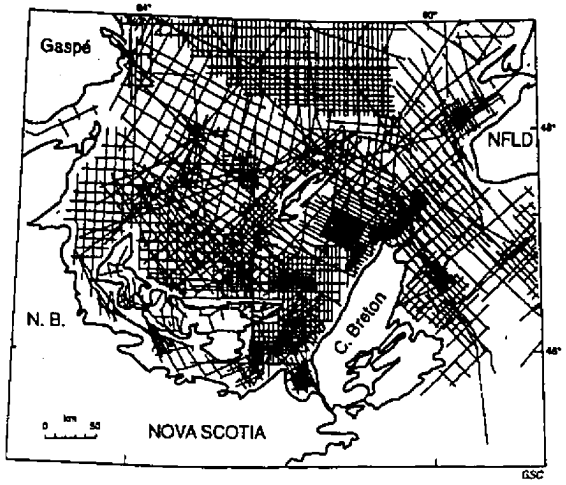


*Figure 4. Map showing location of industry seismic lines in the Gulf of Saint Lawrence and on Prince Edward Island. From Grant and Moir (1992).*

## RESULTS

As discussed above, our sampling strategy enables a rapid overview of the wells to determine if there were marine influences during deposition. Although the results represent an average of each 30 m interval, broader distribution patterns of the agglutinated foraminifera and thecamoebians both downhole and between the two wells are apparent. Agglutinated foraminifera and thecamoebians were identified at all intervals in both wells, with the exception of the 1033-1064 m interval in the Bradelle L-49 well. Variations in the thecamoebian and agglutinated foraminiferal components picked from each interval are plotted in percentage diagrams, together with lithology types (Fig. 6, 7). Lithology types are based on grain counts of the same intervals.

In both wells, the agglutinated foraminifera are dominated by the genera *Trochammina*, *Ammotium* and *Ammobaculites*. The morphological variants within these groups (Plate 1) are similar to those observed in the Sydney Coalfield (Wightman et al., 1993, in press) and the Illinois Basin (Devera et al., 1993). Other groups found include biserial morphotypes and uniserial forms that may include *Reophax*, although the

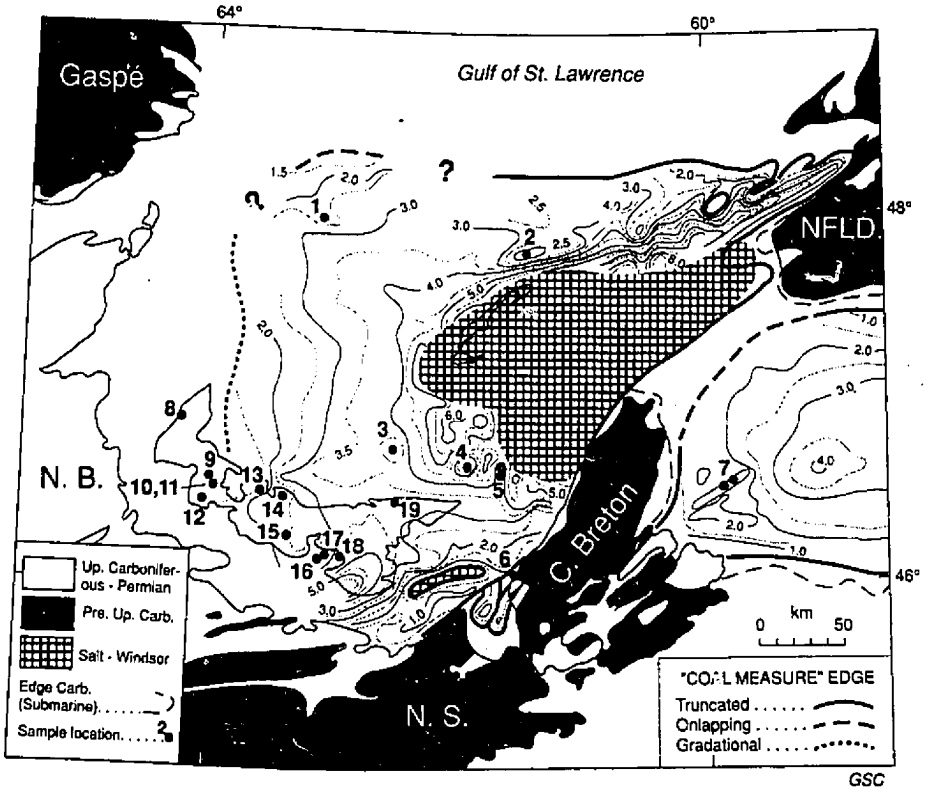


*Figure 5. Map of the present extent and depth of the Coal Measures seismic facies, contour interval 0.5 km, derived from interpretation of industry seismic data (Fig. 4). Areas of evaporite tectonism indicated by cross hatching. Numbers denote well locations and coal mining areas; 1-7 are identified in Figure 1 caption. After Grant and Moir (1992).*

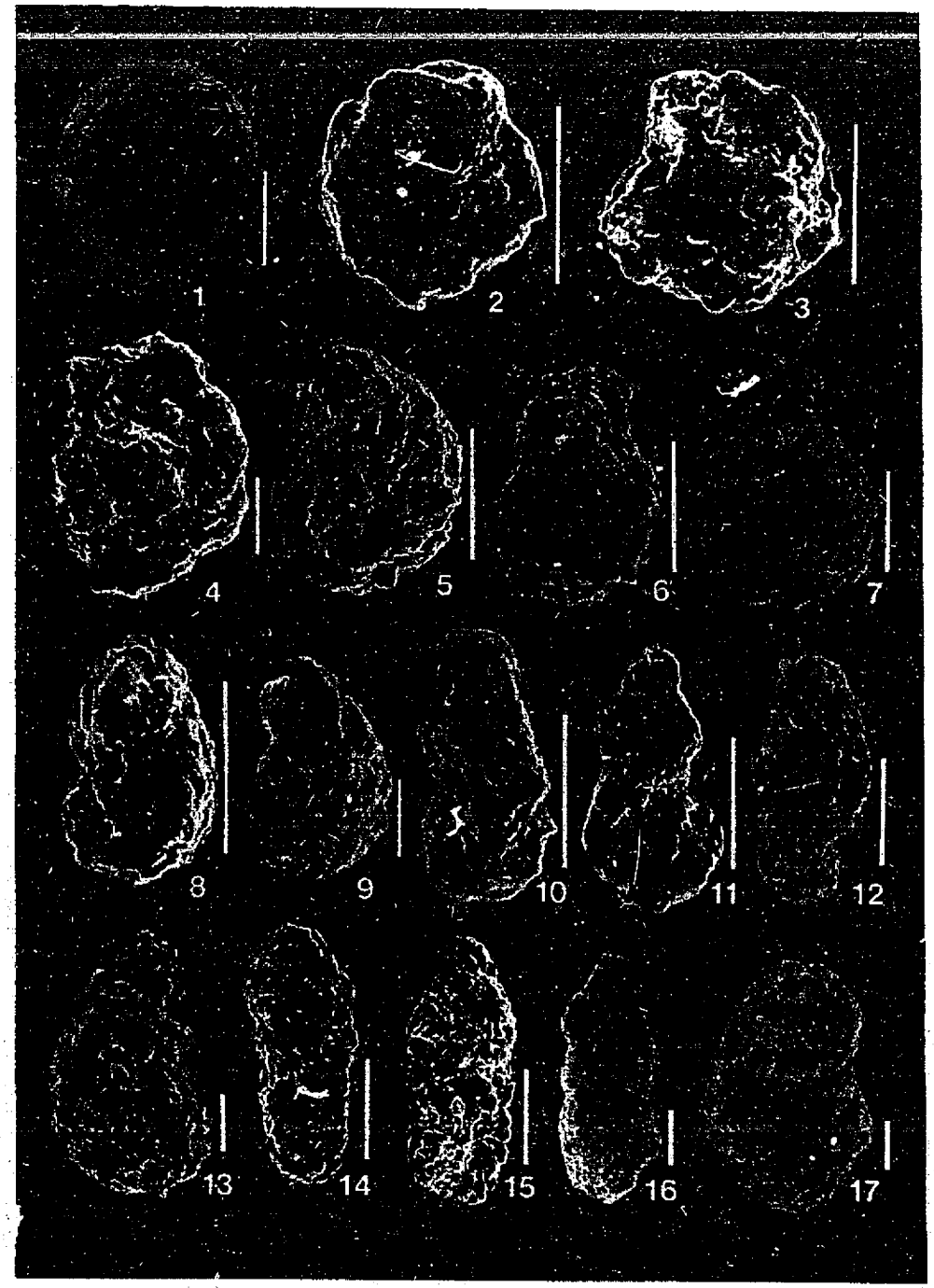


**PLATE 1**

number of specimens is small and the preservation too poor to make accurate identifications. The thecamoebians are of the spherical morphotypes (comparable to recent *Difflugia* and *Centropyxis*), also reported from the Sydney Coalfield (Wightman et al., in press).

In the Bradelle L-49 well, the proportion of thecamoebians in the interval sampled increases downhole to the point where they dominate over the agglutinated foraminiferal groups at intervals below 1829 m. *Trochammina* is dominant over the other groups of agglutinated foraminifera and is generally more abundant in the shallower part of the sample interval. *Ammotium* is represented by low numbers of individuals that occur sporadically in the samples. *Ammobaculites* occurs in more samples than *Ammotium*, and is generally more abundant. Biserial forms occur in low abundances in the 1576-1589 m, 1722-1750 m and 1905-1932 m intervals. Lithologically, grey siltstone is the dominant clast type in the Bradelle L-49 well samples. Red siltstone occurs in equal proportion to the grey siltstone in the upper 91 m of the sample interval, but declines thereafter. The proportion of coal is often highest within the deeper intervals. Sandstone occurs sporadically in most samples, and is more common in the upper part of the sample interval. Limestone clasts occur in the 1661-1719 m interval only.

With the exception of the 2301-2329 m and 2362-2390 m intervals in the East Point E-49 well, agglutinated foraminifera are dominant over the thecamoebians. The uncoiling morphotypes *Ammotium* and *Ammobaculites* represent a greater proportion of the fauna in the sampled interval in this well than in the Bradelle L-49 well, and combined, they dominate the assemblages in the 2332-2359 m and 2786-2813 m intervals. As with the Bradelle L-49 samples, *Ammobaculites* occurs

## PLATE 1

**Scale bar = 100 μm**

**Figure 1.** Thecamoebian, spherical form with a short spine, comparable to the modern genus *Centropyxis*. Bradelle L-49 well, 1244-1274 m.

**Figures 2, 3.** *Trochammina* spp. East Point E-49 well, 2301-2329 m (specimen 2); 2591-2618 m (specimen 3).

**Figures 4-11.** *Ammobaculites* spp. **4**: specimen with well developed coil. Uncoiled portion broken off. East Point E-49 well, 2210-2237 m. **5**: Showing well developed coil. Bradelle L-49 well, 1417-1445 m. **6, 7**: large coiled variants that have retained part of their uncoiled portions. Bradelle L-49 well, 1661-1689 m (specimen 6), 1094-1125 m (specimen 7). **8, 9**: smaller coiled variants. East Point E-49 well, 2484-2512 m (specimen 8), 2179-2207 m (specimen 9). **10, 11**: Specimens with well developed uncoiled portions. Note the preservation of the terminal aperture on specimen 11. East Point E-49 well, 2707-2734 m (specimen 10), 2591-2618 m (specimen 11).

**Figures 12-16.** *Ammotium* spp. **12**: Small coiled variant, Bradelle L-49 well, 1094-1122 m. **13**: Large coiled variant composed of fine sand grains. East Point E-49 well, 2240-2268 m. **14-16**: small coiled variants with typical form of aperture that is drawn out on a short neck. Specimen 16 displays well preserved lobate lateral margins. East Point E-49 well, 2646-2673 m (specimen 14), 2362-2390 m (specimen 15), Bradelle L-49 well, 1094-1122 m (specimen 16).

**Figure 17.** Agglutinated foraminifera of uncertain affinity. The aperture, which has been infilled, appears as a circular depression on the face of the final chamber. Bradelle L-49 well, 1661-1689 m.

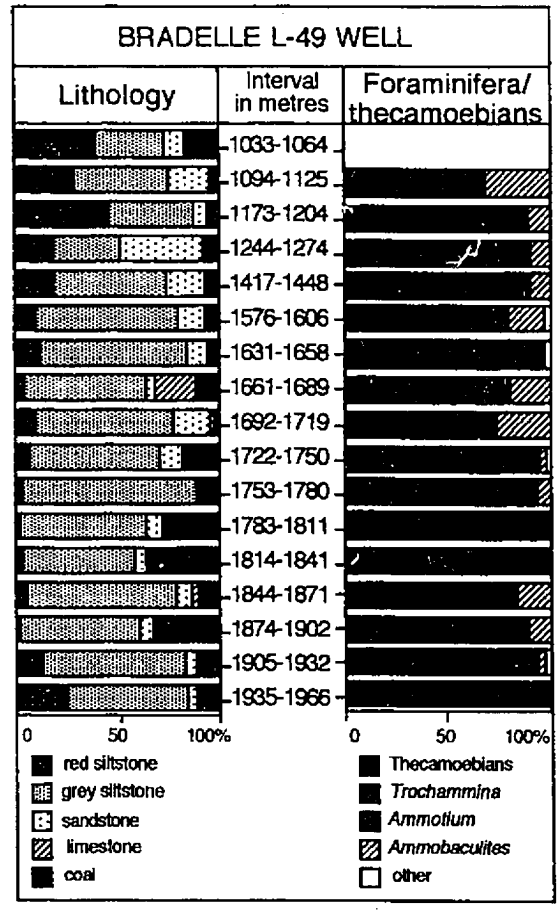


*Figure 6. Percentage diagrams of lithological clasts and agglutinated foraminifera and thecamoebians in the intervals examined in the Bradelle L-49 well.*

more frequently than *Ammotium*, and is usually more abundant. *Trochammina* is present in all intervals and typically comprises 30 to 70% of the fauna. Other types of agglutinated foraminifera, including biserial forms and possible *Reophax*, occur in the 2484-2588 m and 2646-2673 m intervals in moderate proportions. In comparison with the Bradelle L-49 well, the East Point E-49 sample interval is lithologically more sandy. Sandstone is the dominant lithology through most of the samples, and increases in its proportion downhole to compose as much as 80% of the clasts. Red siltstone is most abundant in the upper 61 m of the sample interval, but decreases downhole. Grey siltstone occurs in moderate proportions (<25% of the clasts) through most of the samples, whereas coal is present in small proportions (<15%) at depths below 2271 m. A small amount of limestone was observed in the 2240-2268 m interval.

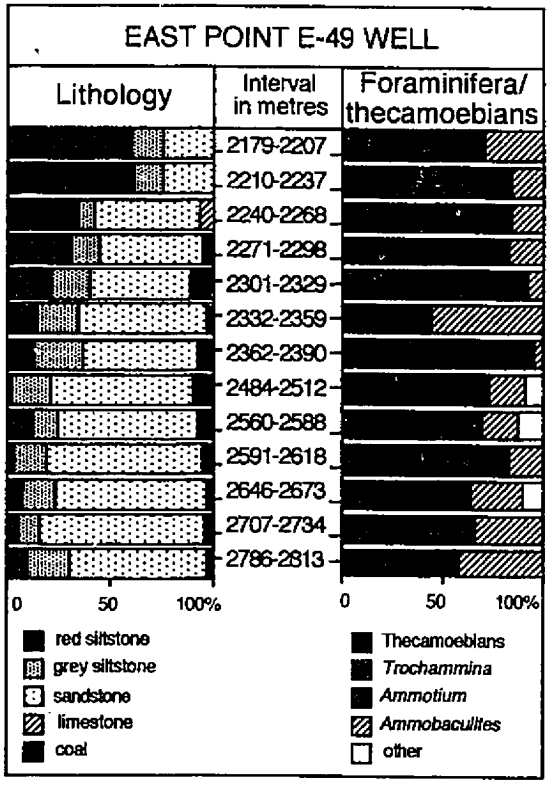


***Figure 7.*** *Percentage diagrams of lithological clasts and agglutinated foraminifera and thecamoebians in the intervals examined in the East Point E-49 well.*

## DISCUSSION

### *Paleoenvironmental interpretation*

The distribution of agglutinated foraminifera and thecamoebian assemblages in the Bradelle L-49 and East Point E-49 wells can be compared with the distribution of similar assemblages in coastal outcrop sections of Westphalian to Stephanian age in the Sydney Basin, Nova Scotia, examined in detail by Wightman et al. (1993, in press). Direct comparison may also be made with the modern distributions of agglutinated assemblages in marginal marine and coastal settings, since the foraminiferal faunas in these environments have evolved little, if at all, and have occupied the same ecological niches for the past 300 Ma (Wightman et al., 1993).

### *Bradelle L-49 well*

The gradual increase in thecamoebians downhole in the Bradelle L-49 well suggests an overall increase in freshwater depositional settings with depth, based on the predominance of thecamoebians in freshwater environments today (Medioli and Scott, 1983). Carboniferous thecamoebian and agglutinated foraminiferal assemblages are, in many cases, mutually exclusive in coal bearing strata from the Sydney Basin, indicating the two groups occupied separate niches in adjacent (freshwater and brackish) environments (Wightman et al., in press).

Brackish water environments are also evident in the Bradelle L-49 well, based on the agglutinated foraminiferal assemblages dominated by *Trochammina*. The 1935-1966 m interval, characterized by thecamoebians and *Trochammina*, suggests restricted high marsh environments may have fluctuated with freshwater environments at the terrestrial extreme of tidal influence within an upper estuarine setting. A similar interpretation has been made for alternation of thecamoebian and *Trochammina* assemblages preserved in the seat earth beneath the Point Aconi coal seam in the Sydney Coalfield (Wightman et al., in press). *Trochammina* dominates higher elevations in modern salt marshes (Scott et al., 1991), but is also found in association with *Ammotium*, *Ammobaculites* and other agglutinants in lower marsh or estuarine environments (Ellison and Nichols, 1976; Scott et al., 1991).

The association of *Ammotium* and *Ammobaculites* in many of the sample intervals of the Bradelle L-49 well suggests middle or lower estuarine deposition. This is supported by the presence of biserial foraminifera, normally associated with more open marine environments and subject to reworking into shallower areas.

### *East Point E-49 well*

The greater abundance of *Ammotium* and *Ammobaculites* in the East Point E-49 samples suggests deposition was under more of a marine influence than the sampled interval in the Bradelle L-49 well. This interpretation is supported by larger proportions of biserial and other forms in three of the intervals. Although thecamoebians are present, there is no obvious trend that would indicate an overall change in depositional environments up- or downhole. The dominance of thecamoebians in the 2301-2329 m and 2362-2390 m intervals suggests, however, a greater freshwater influence during these two episodes.

### *Regional implications*

Within a regional context, the sampled strata of the Bradelle L-49 well were likely to have been deposited in an uppermost estuarine setting, at the terrestrial extreme of tidal influence. The general dominance of finer sediments in this section supports our interpretation of an uppermost estuarine mudflat paleoenvironment, with adjacent freshwater coal-forming swamps and marshes. The sampled strata of the East Point E-49 well, in contrast, were probably deposited in a middle to lower estuarine environment. The dominantly sandy character of the samples accords with this interpretation.

Following Hacquebard's (1986) correlation of the main coal-bearing strata in the Gulf of St. Lawrence and Sydney Basins, the 1033-1448 m interval in the Bradelle L-49 well would correlate with the 2484-2813 m interval in the East Point E-49 well, and would represent all but the lowest (Emery) coal seam of the Sydney Mines Formation of the Sydney Coalfield (Barss and Hacquebard's (1967) Spore Zone C). Gibling (1992) recognized eleven cyclothems within the Sydney Mines Formation, and assuming Hacquebard's (1986) correlations to be correct, we anticipate the cyclothems to be present within the above intervals in the Bradelle L-49 and East Point E-49 wells. Work currently being undertaken by T.A. Rehill (Dalhousie University, Ph.D. thesis) on the downhole characteristics of these two wells will evaluate the existing correlations between the wells, and will help to evaluate the role of cyclothymic deposition in the Maritimes Basin.

The agglutinated foraminifera and thecamoebian assemblages of the Gulf of St. Lawrence are closely similar to those documented from the cyclothems of the Sydney Coalfield (Wightman et al., 1993, in press). Several distinctive paleoenvironments, related to the varying degrees of marine influence associated with cyclothem development have been recognized on the basis of their agglutinated foraminifera and thecamoebian assemblages (Gibling and Wightman, in prep.) The assemblages identified in the Bradelle L-49 and East Point E-49 wells undoubtedly represent the combination of several distinct paleoenvironments that would have developed as a result of varying marine influences during cyclothymic deposition.

## CONCLUSIONS

The discovery of agglutinated foraminifera assemblages in offshore wells in the Gulf of St. Lawrence supports the argument that the regionally extensive Coal Measures seismic facies reflects cyclothymic deposition, including phases of marine incursion. A marine component in this facies enhances the possibility of marine source rocks for hydrocarbon generation, with potential for oil as well as gas resources related to the Coal Measures facies. These new findings highlight the need for further research on the paleogeographic and depositional history of the Gulf of St. Lawrence region of the Maritimes Basin, and for review of the hydrocarbon potential of this region.

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## REFERENCES

**Barss, M.S. and Hacquebard, P.A.**
1967: Age and the stratigraphy of the Pictou Group in the Maritime Provinces as revealed by fossil spores; Geological Association of Canada, Special paper 4, p. 267-282.

**Bird, D.J.**
1987: The depositional environment of the Late Carboniferous, coal-bearing Sydney Mines Formation, Point Aconi area, Cape Breton Island, Nova Scotia; M.Sc. thesis, Dalhousie University, 343 p.

**Devera, J., Staub, J., Kvale, E., Eble, C., Nelson, J., Dimichele, W., and Wightman, W.G.**
1993: Tidally influenced depositional settings in the Tradewater Formation (Westphalian B, C, and D), Illinois Basin, U.S.A; in Carboniferous to Jurassic Pangea: A global view of environments and resources; Canadian Society of Petroleum Geologists, Program and Abstracts, p. 74.

**Ellison, R.L. and Nichols, M.M.**
1976: Modern and Holocene foraminifera in the Chesapeake Bay region; in First International Symposium on Benthonic foraminifera of the continental margins, Part A, Ecology and Biology; Maritime Sediments, Special Publication 1, p. 131-151.

**Gibling, M.R.**
1992: Late Carboniferous alluvial paleovalleys in the Sydney basin of Nova Scotia; Geological Association of Canada, Abstracts, v. 17, p. A39-40.

**Gibling, M.R. and Bird, D.J.**
1990: Late Carboniferous cyclothems in the Sydney Coalfield; Nova Scotia Department of Mines and Energy, Report 90-3, p. 39.

**Gibling, M.R., Calder, J.H., Ryan, R., van de Poll, H.W., and Yeo, G.M.**
1992: Late Carboniferous and Early Permian drainage patterns in Atlantic Canada; Canadian Journal of Earth Sciences, v. 29, p. 338-352.

**Grant, A.C.**
In press: Aspects of seismic character and extent of Upper Carboniferous Coal Measures, Gulf of St. Lawrence and Sydney Basins; Paleogeography, Paleoclimatology, Paleoecology.

**Grant, A.C. and Moir, P.N.**
1992: Observations on coalbed methane potential, Prince Edward Island; in Current Research, Part E; Geological Survey of Canada, Paper 92-1E, p. 267-278.

**Hacquebard, P.A.**
1986: The Gulf of St. Lawrence Carboniferous Basin; the largest coalfield of eastern Canada; Bulletin of Canadian Institute of Mining and Metallurgy, v. 79, p. 67-78.

**Hacquebard, P.A., Gillis, K.S., and Bromley, D.S.**
1989: Re-evaluation of the coal resources of Western Cape Breton Island; Nova Scotia Department of Mines and Energy, Paper 89-3, 47 p.

**Medioli, F.S. and Scott, D.B.**
1983: Holocene Arcellacea (Thecamoebians) from eastern Canada; Cushman Foundation for Foraminiferal Research, Special Publication 21, 63 p.

**Scott, D.B., Suter, J.R., and Kosters, E.C.**
1991: Marsh foraminifera and arcellaceans of the lower Mississippi Delta: Controls on spatial distributions; Micropalaeontology, v. 37, p. 373-392.

**Thibaudeau, S.A. and Medioli, F.S.**
1986: Carboniferous thecamoebian and marsh foraminifera: New stratigraphic tools for ancient paralic deposits; Geological Society of America Abstracts with Programs, v. 18, p. 771.

**Wightman, W.G., Scott, D.B., Medioli, F.S., and Gibling, M.R.**
1992: Upper Pennsylvanian agglutinated foraminifers from the Cape Breton coalfield, Nova Scotia: Their use in the determination of brackish-marine depositional environments; Geological Association of Canada Annual Meeting, Abstracts, v. 17, p. A117.

**Wightman, W.G., Scott, D.B., Medioli, F.S., and Gibling, M.R.**
1993: Carboniferous marsh foraminifera from coal-bearing strata of the Sydney Basin, Nova Scotia: A new tool for identifying paralic coal-forming environments; Geology, v. 21, p. 631-634.

**Wightman, W.G., Scott, D.B., Medioli, F.S., and Gibling, M.R.**
In press: Agglutinated foraminifera and thecamoebians from the late Carboniferous Sydney Coalfield, Nova Scotia: Paleoecology, paleoenvironments and paleogeographical implications; Paleogeography, Paleoclimatology, Paleoecology.

Geological Survey of Canada Project 870050

# APPENDIX III: GEOLOGIC TOPS FOR CMB STUDY WELLS

Table III.1 List of stratigraphic tops for CMB study wells. All unit boundary depths are taken from original gamma-ray/sonic log depths and are measured in metres. Wells are in alphabetical order. Depths marked "approx" for the Windsor Group are measured from seismic data. ("+" positive rotary table and water depths indicate values above sea level)

| **Common Well Name** | **BARTIBOG NO. 1** |
|---|---|
| UWI | rdBartibog-#1 |
| Latitude | 47.21278 |
| Longitude | -65.40139 |
| X Coordinate | 318163.13 |
| Y Coordinate | 52316070.07 |
| Rig Release Date | 29-Aug-67 |
| Rotary Table | 1.5 |
| Water Depth | +89.0 |
| Total Depth | 683.1 |
| | |
| Pick Name | Pick Depth (MD) |
| ======== | ========== |
| Post-Permian Unconformity | 2.3 |
| Cable Head Fm. | 2.3 |
| Green Gables Fm. | 331.9 |
| Bradelle Fm. | 414.4 |
| BASEMENT | 682.7 |
| | |
| **Common Well Name** | **BEATON POINT F-70** |
| UWI (Unique Well Identifier) | D189 |
| Latitude | 46.65553 |
| Longitude | -61.91247 |
| X Coordinate | 583209.53 |
| Y Coordinate | 5167459.63 |
| Rig Release Date | 27-Aug-80 |
| Rotary Table | 27.6 |
| Water Depth | 56.2 |
| Total Depth | 1734 |
| | |
| Pick Name | Pick Depth (MD) |
| ======== | ========== |
| Post-Permian Unconformity | 116.7 |
| Cable Head Fm. | 116.7 |
| Seacow Fm. | 623.3 |
| Magdalen Fm. | 778.8 |
| Green Gables Fm. | 1064.3 |
| Bradelle Fm. | 1200.7 |
| Windsor Group (approx) | 3182.3 |
| coal1 | 835.1 |
| coal2 | 1050.4 |
| coal3 | 1062.5 |
| coal4 | 1100.5 |
| coal5 | 1128.2 |
| coal6 | 1223.2 |
| coal7 | 1231.8 |
| coal8 | 1306.1 |
| coal9 | 1321.6 |
| coal10 | 1420.1 |
| coal11 | 1446 |
| coal12 | 1456.3 |
| coal13 | 1496.1 |

| | |
|---|---|
| coal14 | 1694.7 |
| | |
| **Common Well Name** | **BIRCH GROVE #1** |
| UWI (Unique Well Identifier) | RDBIRCH_GROVE_#1 |
| Latitude | 46.14511 |
| Longitude | -59.93473 |
| X Coordinate | 736725.7 |
| Y Coordinate | 51147380.85 |
| Rig Release Date | 20-May-68 |
| Rotary Table | 3.2 |
| Water Depth | +46.5 |
| Total Depth | 1343.6 |
| | |
| Pick Name | Pick Depth (MD) |
| ======== | ========== |
| Post-Permian Unconformity | 3.5 |
| Green Gables Fm. | 3.5 |
| Bradelle Fm. | 102.4 |
| Namurian/Westphalian Event | 846 |
| Mabou Group | 846 |
| Windsor Group | 1061 |
| Horton Group | 1191.9 |
| coal1 | 142.4 |
| coal2 | 198.4 |
| coal3 | 219.7 |
| coal4 | 266.8 |
| coal5 | 272.2 |
| coal6 | 292.6 |
| coal7 | 304.6 |
| coal8 | 340.6 |
| coal9 | 376.6 |
| | |
| **Common Well Name** | **BLANCHARD NO. 1** |
| UWI (Unique Well Identifier) | rdBlanchard-#1 |
| Latitude | 47.71333 |
| Longitude | -65.89556 |
| X Coordinate | 282819.35 |
| Y Coordinate | 52885000.68 |
| Rig Release Date | 4-Aug-67 |
| Rotary Table | 1.5 |
| Water Depth | +20.7 |
| Total Depth | 718.9 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 1.6 |
| Cable Head Fm. | 1.6 |
| Green Gables Fm. | 390.9 |
| Bradelle Fm. | 447.9 |
| | |
| **Common Well Name** | **BRADELLE L-49** |
| UWI (Unique Well Identifier) | D110 |
| Latitude | 47.97393 |
| Longitude | -63.13841 |
| X Coordinate | 489670.2 |
| Y Coordinate | 53134110.36 |
| Rig Release Date | 1-Dec-73 |
| Rotary Table | 29.9 |
| Water Depth | 56.7 |
| Total Depth | 4368.4 |

| Pick Name | Pick Depth (MD) |
|---|---|
| Post-Permian Unconformity | 116.1 |
| Naufrage Fm. | 116.1 |
| Cable Head Fm. | 918.1 |
| Green Gables Fm. | 1417.7 |
| Bradelle Fm. | 1498 |
| Bird Rock Fm. | 1793.9 |
| Brion Island Fm. | 2105.2 |
| Namurian/Westphalian Event | 2395 |
| Mabou Group | 2395 |
| Windsor Group | 2879.9 |
| Horton Group | 2916.6 |
| coal1 | 672.7 |
| coal2 | 863.8 |
| coal3 | 913.1 |
| coal4 | 1018.8 |
| coal5 | 1030.6 |
| coal6 | 1074.3 |
| coal7 | 1079.1 |
| coal8 | 1109 |
| coal9 | 1174.5 |
| coal10 | 1207.6 |
| coal11 | 1211.2 |
| coal12 | 1223.4 |
| coal13 | 1245.5 |
| coal14 | 1262.8 |
| coal15 | 1306.6 |
| coal16 | 1508.7 |
| coal17 | 1539.1 |
| coal18 | 1584.8 |
| coal19 | 1594.2 |
| coal20 | 1613.2 |
| coal21 | 1630.5 |
| coal22 | 1643.1 |
| coal23 | 1668.4 |
| coal24 | 1677 |
| coal25 | 1690 |
| coal26 | 1698.3 |
| coal27 | 1706.2 |
| coal28 | 1724.3 |
| coal29 | 1748.4 |
| coal30 | 1754.7 |
| coal31 | 1785.8 |
| coal32 | 1758.2 |
| coal33 | 1763 |
| coal34 | 1814.2 |
| coal35 | 1828 |
| coal36 | 1841.4 |
| coal37 | 1857.2 |
| coal38 | 1870.2 |
| coal39 | 1894.6 |
| coal40 | 1899.4 |
| coal41 | 1904.9 |
| coal42 | 1908.8 |
| coal43 | 1931.3 |
| coal44 | 1986.1 |
| coal45 | 2005 |
| coal46 | 2018.8 |

| | |
|---|---|
| coal47 | 2051.9 |
| coal48 | 2160.4 |
| | |
| **Common Well Name** | **BRION ISLAND NO.1** |
| UWI (Unique Well Identifier) | D037 |
| Latitude | 47.78463 |
| Longitude | -61.4661 |
| X Coordinate | 614896.4 |
| Y Coordinate | 52935020.78 |
| Rig Release Date | 11-Dec-70 |
| Rotary Table | 4.8 |
| Water Depth | +6.6 |
| Total Depth | 3168.7 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 7.9 |
| Naufrage Fm. | 7.9 |
| Cable Head Fm. | 405.1 |
| Green Gables Fm. | 802.3 |
| Bradelle Fm. | 1133.3 |
| Bird Rock Fm. | 1538.3 |
| Brion Island Fm. | 1737 |
| Namurian/Westphalian Event | 2048.5 |
| Mabou Group | 2048.5 |
| Windsor Group | 2747.5 |
| coal1 | 843.6 |
| coal2 | 868.6 |
| coal3 | 871.8 |
| coal4 | 953 |
| coal5 | 1009.3 |
| coal6 | 1034.2 |
| coal7 | 1086.7 |
| coal8 | 1095.9 |
| coal9 | 1125.9 |
| coal10 | 1127.9 |
| coal11 | 1197.7 |
| coal12 | 1256.5 |
| coal13 | 1275.2 |
| coal14 | 1285.8 |
| coal15 | 1297.9 |
| coal16 | 1300.6 |
| coal17 | 1320.4 |
| coal18 | 1339.7 |
| coal19 | 1348.5 |
| coal20 | 1356.2 |
| coal21 | 1366.3 |
| coal22 | 1374.2 |
| coal23 | 1391.3 |
| coal24 | 1430.9 |
| coal25 | 1437 |
| coal26 | 1482.2 |
| coal27 | 1631.6 |
| coal28 | 1634.7 |
| | |
| **Common Well Name** | **CABLEHEAD E-95** |
| UWI (Unique Well Identifier) | D230 |
| Latitude | 46.73803 |
| Longitude | -62.495 |
| X Coordinate | 538580.14 |

| | |
|---|---|
| Y Coordinate | 51761760.56 |
| Rig Release Date | 7-Sep-83 |
| Rotary Table | 28 |
| Water Depth | 54.7 |
| Total Depth | 3235 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 150.4 |
| Naufrage Fm. | 150.4 |
| Cable Head Fm. | 1072.7 |
| Seacow Fm. | 1596.8 |
| Magdalen Fm. | 1890.6 |
| Green Gables Fm. | 2253.6 |
| Bradelle Fm. | 2710.3 |
| Windsor Group (approx) | 4860.5 |
| coal1 | 1397 |
| coal2 | 1415.3 |
| coal3 | 1445.4 |
| coal4 | 2258.5 |
| coal5 | 2471.4 |
| coal6 | 2499.3 |
| coal7 | 2509.8 |
| coal8 | 2756.1 |
| coal9 | 2867.1 |
| coal11 | 2338.1 |
| | |
| Common Well Name | EAST POINT E-47 |
| UWI (Unique Well Identifier) | D188 |
| Latitude | 46.60414 |
| Longitude | -61.625 |
| X Coordinate | 605304.18 |
| Y Coordinate | 51620930.23 |
| Rig Release Date | 29-Jul-80 |
| Rotary Table | 25 |
| Water Depth | 85 |
| Total Depth | 2662 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 110.6 |
| Naufrage Fm. | 110.6 |
| Cable Head Fm. | 201.0 |
| Seacow Fm. | 743.5 |
| Magdalen Fm. | 1545.3 |
| Green Gables Fm. | 1869 |
| Bradelle Fm. | 2604.9 |
| Windsor Group (approx) | 3812.2 |
| coal1 | 2368.6 |
| coal2 | 2505.8 |
| coal3 | 2613.9 |
| | |
| Common Well Name | EAST POINT E-49 |
| UWI (Unique Well Identifier) | D014 |
| Latitude | 46.63972 |
| Longitude | -61.62389 |
| X Coordinate | 605320.24 |
| Y Coordinate | 51660480.64 |
| Rig Release Date | 16-Nov-70 |
| Rotary Table | 9.7 |

| | |
|---|---|
| Water Depth | 61.8 |
| Total Depth | 3484.6 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 71.3 |
| Naufrage Fm. | 71.3 |
| Cable Head Fm. | 480.0 |
| Seacow Fm. | 955.8 |
| Magdalen Fm. | 1581.3 |
| Green Gables Fm. | 1877.9 |
| Bradelle Fm. | 2395.6 |
| Mid-Westphalian Event | 2922.3 |
| Namurian/Westphalian Event | 2922.3 |
| Mabou Group | 2922.3 |
| Windsor Group | 3735.6 |
| coal1 | 2276.4 |
| coal2 | 2282.2 |
| coal3 | 2319.1 |
| coal4 | 2352.1 |
| coal5 | 2366.3 |
| coal6 | 2384.8 |
| coal7 | 2489.9 |
| coal8 | 2603.8 |
| coal9 | 2710.1 |
| coal10 | 2729.7 |
| | |
| **Common Well Name** | **FREDERICTON #2** |
| UWI (Unique Well Identifier) | FRED-#2 |
| Latitude | 45.9322 |
| Longitude | -66.6586 |
| X Coordinate | 216366.41 |
| Y Coordinate | 50930250.5 |
| Rig Release Date | 26-Apr-79 |
| Rotary Table | 1.5 |
| Water Depth | +112.5 |
| Total Depth | 1102 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 1.5 |
| Naufrage Fm. | 1.5 |
| Cable Head Fm. | 330.9 |
| Green Gables Fm. | 556.4 |
| Bradelle Fm. | 853.5 |
| Bird Rock Fm. | 1005.7 |
| Brion Island Fm. | 1045.1 |
| | |
| **Common Well Name** | **GREEN GABLES NO 1** |
| UWI (Unique Well Identifier) | dgreeng |
| Latitude | 46.47744 |
| Longitude | -63.36117 |
| X Coordinate | 472275.55 |
| Y Coordinate | 51471600.42 |
| Rig Release Date | 11-Sep-72 |
| Rotary Table | 6.4 |
| Water Depth | +61.9 |
| Total Depth | 3389.2 |
| | |
| Pick Name | Pick Depth (MD) |

| | |
|---|---|
| Post-Permian Unconformity | 6.4 |
| Naufrage Fm. | 6.4 |
| Cable Head Fm. | 935 |
| Green Gables fm. | 1514.5 |
| Bradelle Fm. | 1743.9 |
| Mid-Westphalian Event | 2224.2 |
| Brion Island Fm. | 2224.2 |
| Namurian/Westphalian Event | 2417.7 |
| Mabou Group | 2417.7 |
| Windsor Group | 2971 |
| coal1 | 1650.6 |
| coal2 | 1708.7 |
| coal3 | 1718.8 |
| coal4 | 1830.2 |
| coal5 | 1839.5 |
| coal6 | 1856.3 |
| coal7 | 1872 |
| coal8 | 1886.9 |
| coal9 | 1946.8 |
| coal10 | 2005.9 |
| coal11 | 2023.2 |
| coal12 | 2100.3 |
| coal13 | 2165 |
| | |
| **Common Well Name** | **HASTINGS NO. 1** |
| UWI (Unique Well Identifier) | rdHASTINGS NO. 1 |
| Latitude | 45.84306 |
| Longitude | -64.0813° |
| X Coordinate | 416029.27 |
| Y Coordinate | 50771780.66 |
| Rig Release Date | 11-Aug-75 |
| Rotary Table | 18.6 |
| Water Depth | +74.6 |
| Total Depth | 2939.5 |
| | |
| Pick Name | Pick Depth (MD) |
| | |
| Post-Permian Unconformity | 6.4 |
| Naufrage Fm. | 6.4 |
| Cable Head Fm. | 375.7 |
| Green Gables Fm. | 666.4 |
| Bradelle Fm. | 930.5 |
| Mid-Westphalian Event | 1240.9 |
| Brion Island Fm. | 1240.9 |
| Namurian/Westphalian Event | 2669.8 |
| Mabou Group | 2669.8 |
| Basement | 2801.1 |
| coal1 | 1055 |
| coal2 | 1082.1 |
| coal3 | 1114.8 |
| coal4 | 1147.1 |
| coal5 | 1181.9 |
| coal6 | 1234.9 |
| coal7 | 1259.3 |
| coal8 | 1307.6 |
| coal9 | 1411.7 |
| coal10 | 1439.2 |
| coal11 | 1596.2 |
| coal12 | 1663.1 |

| | |
|---|---|
| coal13 | 1728.7 |
| coal14 | 1857.6 |
| coal15 | 1929.3 |
| coal16 | 1966.8 |
| coal17 | 2067.4 |
| coal18 | 2086.2 |
| coal19 | 2109.1 |
| | |
| **Common Well Name** | **HILLSBOROUGH #1** |
| UWI (Unique Well Identifier) | RDHILLSBOROUGH #1 |
| Latitude | 46.12417 |
| Longitude | -63.08667 |
| X Coordinate | 493304.22 |
| Y Coordinate | 51078470.05 |
| Rig Release Date | 5-Dec-44 |
| Rotary Table | 6.4 |
| Water Depth | 7.3 |
| Tc tal Depth | 4479.3 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 13.7 |
| Naufrage Fm. | 13.7 |
| Cable Head Fm. | 1056 |
| Green Gables Fm. | 1500.2 |
| Bradelle Fm. | 1896.8 |
| Mid-Westphalian Event | 2170.5 |
| Brion Island Fm. | 2170.5 |
| Namurian/Westphalian Event | 2395.1 |
| Mabou Group | 2395.1 |
| Windsor Group | 3176.8 |
| coal1 | 1243.6 |
| coal2 | 1399.5 |
| coal3 | 1631.4 |
| coal4 | 2008 |
| coal5 | 2264.7 |
| coal6 | 2324.7 |
| | |
| **Common Well Name** | **IRISHTOWN NO. 1** |
| UWI (Unique Well Identifier) | dirish |
| Latitude | 46.50107 |
| Longitude | -63.60428 |
| X Coordinate | 453633.6 |
| Y Coordinate | 51498990.29 |
| Rig Release Date | 5-Apr-72 |
| Rotary Table | 6.4 |
| Water Depth | 39.9 |
| Total Depth | 4107.8 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 7.1 |
| Naufrage Fm. | 7.1 |
| Cable Head Fm. | 519 |
| Green Gables Fm. | 1083.4 |
| Bradelle Fm. | 1299.9 |
| Bird Rock Fm. | 1441 |
| Brion Island Fm. | 1560.8 |
| Namurian/Westphalian Event | 1746.2 |
| Mabou Group | 1746.2 |

| | |
|---|---|
| Windsor Group | 1913.5 |
| Volcanics | 2540.9 |
| Horton Group | 3029.8 |
| coal1 | 976 |
| coal2 | 1076.4 |
| coal3 | 1174.1 |
| coal4 | 1337.3 |
| coal5 | 1355.8 |
| coal6 | 1410.3 |
| coal7 | 1510.6 |
| coal8 | 1578 |
| coal9 | 1723.2 |
| | |
| **Common Well Name** | **NDDME M-1** |
| UWI (Unique Well Identifier) | rdMabou-#1 |
| Latitude | 46.12183 |
| Longitude | -61.48967 |
| X Coordinate | 616691.15 |
| Y Coordinate | 51086920.88 |
| Rig Release Date | 1978 |
| Rotary Table | 10.4 |
| Water Depth | 76.6 |
| Total Depth | 1229 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 98.4 |
| Cable Head Fm. | 98.4 |
| Seacow Fm. | 329.5 |
| Magdalen Fm. | 636.2 |
| Bradelle Fm. | 835.9 |
| Bird Rock Fm. | 1139.8 |
| coal1 | 317.6 |
| coal2 | 320.8 |
| coal3 | 327.5 |
| coal4 | 392 |
| coal5 | 424.8 |
| coal6 | 442.7 |
| coal7 | 532.5 |
| coal8 | 559.9 |
| coal9 | 677.4 |
| coal10 | 684 |
| coal11 | 724.3 |
| coal12 | 759.7 |
| coal13 | 794.7 |
| coal14 | 930.7 |
| coal15 | 943.1 |
| coal16 | 1018.8 |
| coal17 | 1022.8 |
| coal18 | 1042.6 |
| coal19 | 1073.2 |
| coal20 | 1083.8 |
| coal21 | 1151.8 |
| coal22 | 1160.5 |
| coal23 | 1178.8 |
| coal24 | 1198.2 |
| | |
| **Common Well Name** | **NSDME M-2A** |
| UWI (Unique Well Identifier) | rdMabou-#2A |
| Latitude | 46.138 |

| | |
|---|---|
| Longitude | -61.49133 |
| X Coordinate | 616528.28 |
| Y Coordinate | 5110486O.68 |
| Rig Release Date | 1978 |
| Rotary Table | 10.4 |
| Water Depth | 81 |
| Total Depth | 1464 |
| | |
| Pick Name | Pick Depth (MD) |
| ---------- | ---------- |
| Post-Permian Unconformity | 101.4 |
| Naufrage Fm. | 101.4 |
| Cable Head Fm. | 421.3 |
| Seacow Fm. | 634.8 |
| Magdalen Fm. | 988.3 |
| Bradelle Fm. | 1097.9 |
| Bird Rock Fm. | 1287.9 |
| coal1 | 443.1 |
| coal2 | 549.3 |
| coal3 | 753.1 |
| coal4 | 771.7 |
| coal5 | 846 |
| coal6 | 873.6 |
| coal7 | 1011.4 |
| coal8 | 1033.4 |
| coal9 | 1057.4 |
| coal10 | 1078.7 |
| coal11 | 1237.6 |
| coal12 | 1250.8 |
| coal13 | 1259.6 |
| coal14 | 1381.4 |
| coal15 | 1395.2 |
| coal16 | 1406.5 |
| coal17 | 1425 |
| coal18 | 1444.9 |
| coal19 | 1458.2 |
| | |
| Common Well Name | MIDDLESEX NO. 1 |
| UWI (Unique Well Identifier) | rdMiddlesex-#1 |
| Latitude | 45.97772 |
| Longitude | -65.00256 |
| X Coordinate | 344876.3 |
| Y Coordinate | 50935210.97 |
| Rig Release Date | 16-Oct-82 |
| Rotary Table | 7 |
| Water Depth | 163.7 |
| Total Depth | 1835 |
| | |
| Pick Name | Pick Depth (MD) |
| ---------- | ---------- |
| Post-Permian Unconformity | 5 |
| Naufrage Fm. | 5 |
| Cable Head Fm. | 414.1 |
| Green Gables Fm. | 660.2 |
| Bradelle Fm. | 682.8 |
| Mid-Westphalian Event | 824.7 |
| Brion Island Fm. | 824.7 |
| Namurian/Westphalian Event | 1042.1 |
| Mabou Group | 1042.1 |
| Windsor Group | 1277.6 |

| | |
|---|---|
| Common Well Name | NORTHUMBERLAND STRAIT F-25 |
| UWI (Unique Well Identifier) | D015 |
| Latitude | 46.07365 |
| Longitude | -62.06268 |
| X Coordinate | 572482.55 |
| Y Coordinate | 51026570.58 |
| Rig Release Date | 17-Jun-70 |
| Rotary Table | 9.4 |
| Water Depth | 29.9 |
| Total Depth | 2974.7 |
| | |
| Pick Name | Pick Depth (MD) |
| | |
| Post-Permian Unconformity | 29.9 |
| Brion Island Fm. | 29.9 |
| Namurian/Westphalian Event | 195.5 |
| Mabou Group | 195.5 |
| Windsor Group | 844.5 |
| Horton Group | 2016.5 |
| Top Fountain Lake | 2513.8 |
| BASEMENT | 2785.8 |
| | |
| Common Well Name | NAUFRAGE NO.1 |
| UWI (Unique Well Identifier) | D150 |
| Latitude | 46.46833 |
| Longitude | -62.46417 |
| X Coordinate | 541139.34 |
| Y Coordinate | 51462240.13 |
| Rig Release Date | 23-Oct-75 |
| Rotary Table | 4.1 |
| Water Depth | +22.2 |
| Total Depth | 3105.3 |
| | |
| Pick Name | Pick Depth (MD) |
| | |
| Post-Permian Unconformity | 5 |
| Naufrage Fm. | 5 |
| Cable Head Fm. | 1139.9 |
| Seacow Fm. | 1846.2 |
| Magdalen Fm. | 1956.7 |
| Green Gables Fm. | 2272.6 |
| Bradelle Fm. | 2665.2 |
| Windsor Group (approx) | 5103 |
| coal1 | 1886.1 |
| coal2 | 1906 |
| coal3 | 1909.7 |
| coal4 | 1992.4 |
| coal5 | 2081.8 |
| coal6 | 2152.2 |
| coal7 | 2165.3 |
| coal8 | 2259.7 |
| coal9 | 2324.3 |
| coal10 | 2394 |
| coal12 | 2499.6 |
| coal13 | 2561.1 |
| coal14 | 2735.2 |
| coal15 | 2793.8 |
| coal16 | 2928.7 |
| | |

| Common Well Name | NORTH SYDNEY F-24 |
|---|---|
| UWI (Unique Well Identifier) | D163 |
| Latitude | 46.55642 |
| Longitude | -59.81263 |
| X Coordinate | 744313.4 |
| Y Coordinate | 51608090.57 |
| Rig Release Date | 14-Jul-76 |
| Rotary Table | 14.6 |
| Water Depth | 59.7 |
| Total Depth | 1686.7 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 73.2 |
| Cable Head Fm. | 73.2 |
| Seacow Fm. | 669.2 |
| Magdalen Fm. | 735.9 |
| Green Gables Fm. | 880.9 |
| Bradelle Fm. | 946.2 |
| Mid-Westphalian Event | 1437.8 |
| Namurian/Westphalian Event | 1437.8 |
| Mabou Group | 1437.8 |
| SB1 (Unconformity) | 1607.5 |
| Horton Group | 1607.5 |
| coal1 | 543.6 |
| coal2 | 645.8 |
| coal3 | 758.8 |
| coal4 | 803.3 |
| coal5 | 848.6 |
| coal6 | 920.9 |
| coal10 | 967 |
| coal7 | 1006.6 |
| coal8 | 1014 |
| coal9 | 1020.6 |
| | |
| Common Well Name | NORTH SYDNEY P-05 |
| UWI (Unique Well Identifier) | d134 |
| Latitude | 46.57951 |
| Longitude | -59.75051 |
| X Coordinate | 748968.28 |
| Y Coordinate | 51635690 |
| Rig Release Date | 8-Sep-74 |
| Rotary Table | 29.8 |
| Water Depth | 62.8 |
| Total Depth | 1641.3 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 92.6 |
| Cable Head Fm. | 92.6 |
| Seacow Fm. | 645.9 |
| Magdalen Fm. | 707 |
| Green Gables Fm. | 849.3 |
| Bradelle Fm. | 916.9 |
| Mid-Westphalian Event | 1362.9 |
| Namurian/Westphalian Event | 1362.9 |
| Mabou Group | 1362.9 |
| SB1 (Unconformity) | 1539.9 |
| Horton Group | 1539.9 |
| coal1 | 522.2 |

| | |
|---|---|
| coal2 | 525.6 |
| coal3 | 621.5 |
| coal4 | 730.5 |
| coal5 | 775.2 |
| coal6 | 815.3 |
| coal7 | 876.5 |
| coal8 | 879.1 |
| coal9 | 883 |
| coal10 | 962.2 |
| coal11 | 966.9 |
| coal12 | 1367.3 |
| | |
| **Common Well Name** | **NSDME P-58** |
| UWI (Unique Well Identifier) | P-58 |
| Latitude | 45.56 |
| Longitude | -62.666 |
| X Coordinate | 526066.62 |
| Y Coordinate | 50452160.6 |
| Rig Release Date | Jul-68 |
| Rotary Table | 6 |
| Water Depth | +24 |
| Total Depth | 845 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 0.9 |
| Cable Head Fm. | 0.9 |
| Green Gables Fm. | 89.3 |
| Bradelle Fm. | 124.1 |
| Bird Rock Fm. | 400.3 |
| Brion Island Fm. | 454 |
| | |
| **Common Well Name** | **NSDME PH-3** |
| UWI (Unique Well Identifier) | rdPort-Hood-Island |
| Latitude | 45.995 |
| Longitude | -61.56 |
| X Coordinate | 611512.18 |
| Y Coordinate | 50944990.98 |
| Rig Release Date | 1975 |
| Rotary Table | 7.5 |
| Water Depth | +7.5 |
| Total Depth | 778 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 7.3 |
| Cable Head Fm. | 7.3 |
| Green Gables Fm. | 82.7 |
| Bradelle Fm. | 177.7 |
| Bird Rock Fm. | 451.4 |
| Brion Island Fm. | 598.1 |
| coal1 | 591.4 |
| coal2 | 600.6 |
| | |
| **Common Well Name** | **ST. ISIDORE NO. 1** |
| UWI (Unique Well Identifier) | rdSt.-Isodore-#1 |
| Latitude | 47.54472 |
| Longitude | -65.0586 |
| X Coordinate | 345135.33 |
| Y Coordinate | 52677540.78 |

| | |
|---|---|
| Rig Release Date | 16-Jul-67 |
| Rotary Table | 1.5 |
| Water Depth | +62.5 |
| Total Depth | 732.5 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 2.2 |
| Cable Head Fm. | 2.2 |
| Green Gables Fm. | 364.8 |
| Bradelle Fm. | 473.8 |
| | |
| **Common Well Name** | **ST. ISIDORE NO. 2** |
| UWI (Unique Well Identifier) | rdSt.-Isodore-#2 |
| Latitude | 47.52667 |
| Longitude | -65.16056 |
| X Coordinate | 337366.87 |
| Y Coordinate | 52659570.89 |
| Rig Release Date | 12-Sep-67 |
| Rotary Table | 1.5 |
| Water Depth | +73.8 |
| Total Depth | 642.2 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 1.6 |
| Cable Head Fm. | 1.6 |
| Green Gables Fm. | 277.5 |
| Bradelle Fm. | 374 |
| Unconformity | 641.6 |
| BASEMENT | 641.6 |
| | |
| **Common Well Name** | **ST. PAUL P-91** |
| UWI (Unique Well Identifier) | D235 |
| Latitude | 47.18278 |
| Longitude | -60.22694 |
| X Coordinate | 710096.95 |
| Y Coordinate | 52292060.68 |
| Rig Release Date | 31-Dec-83 |
| Rotary Table | 24.9 |
| Water Depth | 173.6 |
| Total Depth | 2883 |
| | |
| Pick Name | Pick Depth (MD) |
| ========== | ========== |
| Post-Permian Unconformity | 200.1 |
| Bradelle Fm. | 200.1 |
| Bird Rock Fm. | 820.3 |
| Brion Island Fm. | 1134.2 |
| Namurian/Westphalian Event | 1444.3 |
| Mabou Group | 1444.3 |
| Windsor Group | 2183.9 |
| Horton Group | 2307.1 |
| coal1 | 1872.6 |
| | |
| **Common Well Name** | **TYRONE NO. 1** |
| UWI (Unique Well Identifier) | D143 |
| Latitude | 46.26942 |
| Longitude | -63.33886 |
| X Coordinate | 473888.85 |

| | |
|---|---|
| Y Coordinate | 51240380.02 |
| Rig Release Date | 19-Jul-77 |
| Rotary Table | 4.2 |
| Water Depth | +110.3 |
| Total Depth | 4166.6 |
| | |
| Pick Name | Pick Depth (MD) |
| ======== | ========== |
| Post-Permian Unconformity | 4.2 |
| Naufrage Fm. | 4.2 |
| Cable Head Fm. | 1430.2 |
| Seacow Fm. | 2159.7 |
| Magdalen Fm. | 2348.4 |
| Green Gables Fm. | 2585.1 |
| Bradelle Fm. | 2925.1 |
| Bird Rock Fm. | 3100.4 |
| Brion Island Fm. | 3117.7 |
| Namurian/Westphalian Event | 3258.5 |
| Mabou Group | 3258.5 |
| Windsor Group | 3948.7 |
| coal1 | 1541.9 |
| coal2 | 1695.6 |
| coal3 | 1737.4 |
| coal4 | 1762.8 |
| coal5 | 2170.7 |
| coal6 | 2210.5 |
| coal7 | 2402.3 |
| coal8 | 2494.1 |
| coal9 | 2547 |
| coal10 | 2631.5 |
| coal11 | 2681 |
| coal12 | 2691.8 |
| coal13 | 2927.9 |
| coal14 | 2969.3 |
| coal15 | 2995.7 |
| coal16 | 3060.6 |
| coal17 | 3185.9 |
| | |
| **Common Well Name** | **IMPERIAL WELLINGTON NO.1** |
| UWI (Unique Well Identifier) | rdWellington_no1 |
| Latitude | 46.43631 |
| Longitude | -64.02361 |
| X Coordinate | 421364.64 |
| Y Coordinate | 51430130.28 |
| Rig Release Date | 3-Jul-58 |
| Rotary Table | 5.1 |
| Water Depth | +12.8 |
| Total Depth | 2960.8 |
| | |
| Pick Name | Pick Depth (MD) |
| ======== | ========== |
| Post-Permian Unconformity | 5.5 |
| Cable Head Fm. | 5.5 |
| Green Gables Fm. | 598.8 |
| Bradelle Fm. | 645.7 |
| Mid-Westphalian Event | 884.9 |
| Brion Island Fm. | 884.9 |
| Namurian/Westphalian Event | 1184 |
| Mabou Group | 1184 |
| Windsor Group | 1331.1 |

| | |
|---|---|
| Volcanics | 1470.7 |
| Horton Group | 1641.9 |
| coal1 | 643.2 |
| coal2 | 690.7 |
| coal3 | 717.5 |
| coal4 | 767.1 |
| coal5 | 827.3 |
| coal6 | 881.6 |
| coal7 | 952.9 |
| coal8 | 1066.1 |

# APPENDIX IV: GEOLOGIC INTERPRETATIONS OF EASTERN UNITED STATES LATE CARBONIFEROUS BASINS

## 1. Sedimentation North of the "Alleghanian" Orogen

Based on the present structural orientations, the Narragansett and Norfolk Basins (Fig. 1.4) formed on the Maritimes Basin side of the Carboniferous paleodrainage drainage divide during the Late Paleozoic (Fig. 4.3). Structural, petrologic and metamorphic data from the area suggest that a fold and thrust belt was present in south-central New England during the Late Paleozoic and the Narragansett Basin was a retro-foreland basin (Wintsch and Sutter, 1986). The basins contain a series of highly metamorphosed Late Carboniferous and Early Permian clastic wedges which collectively attain thicknesses between 3 and 6 km. The strata display paleoflow directions that range from north-northeast to south-southwest.

The interpreted early phase of clastic deposition in the Narragansett Basin is recorded by the basal Pondville Conglomerate and the Wamsutta Formation (Fig. 4.3, Table 4.1). The coarseness of the Pondville Conglomerate suggests a local source area of considerable relief (Lyons et al., 1976; Towe, 1959). The complete succession lies unconformably on Acadian basement and indicates a progressive change from bed-load dominated fluvial to alluvial plain deposition (Skehan et al., 1986; Lyons, 1979; Oleksyshyn, 1976; Lyons et al., 1976; ). The upper part of the cycle (Wamsutta Formation) shows indictions of repeated subaerial exposure, mudcracks, raindrop prints, red oxidation and in situ fossils suggesting rapid subsidence contemporaneous with rapid deposition of the sediments (Skehan et al., 1986; Lyons, 1979; Lyons et al., 1976; Towe, 1959).

The intermediate (mid) phase of clastic wedge development is represented by the Rhode Island Formation (Fig. 4.3, Table 4.2), which is the thickest and most widely distributed unit in the area (Skehan et al., 1986; Towe, 1959). The formation was deposited in a medial to distal alluvial fan environment and is the only coal-bearing formation in the area with coal ranks ranging between anthracite and meta-anthracite

(Hower et al., 1993; Oleksyshyn, 1976).

The last phase of clastic wedge development, the Dighton Conglomerate, conformably overlies the Rhode Island Formation (Fig. 4.3, Table 4.3) and is the depositional product of broad alluvial fans (Skehan et al., 1986; Oleksyshyn, 1976). Oleksyshyn (1976) proposed that the coarseness of this unit suggests both rapid subsidence during deposition as well as the probable existence of substantial amounts of additional overlying section that has since been eroded. This suggestion is supported by Wintsch and Sutter (1986) who interpreted uplift and erosion during the Permian and Triassic based on changes in structural orientations.

## 2. Sedimentation South-Southwest of the "Alleghanian" Orogen

### Post-Mississippian-Pennsylvanian Unconformity Strata (Early Phase)

The interpreted early phase of clastic deposition (Fig. 4.3) in the Pennsylvania Anthracite Region, Central Appalachian, Eastern Interior and Michigan Basins is shown in Table 4.1. The phase consists of a coarse-grained basal member with an overlying relatively finer grained member. The basal member typically lies on the Mississippian-Pennsylvanian unconformity and consists of mature, grey to buff, coarse-grained quartz-rich sandstones and conglomerates composed predominantly of orthoquartzite clasts (Wood et al., 1956, 1986; Arkle, 1974). The succession fines upwards slightly to fine- to coarse-grained sandstones, minor shales and a few coals (Archer and Greb, 1995). The basal sandstones were deposited in bed-load dominated fluvial deltaic systems that prograded from the east, northeast and north (Trask and Palmer, 1986; Shideler, 1969; Donaldson and Shumaker, 1981). The sands typically form extensive multi-story sandsheets and linear belts, however, in the Appalachian, Illinois and Michigan basins, some sands are locally associated with paleovalley incision of up to 140m into the underlying Mississippian strata (Archer and Greb, 1995; Trask and Palmer, 1986). The general coarseness and regional distribution of the basal sandstones are interpreted to reflect renewed uplift of the source area (Wood et al., 1986; Tankard, 1986; Donaldson and Shumaker, 1981; Arkle, 1974).

The progradation of the first Pennsylvanian clastic pulse is closely associated with an influx of aluminum rich clays which are attributed to tropical soil formation during renewed uplift of the source area to the north (Donaldson and Shumaker, 1981). A somewhat similar observation was made by Weaver (1960) who recognized a regionally extensive variation in clay mineral composition across the Mississippian-Pennsylvanian unconformity, from predominantly a montmorillonite-mixed-layer clay facies to an illite-chlorite-kaolinite-mixed-layer clay facies. Recent work by Hower et al. (1993) suggests a predominance of Fe-rich chlorites in the Late Namurian to Permian strata in the Pennsylvania Anthracite Region.

These upper deposits are relatively finer-grained (Arkle, 1974; Wood et al., 1986) and conformably overlie the basal sandstones and conglomerates (Table 4.1). The upper cycle is composed of dark mudstones, shales with thin sandstones, isolated sandstone bodies, limestones and discontinuous coals (Landing and Wardlaw, 1981; Trask and Palmer, 1986; Tankard, 1986). The succession generally fines upwards into a capping transgressive estuarine facies with locally developed, discontinuous coals (Archer and Greb, 1995). The decreasing coarse to fine ratio upsection suggests a progressive change from bed-load dominated systems to broad alluvial/coastal plains with low-gradient stream systems that result in an increased cyclothem style of deposition (Landing and Wardlaw, 1981). Shideler (1969) suggested that the decrease in coarse sediment towards the top of the Saginaw Formation in the Michigan Basin reflects a period of increasing tectonic quiescence.

**Post-Mississippian-Pennsylvanian Unconformity Strata (Mid Phase)**

The interpreted intermediate phase of clastic deposition (Fig. 4.3, Table 4.2) in the Appalachian basin comprises the lower part of what Donaldson (1974) referred to as West Virginia deltaic complex. The basal brownish-red sandstones and conglomerates are less mature, contain more feldspar and coal development tends to be more extensive as compared to the underlying early clastic phase (Trask and Palmer, 1986; Arkle, 1974; Landing and Wardlaw, 1981; Shideler 1969). The sandstones and conglomerates tend to

be tabular and lenticular in form (Wood et al., 1986), however, the sandstones locally occur as multi-story channel bodies that coalesce to form relatively continuous sandstone sheets (Tankard, 1986). In the Michigan Basin, the lower sands are locally associated with incised paleovalleys which cut into the underlying Saginaw Formation (Landing and Wardlaw, 1981). The basal coarse-grained succession was deposited in a bed-load dominated fluvial-deltaic system that prograded from the southeast (Tankard, 1986; Shideler, 1969; Donaldson and Shumaker, 1981). The relative coarseness of the lower succession suggests renewed uplift of the Appalachian source area (Wood et al., 1986; Shideler, 1969). In the Michigan Basin, the upper boundary of the Grand River Formation is marked by an unconformity representing 900m of erosion due to Permian - Triassic uplift (Fig. 4.3) (Cercone, 1984).

The coarser-grained lower succession progressively fines upwards into a package which is composed of finer-grained sandstones, overbank mudstones, shales with local thin limestones and coals, which increase in abundance towards the top of the formation (Pryor and Sable, 1974; Arkle, 1974). The sandstones were deposited in a series of extensive sandstone sheets and bodies but in contrast to the underlying coarse-grained sediments they tend to have a higher percentage of metamorphic clasts (Trask and Palmer, 1986). The influence of primary fluvial deposition decreases, as indications of marine invasions increase towards the top of the formation.

The basal coarse-grained succession is conformably overlain by a succession of relatively finer-grained strata composed of minor sandstones, siltstones and shales and locally some conglomerates (Wood et al., 1986). This part of the intermediate phase is characterized (Table 4.2) by well-developed cyclic deposits (cyclothems) which contain widespread coal and limestone deposits (Fig. 4.3) (Trask and Palmer, 1986; Arkle, 1974) representing the most important coal-bearing phase in the eastern United States. A broad alluvial to coastal plain environment of deposition is interpreted for this part of the intermediate phase (Wood et al., 1986; Donaldson and Shumaker, 1981).

Further increases in marine influence are displayed by the uppermost strata in the intermediate phase. The clastic cycle culminates with a transgression which resulted in

maximum development of major marine limestones, shales, and local cherts and ironstones (Arkle, 1974; Pryor and Sable, 1974; Donaldson and Shumaker, 1981).

**Post-Mississippian-Pennsylvanian Unconformity Strata (Late Phase)**

Renewed uplift in the Early Stephanian led to a late phase of Carboniferous clastic deposition (Fig. 4.3, Table 4.3) in eastern United States (Wood et al., 1986). Near the Appalachian sediment source, the basal portion of the phase consists of a coarse-grained redbed sandstone succession that displays evidence of extensive subaerial exposure (Arkle, 1974; Donaldson and Shumaker, 1981). Locally, the basal strata were deposited as extensive blankets of coarse sandstones and gravels (Wood et al., 1986). Farther away from the source area, the basal portion of the phase consists of thick well developed sandstone bodies, shales, thin argillaceous limestones and thin coals; all of which exhibit significantly less evidence of marine incursions as compared to the underlying mid clastic phase strata (Pryor and Sable, 1974). The relative coarseness of the lower succession suggests renewed source area uplift to the southeast (Wood et al., 1986). The lower succession was deposited by a series of fluvial-deltaic complexes, which in the Appalachian Basin is referred to as the Grafton Delta Phase of the West Virginia deltaic complex (Donaldson, 1974).

Conformably overlying the coarser-grained successions is a series of relatively finer-gained strata typically composed of red and grey shales, subgraywacke sandstones, clay-shale and extensive coals and lacustrine limestones (Table 4.3) (Donaldson and Shumaker, 1981; Arkle, 1974). The upper parts of the late phase strata suggested that increasing marine incursions from the west culminated with the development of the major marine limestones (Wood et al., 1986). In the Pennsylvania Anthracite Region and the Illinois and Narragansett/Norfolk basins, portions of the late phase have been removed by Post-Pennsylvanian erosion (Fig. 4.3).

In the Appalachian Basin, the last phase of clastic deposition is locally overlain by a thick (100m) grey shale succession which is then overlain by the redbed dominated Dunkard Group (Fig. 4.3) (Arkle, 1974). The group is characterized by a return to low

gradient alluvial plain environments with predominantly suspended-load fluvial systems consisting of medium to coarse grained channel sandstones, overbank deposits, coals and limestones (Donaldson and Shumaker, 1981; Beerbower, 1969). There is a noticeable absence of marine fossils, suggesting a return to a continental setting (Arkle, 1974; Beerbower, 1969).

## APPENDIX V: CMB ROCK-EVAL PYROLYSIS/TOC CONTENT DATA

Table V.1 List of REESA (Rock Eval Expert System Analysis) Rules used by the BasinMod software. Developed originally by K.E. Peters (Chevron Overseas Petroleum Inc.) and D.A. Nelson (Chevron Corporation) to aid in the interpretation of large quantities of Rock-Eval pyrolysis data and total organic carbon (TOC) data (modified from Peters, 1986).

| |
|---|
| **Rule 1**<br>Reject TMAX if TMAX = 0.0. |
| **Rule 2**<br>Reject TMAX if S2 is less than tolerance (default 0.2 mg HC/g rock). This rule changes according to the precision of measurement of S2. |
| **Rule 3**<br>If TOC is less than tolerance (default 0.4 wt%), then reject TMAX, S2/S3, HI, and OI. When TOC is not measured, rules rejecting TMAX based on low TOC are suppressed. |
| **Rule 4**<br>If TMAX is below tolerance (default 395 °C), reject TMAX. |
| **Rule 5**<br>Reject PI if S1+S2 less than tolerance (default 2 mg HC/g rock). This rule changes according to the precision of measurement of S1, S2, and S3. |
| **Rule 6**<br>Reject TMAX if HI is less than tolerance (default 50 mg HC/g TOC), and TOC is greater than tolerance (default 1.0). |
| **Rule 7**<br>Reject HI if HI > tolerance (default 1100 mg HC/g TOC). |
| **Rule 8**<br>Reject OI if OI > tolerance (default 300 mg $CO_2$/g rock). |
| **Rule 9**<br>Reject all if depth > tolerance (default 20,000 ft). |
| **Rule 10**<br>(all numerical values are user-changeable tolerances)<br>If TMAX < 435 °C, and if PI > 0.2, or if (S1/TOC) x 1000 > 300, of if (S1/S2) > 0.3, then:<br>**a.** Reject TMAX and flag S1, TMAX migrated. |
| **Rule 10b**<br>Same conditions as Rule 10 and If S1 > tolerance (default 1 mg HC/g rock), accept PI and flag PI migrated. |
| **Rule 10c**<br>Same conditions as Rule 10 and If TOC > tolerance (default 1 wt%) and S1 < tolerance (default 1 mg HC/g rock), accept HI, S2, OI, S2/S3 and flag HI, S2, OI, S2/S3 migrated. |
| **Rule 10d**<br>Same conditions as Rule 10 and:<br>If TOC < tolerance (default 1 wt%), reject HI, S2, OI, S2/S3 and flag HI, S2, OI, S2, S3 migrated. |

| |
|---|
| **Rule 10e**<br>Same conditions as Rule 10 and:<br>If TOC > tolerance (default 1 wt%) and S1 > tolerance (default 1 mg HC/g rock), reject HI, S2, OI, S2/S3. |
| **Rule 11**<br>(all numerical values are user-changeable tolerances)<br>For 435 °C < TMAX < 460 °C and if PI > 0.4, then<br>**a.** Reject TMAX and flag S1, TMAX migrated. |
| **Rule 11b**<br>Same conditions as Rule 11 and If S1 > tolerance (default 1 mg HC/g rock), accept PI and flag PI migrated. |
| **Rule 11c**<br>Same conditions as Rule 11 and If TOC > tolerance (default 1 wt%) and S1 < tolerance (default 1 mg HC/g rock), accept HI, S2, OI, S2/S3 and flag HI, S2, OI, S2/S3 migrated. |
| **Rule 11d**<br>Same conditions as Rule 11 and:<br>If TOC < tolerance (default 1 wt%), reject HI, S2, OI, S2/S3 and flag HI, S2, OI, S2/S3 migrated. |
| **Rule 11e**<br>Same conditions as Rule 11 and:<br>If TOC > tolerance (default 1 wt%) and S1 > tolerance (default 1 mg HC/g rock), reject HI, S2, OI, S2/S3. |
| **Rule 12a**<br>If a sample TMAX is greater than 460 °C, and the following five sample TMAX values are smaller, then the sample TMAX is rejected. |
| **Rule 12b**<br>If a sample TMAX is less than 435 °C, and the preceding five sample TMAX values are larger, then the sample TMAX is rejected. |
| **Rule 13**<br>Reject TMAX if its value differs more than 8 °C from current least squares regression line. |
| **Rule 14**<br>Three-step method for calculating maturation: |
| **Rule 14.1**<br>Select depth range covered by best fit line between accepted Tmax values of 435 °C and 460 °C. Calculate average accepted HI in this depth range. If average HI in this range is > 250 mg HC/g TOC, then top oil window is set to 445 °C. If less than 250 mg HC/g TOC, then top oil window is set to 435 °C. |
| **Rule 14.2**<br>Calculate the best fit line for accepted PI in the depth range covered by the best fit line between accepted Tmax values of 435 °C and 460 °C. Define top oil window where PI=0.1. |
| **Rule 14.3**<br>Compare the best fit values for top of oil window based on Tmax (Step 1) and PI(Step 2). If they are within 2000 feet apart, then average or accept the value determined from the best fit lines showing the least standard deviation. |

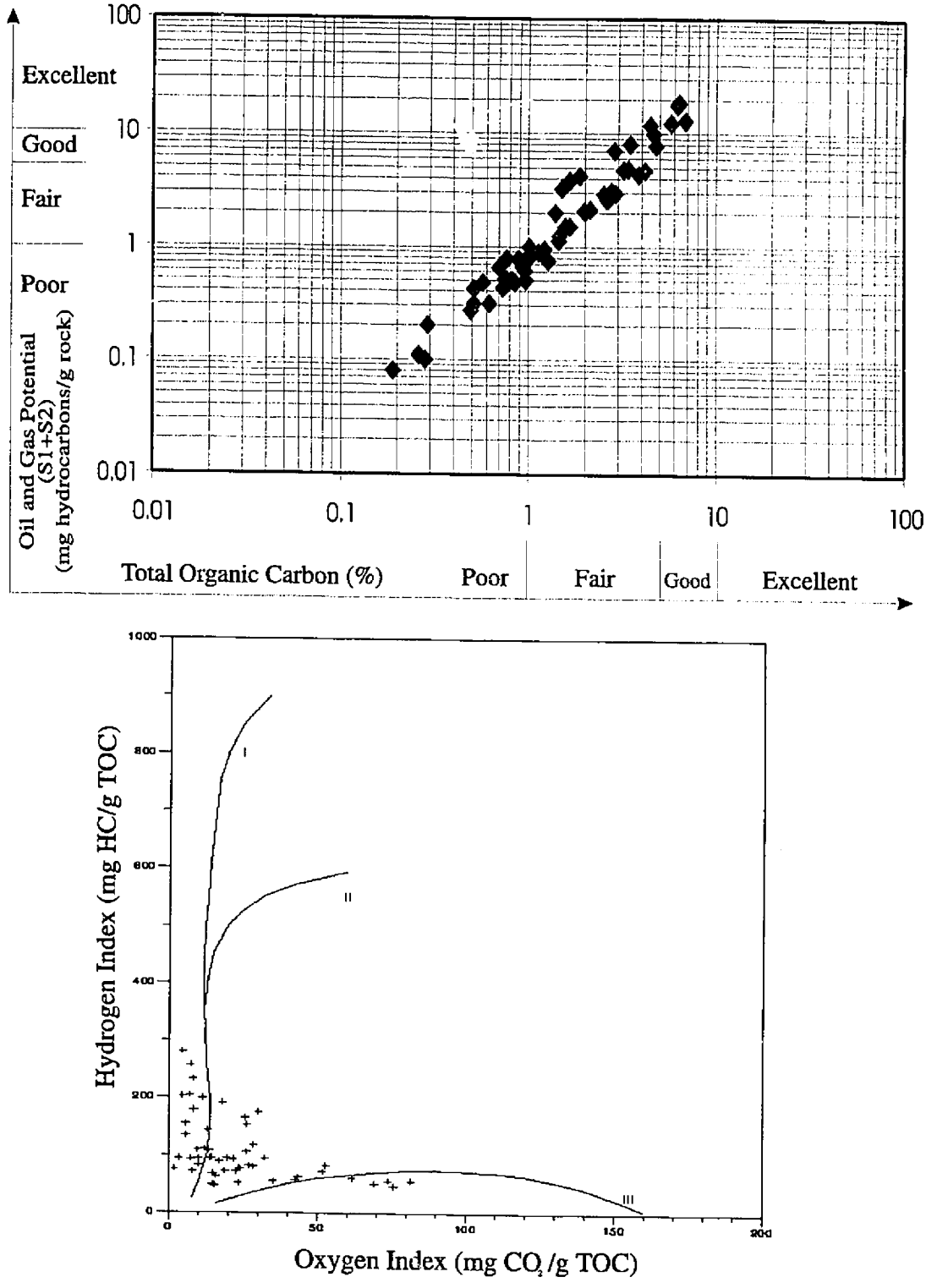



Figure V.1 (Top) Oil and gas potential of samples from Beaton Point F-70 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from Beaton Point F-70. The hydrogen and oxygen indices have been filtered using REESA rules.

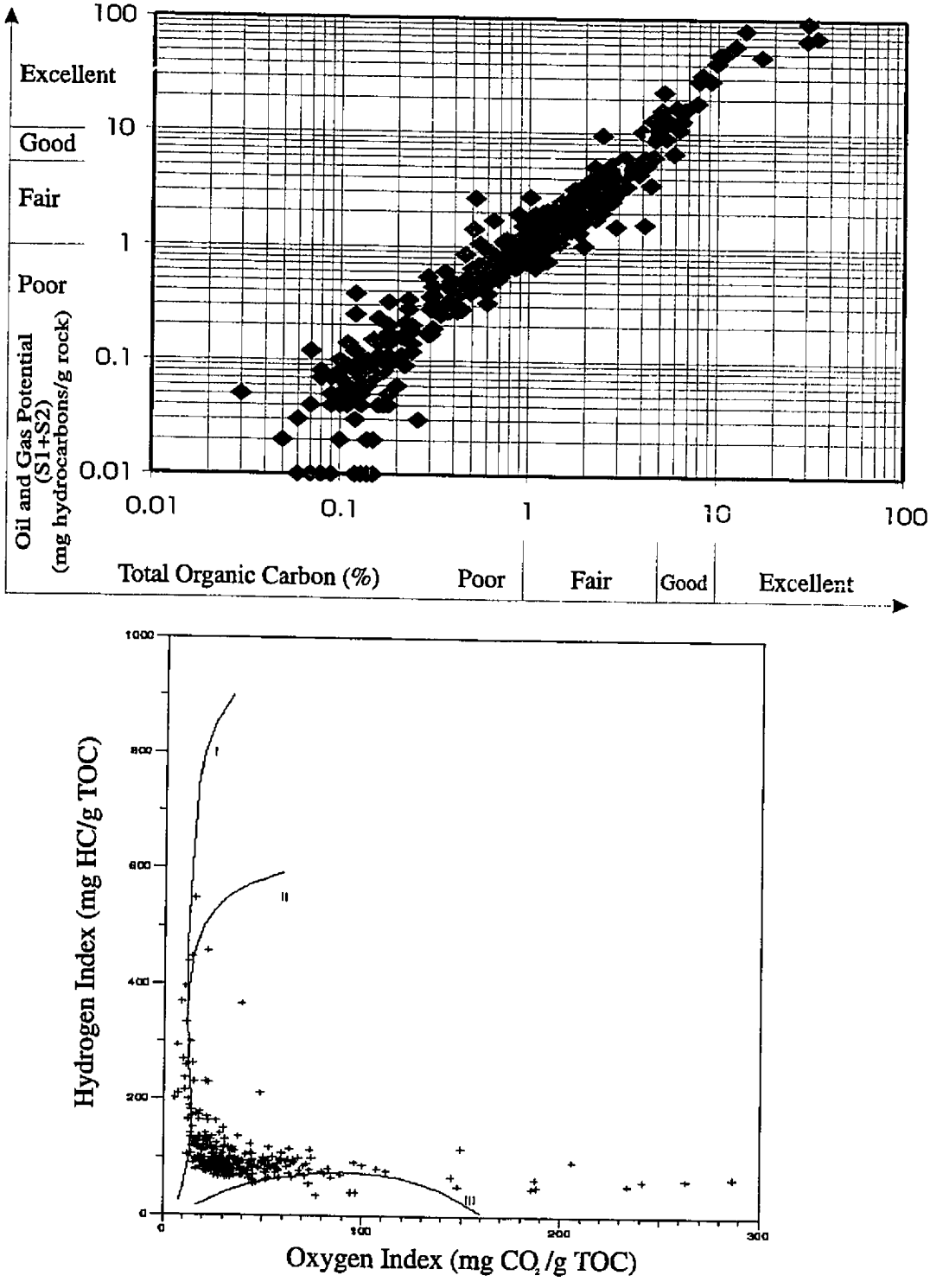



Figure V.2 (Top) Oil and gas potential of samples from Bradelle L-49 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from Bradelle L-49. The hydrogen and oxygen indices have been filtered using REESA rules.

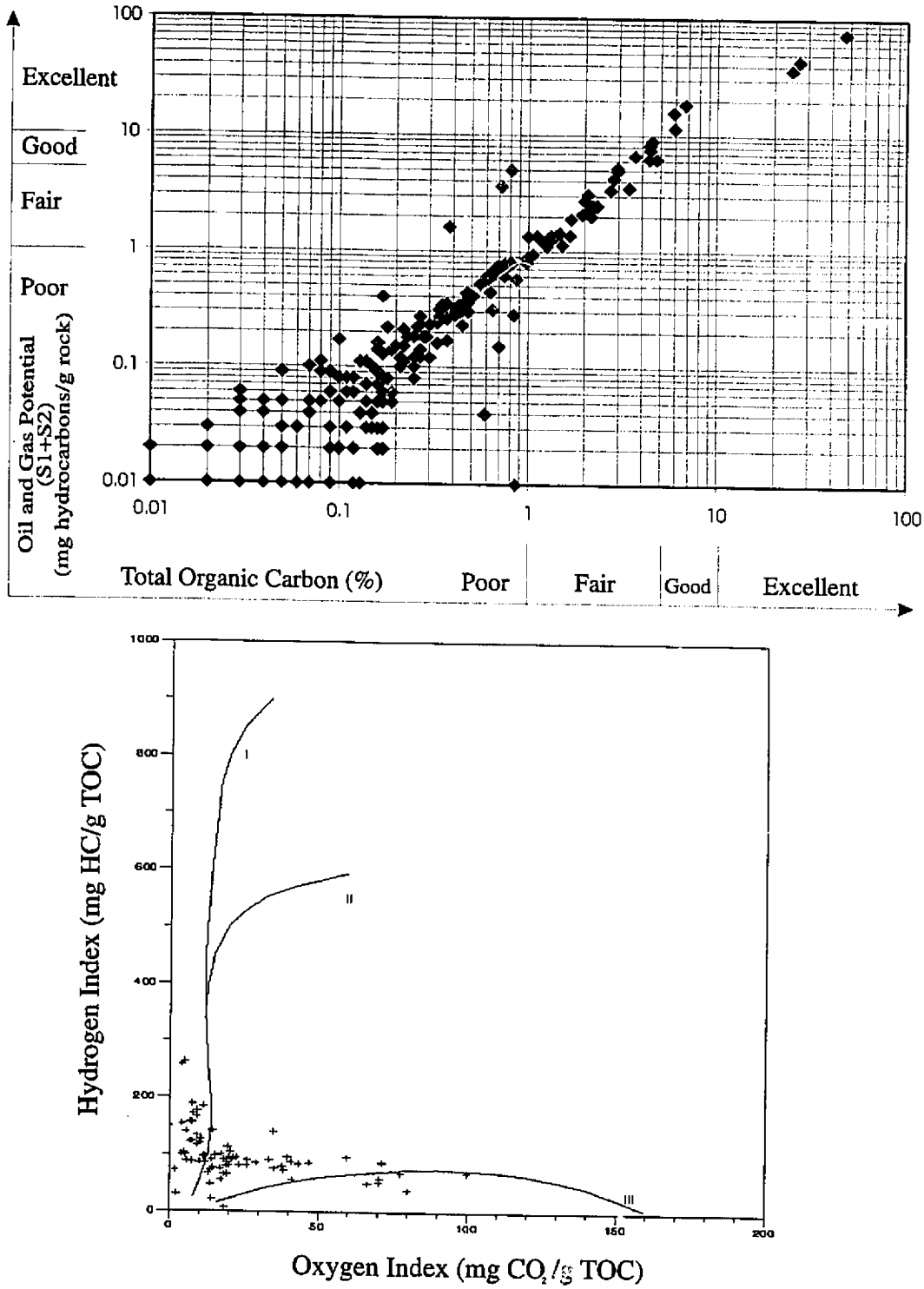



Figure V.3 (Top) Oil and gas potential of samples from Cable Head E-95 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from Cable Head E-95. The hydrogen and oxygen indices have been filtered using REESA rules.

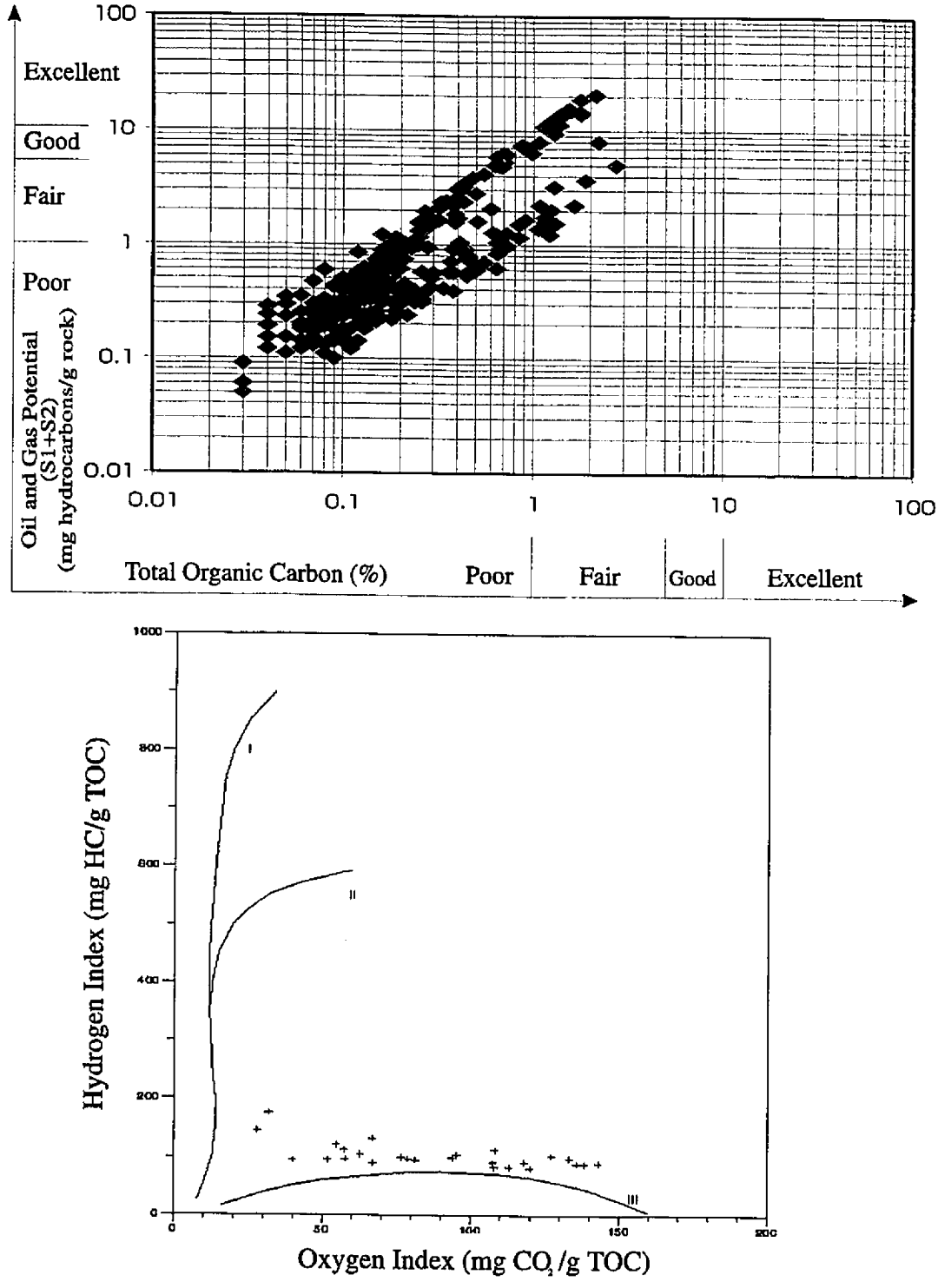



Figure V.4 (Top) Oil and gas potential of samples from East Point E-49 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from East Point E-49. The hydrogen and oxygen indices have been filtered using REESA rules.

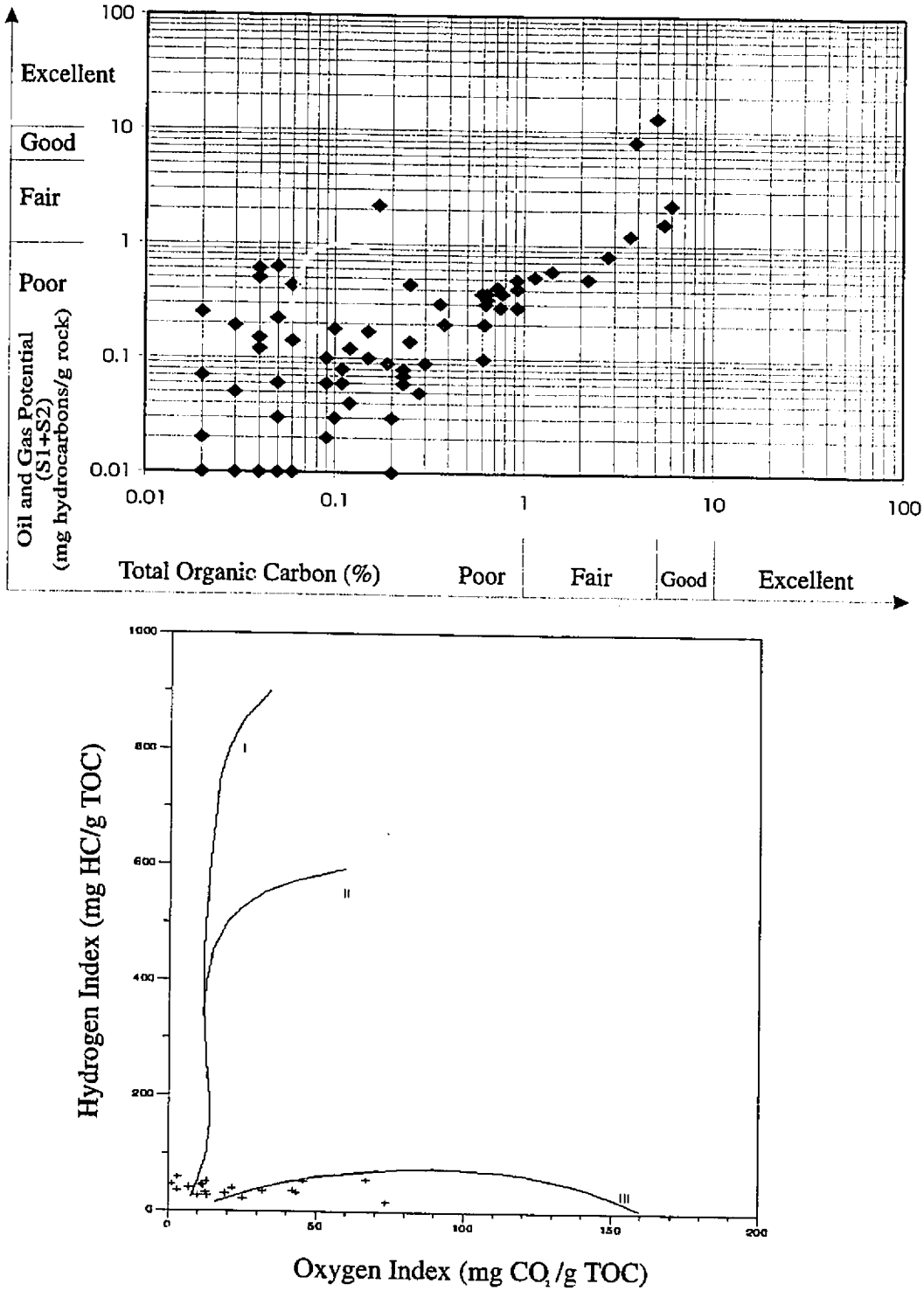



Figure V.5 (Top) Oil and gas potential of samples from Naufrage No.1 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from Naufrage No.1. The hydrogen and oxygen indices have been filtered using REESA rules.

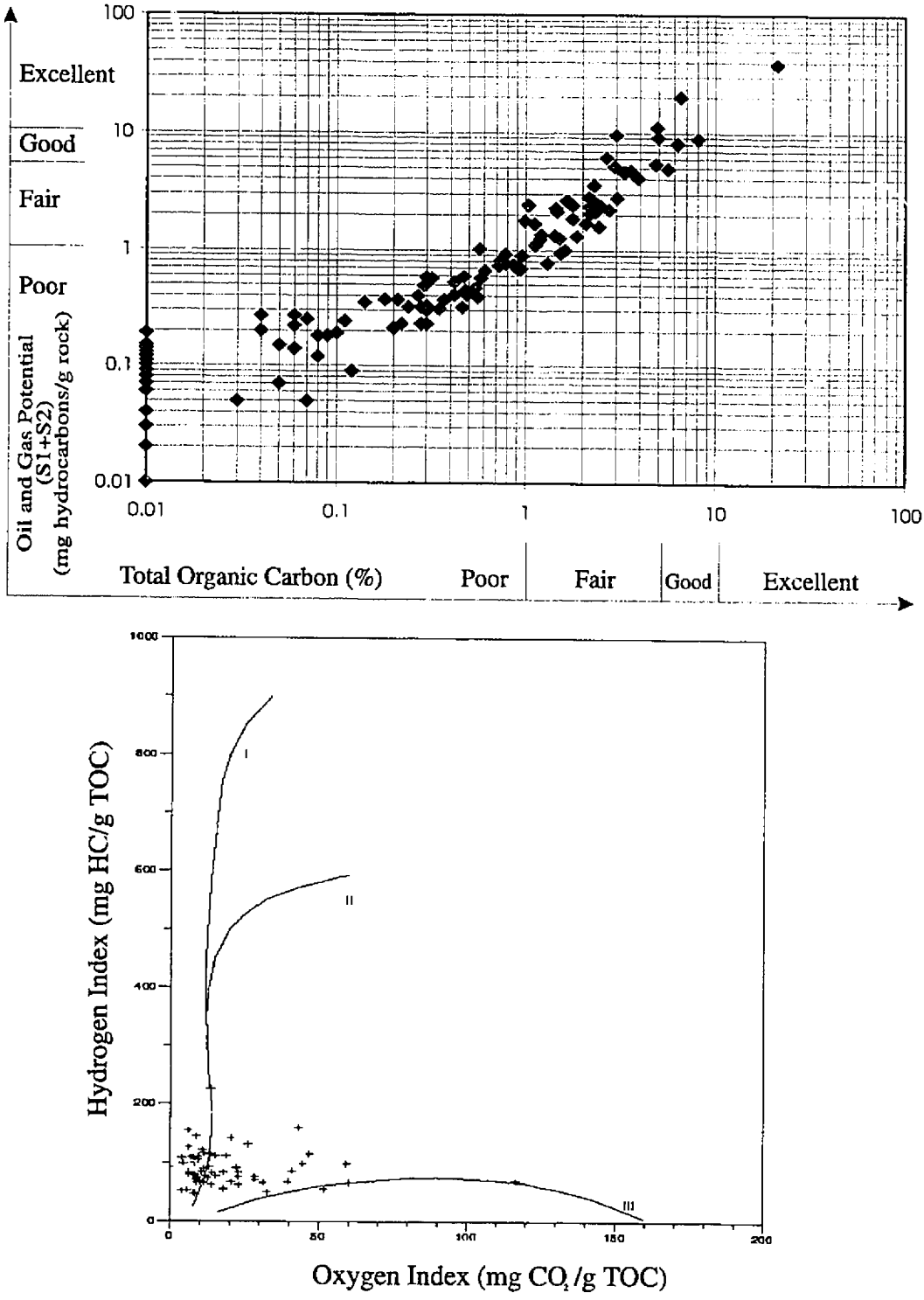
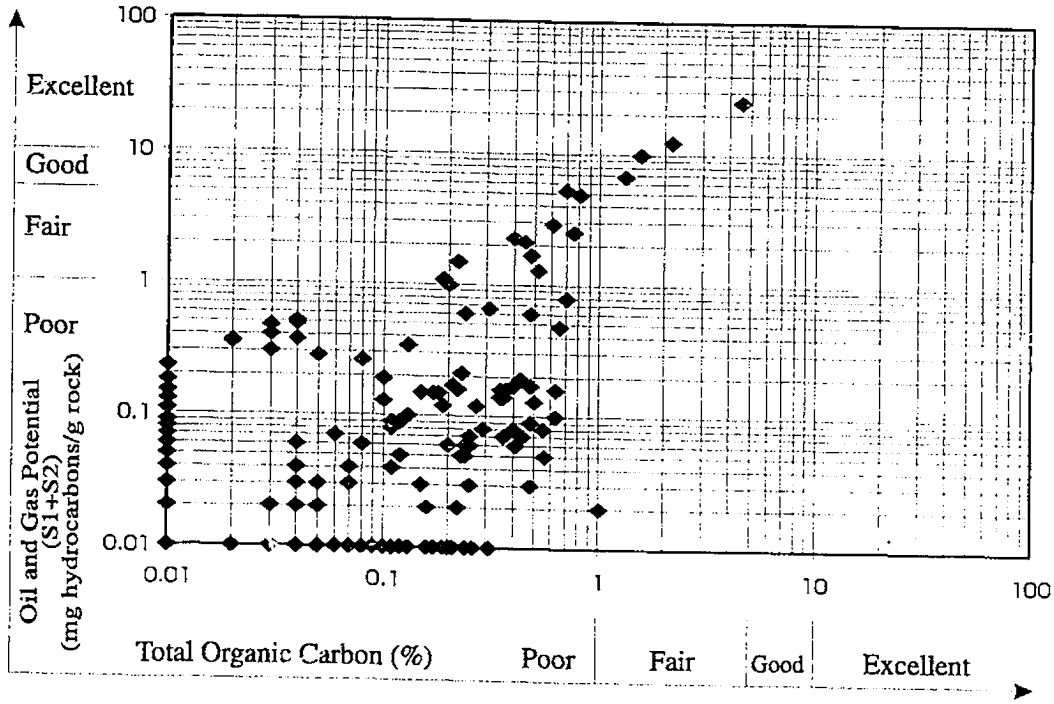



Figure V.6 (Top) Oil and gas potential of samples from North Sydney F-24 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from North Sydney F-24. The hydrogen and oxygen indices have been filtered using REESA rules.



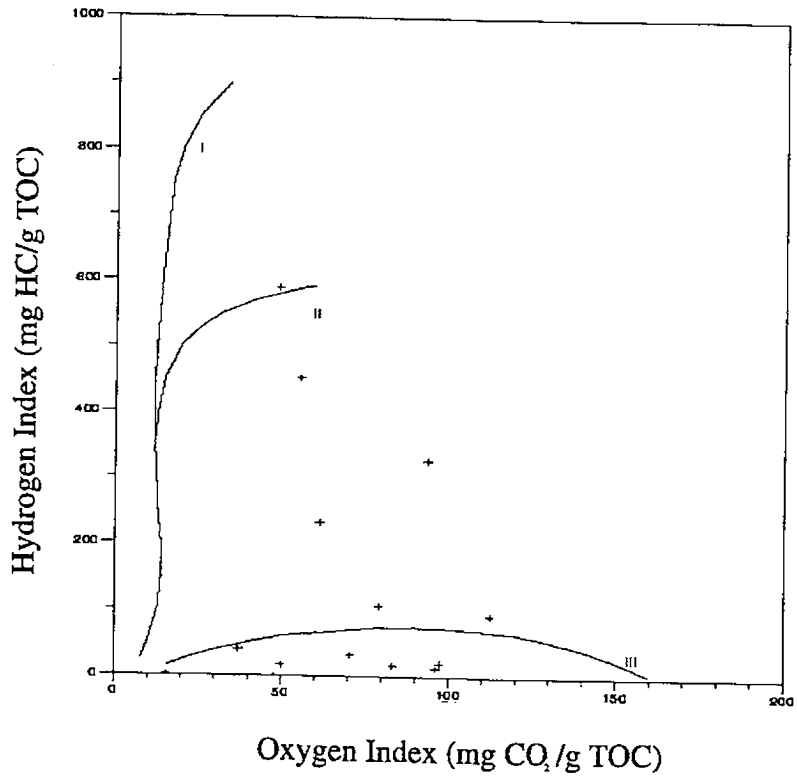




Figure V.7 (Top) Oil and gas potential of samples from St. Paul P-91 (Fig. 2.3) in relation to TOC (wt%) contents. Framework for plot after Christiansen (1989). (Bottom) Pseudo-van Krevelen diagram showing the hydrogen and oxygen indices for samples from St. Paul P-91. The hydrogen and oxygen indices have been filtered using REESA rules.

Table V.2 Rock-Eval/TOC data for Beaton Point F-70.

| DEPTH (M) | TOC | PI | S1+S2 | TMAX | S1 | S2 | S3 | HI | OI |
|---|---|---|---|---|---|---|---|---|---|
| 1400.1 | 0.29 | 0.05 | 0.2 | 465 | 0.01 | 0.19 | 0.5 | 65 | 172 |
| 1410.1 | 0.19 | 0 | 0.08 | 459 | 0 | 0.08 | 0.71 | 42 | 373 |
| 1420.1 | 3.21 | 0.03 | 4.75 | 438 | 0.14 | 4.61 | 0.43 | 143 | 13 |
| 1430.1 | 0.77 | 0.04 | 0.46 | 480 | 0.02 | 0.44 | 0.33 | 57 | 42 |
| 1440.1 | 0.77 | 0.06 | 0.78 | 446 | 0.05 | 0.73 | 0.25 | 94 | 32 |
| 1450.1 | 4.16 | 0.04 | 4.67 | 444 | 0.2 | 4.47 | 0.57 | 107 | 13 |
| 1460.1 | 3.85 | 0.03 | 4.32 | 446 | 0.13 | 4.19 | 0.38 | 108 | 9 |
| 1470.1 | 0.51 | 0 | 0.42 | 447 | 0 | 0.42 | 0.27 | 82 | 52 |
| 1480.1 | 2.53 | 0.04 | 2.93 | 451 | 0.13 | 2.8 | 0.31 | 110 | 12 |
| 1490.1 | 1.02 | 0.04 | 1 | 442 | 0.04 | 0.96 | 0.2 | 94 | 19 |
| 1500.1 | 0.96 | 0.03 | 0.61 | 447 | 0.02 | 0.59 | 0.42 | 61 | 43 |
| 1510.1 | 0.89 | 0.05 | 0.77 | 448 | 0.04 | 0.73 | 0.24 | 82 | 26 |
| 1520.1 | 0.26 | 0 | 0.11 | 458 | 0 | 0.11 | 0.25 | 42 | 96 |

Table V.3 Rock-Eval/TOC data for Bradelle L-49.

| DEPTH (F) | TOC | PI | S1+S2 | TMAX | S1 | S2 | S3 | HI | OI |
|---|---|---|---|---|---|---|---|---|---|
| 3210 | 0.76 | 0.28 | 1.16 | 418 | 0.32 | 0.84 | 4.59 | 110 | 603 |
| 3220 | 2.39 | 0.14 | 2.15 | 438 | 0.31 | 1.84 | 2.68 | 76 | 112 |
| 3230 | 1.16 | 0.2 | 0.9 | 440 | 0.18 | 0.72 | 2.8 | 62 | 241 |
| 3240 | 0.64 | 0.24 | 0.67 | 440 | 0.16 | 0.51 | 4.19 | 79 | 654 |
| 3250 | 0.42 | 0.21 | 0.42 | 436 | 0.09 | 0.33 | 3.13 | 78 | 745 |
| 3260 | 0.65 | 0.19 | 0.53 | 444 | 0.1 | 0.43 | 3.3 | 66 | 507 |
| 3270 | 1.16 | 0.37 | 1.75 | 388 | 0.65 | 1.1 | 2.39 | 94 | 206 |
| 3280 | 1.85 | 0.13 | 1.34 | 437 | 0.17 | 1.17 | 4.87 | 63 | 263 |
| 3290 | 1.1 | 0.15 | 0.82 | 436 | 0.12 | 0.7 | 2.06 | 63 | 187 |
| 3300 | 1.13 | 0.24 | 1 | 440 | 0.24 | 0.76 | 3.24 | 67 | 286 |
| 3310 | 0.68 | 0.23 | 0.64 | 454 | 0.15 | 0.49 | 3.04 | 72 | 447 |
| 3320 | 4.12 | 0.11 | 1.59 | 446 | 0.17 | 1.42 | 3.17 | 34 | 76 |
| 3330 | 2.9 | 0.23 | 1.52 | 444 | 0.35 | 1.17 | 2.74 | 40 | 94 |
| 3340 | 1.09 | 0.17 | 0.66 | 437 | 0.11 | 0.55 | 2.05 | 50 | 188 |
| 3350 | 1.97 | 0.09 | 1.03 | 443 | 0.09 | 0.94 | 3.66 | 47 | 185 |
| 3360 | 1.26 | 0.15 | 0.75 | 440 | 0.11 | 0.64 | 1.87 | 50 | 148 |
| 3370 | 2.46 | 0.27 | 2.75 | 434 | 0.73 | 2.02 | 0.96 | 82 | 39 |
| 3380 | 1.09 | 0.25 | 0.8 | 441 | 0.2 | 0.6 | 0.8 | 55 | 73 |
| 3390 | 0.6 | 0.25 | 0.32 | 437 | 0.08 | 0.24 | 0.58 | 40 | 96 |
| 3400 | 7.76 | 0.03 | 18.48 | 430 | 0.56 | 17.92 | 1.65 | 230 | 21 |
| 3410 | 2.28 | 0.1 | 1.77 | 441 | 0.18 | 1.59 | 0.98 | 69 | 42 |
| 3420 | 2.25 | 0.06 | 5.06 | 378 | 0.3 | 4.76 | 1.09 | 211 | 48 |
| 3430 | 6.77 | 0.03 | 15.98 | 432 | 0.48 | 15.5 | 1.53 | 228 | 22 |
| 3440 | 1.59 | 0.1 | 1.39 | 437 | 0.14 | 1.25 | 1.17 | 78 | 73 |
| 3450 | 1.87 | 0.12 | 1.9 | 434 | 0.23 | 1.67 | 1.08 | 89 | 57 |
| 3460 | 2.43 | 0.06 | 2.04 | 436 | 0.12 | 1.92 | 0.99 | 79 | 40 |
| 3470 | 1.51 | 0.08 | 1.35 | 431 | 0.11 | 1.24 | 0.68 | 82 | 45 |
| 3480 | 4.44 | 0.06 | 3.54 | 439 | 0.2 | 3.34 | 1.49 | 75 | 33 |
| 3490 | 0.79 | 0.24 | 0.67 | 428 | 0.16 | 0.51 | 1.31 | 64 | 165 |
| 3500 | 0.88 | 0.09 | 0.74 | 437 | 0.07 | 0.67 | 0.7 | 76 | 79 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3510 | 2.34 | 0.11 | 2.54 | 435 | 0.29 | 2.25 | 0.78 | 96 | 33 |
| 3520 | 29.9 | 0.02 | 65.96 | 431 | 1.29 | 64.67 | 3.23 | 216 | 10 |
| 3520 | 34.18 | 0.02 | 70.27 | 433 | 1.22 | 69.05 | 1.98 | 202 | 5 |
| 3520 | 12.48 | 0.02 | 58.3 | 426 | 1.18 | 57.12 | 2.76 | 457 | 22 |
| 3530 | 5.37 | 0.03 | 9.02 | 432 | 0.26 | 8.76 | 1.19 | 163 | 22 |
| 3540 | 1.52 | 0.08 | 1.56 | 438 | 0.13 | 1.43 | 0.81 | 94 | 53 |
| 3550 | 1.62 | 0.21 | 1.8 | 435 | 0.38 | 1.42 | 0.71 | 87 | 43 |
| 3560 | 1.61 | 0.07 | 1.51 | 435 | 0.11 | 1.4 | 0.62 | 86 | 38 |
| 3570 | 1.65 | 0.19 | 1.88 | 439 | 0.36 | 1.52 | 1.08 | 92 | 65 |
| 3580 | 2.81 | 0.06 | 2.77 | 438 | 0.16 | 2.61 | 1 | 92 | 35 |
| 3590 | 1.68 | 0.07 | 1.41 | 438 | 0.1 | 1.31 | 0.6 | 77 | 35 |
| 3600 | 1.93 | 0.06 | 2.08 | 437 | 0.12 | 1.96 | 0.55 | 101 | 28 |
| 3610 | 1.94 | 0.12 | 1.65 | 437 | 0.2 | 1.45 | 0.55 | 74 | 28 |
| 3620 | 1.36 | 0.17 | 1.09 | 442 | 0.19 | 0.9 | 0.42 | 66 | 30 |
| 3630 | 0.66 | 0.17 | 0.54 | 436 | 0.09 | 0.45 | 0.47 | 68 | 71 |
| 3640 | 1.38 | 0.13 | 1.52 | 436 | 0.19 | 1.33 | 0.4 | 96 | 28 |
| 3650 | 6.29 | 0.03 | 10.72 | 434 | 0.32 | 10.4 | 0.78 | 165 | 12 |
| 3660 | 2.33 | 0.05 | 2.43 | 440 | 0.11 | 2.32 | 0.63 | 99 | 27 |
| 3670 | 1.9 | 0.06 | 1.78 | 440 | 0.11 | 1.67 | 0.5 | 87 | 26 |
| 3680 | 1.92 | 0.09 | 1.86 | 439 | 0.17 | 1.69 | 0.62 | 88 | 32 |
| 3690 | 1.23 | 0.1 | 1.16 | 436 | 0.12 | 1.04 | 0.46 | 84 | 37 |
| 3700 | 2.17 | 0.15 | 2.1 | 443 | 0.31 | 1.79 | 0.56 | 82 | 25 |
| 3710 | 1.94 | 0.18 | 1.99 | 439 | 0.36 | 1.63 | 0.46 | 84 | 23 |
| 3720 | 2.14 | 0.16 | 2.13 | 437 | 0.35 | 1.78 | 0.44 | 83 | 20 |
| 3730 | 3.34 | 0.32 | 5.67 | 438 | 1.81 | 3.86 | 0.88 | 115 | 26 |
| 3740 | 1.4 | 0.17 | 1.36 | 439 | 0.23 | 1.13 | 0.42 | 80 | 29 |
| 3750 | 3.87 | 0.16 | 4.39 | 445 | 0.72 | 3.67 | 0.78 | 94 | 20 |
| 3760 | 1.97 | 0.15 | 1.97 | 442 | 0.29 | 1.68 | 0.49 | 85 | 24 |
| 3770 | 3.38 | 0.06 | 4.43 | 441 | 0.27 | 4.16 | 0.55 | 123 | 16 |
| 3780 | 2 | 0.12 | 1.89 | 440 | 0.22 | 1.67 | 0.42 | 83 | 21 |
| 3790 | 2.91 | 0.14 | 3.11 | 440 | 0.45 | 2.66 | 0.67 | 91 | 23 |
| 3800 | 4.57 | 0.06 | 6.2 | 440 | 0.4 | 5.8 | 0.69 | 126 | 15 |
| 3810 | 2.43 | 0.29 | 3.63 | 436 | 1.07 | 2.56 | 0.73 | 105 | 30 |
| 3820 | 2.06 | 0.16 | 1.87 | 439 | 0.29 | 1.58 | 0.54 | 76 | 26 |
| 3830 | 2.1 | 0.17 | 1.96 | 439 | 0.33 | 1.63 | 0.49 | 77 | 23 |
| 3840 | 1.91 | 0.2 | 1.61 | 439 | 0.32 | 1.29 | 0.53 | 67 | 27 |
| 3850 | 30.43 | 0.03 | 93.75 | 430 | 2.67 | 91.08 | 4.15 | 299 | 13 |
| 3850 | 14.04 | 0.04 | 80.08 | 425 | 3.12 | 76.96 | 2.17 | 548 | 15 |
| 3860 | 2.67 | 0.12 | 2.92 | 437 | 0.34 | 2.58 | 0.88 | 96 | 32 |
| 3870 | 2.88 | 0.12 | 3.42 | 441 | 0.4 | 3.02 | 0.71 | 104 | 24 |
| 3880 | 3.95 | 0.13 | 5.39 | 437 | 0.72 | 4.67 | 0.68 | 118 | 17 |
| 3890 | 1.89 | 0.2 | 2.27 | 438 | 0.45 | 1.82 | 0.57 | 96 | 30 |
| 3900 | 2.92 | 0.18 | 4.09 | 439 | 0.73 | 3.36 | 0.65 | 115 | 22 |
| 3910 | 1.81 | 0.32 | 2.52 | 438 | 0.81 | 1.71 | 0.58 | 94 | 32 |
| 3920 | 2.05 | 0.29 | 2.42 | 440 | 0.69 | 1.73 | 0.58 | 84 | 28 |
| 3930 | 2.28 | 0.28 | 3.12 | 435 | 0.86 | 2.26 | 0.55 | 99 | 24 |
| 3940 | 2 | 0.17 | 2.27 | 434 | 0.39 | 1.88 | 0.49 | 94 | 24 |
| 3950 | 2.51 | 0.16 | 3.34 | 439 | 0.53 | 2.81 | 0.5 | 111 | 19 |
| 3960 | 2.06 | 0.21 | 2.22 | 435 | 0.47 | 1.75 | 0.41 | 84 | 19 |
| 3970 | 1.46 | 0.36 | 1.91 | 434 | 0.69 | 1.22 | 0.91 | 83 | 62 |
| 3980 | 2.35 | 0.11 | 2.47 | 439 | 0.27 | 2.2 | 0.55 | 93 | 23 |

| 3990 | 3.17 | 0.09 | 4.55 | 439 | 0.4 | 4.15 | 0.51 | 130 | 16 |
|---|---|---|---|---|---|---|---|---|---|
| 4000 | 2.67 | 0.19 | 3.26 | 442 | 0.62 | 2.64 | 0.55 | 98 | 20 |
| 4010 | 4.22 | 0.17 | 5.23 | 444 | 0.89 | 4.34 | 0.82 | 102 | 19 |
| 4020 | 1.97 | 0.19 | 2.04 | 441 | 0.39 | 1.65 | 0.58 | 83 | 29 |
| 4030 | 2.25 | 0.19 | 2.2 | 442 | 0.41 | 1.79 | 0.54 | 79 | 24 |
| 4040 | 2.6 | 0.2 | 3.06 | 442 | 0.62 | 2.44 | 0.49 | 93 | 18 |
| 4050 | 2.77 | 0.1 | 2.55 | 438 | 0.25 | 2.3 | 0.52 | 83 | 18 |
| 4060 | 3.79 | 0.15 | 5.23 | 442 | 0.81 | 4.42 | 0.66 | 116 | 17 |
| 4070 | 2.62 | 0.14 | 3.09 | 441 | 0.44 | 2.65 | 0.74 | 101 | 28 |
| 4080 | 1.4 | 0.15 | 1.24 | 439 | 0.19 | 1.05 | 0.55 | 75 | 39 |
| 4090 | 1.5 | 0.15 | 1.5 | 439 | 0.22 | 1.28 | 0.42 | 85 | 28 |
| 4100 | 1.86 | 0.12 | 1.63 | 441 | 0.2 | 1.43 | 0.39 | 76 | 20 |
| 4110 | 2.26 | 0.11 | 2.2 | 442 | 0.25 | 1.95 | 0.49 | 86 | 21 |
| 4120 | 1.82 | 0.16 | 1.66 | 439 | 0.26 | 1.4 | 0.37 | 76 | 20 |
| 4130 | 3.14 | 0.13 | 3.31 | 444 | 0.43 | 2.88 | 0.48 | 91 | 15 |
| 4140 | 2.22 | 0.15 | 1.97 | 438 | 0.29 | 1.68 | 0.48 | 75 | 21 |
| 4150 | 2.16 | 0.09 | 1.9 | 440 | 0.18 | 1.72 | 0.55 | 79 | 25 |
| 4160 | 3.12 | 0.12 | 4.27 | 441 | 0.5 | 3.77 | 0.63 | 120 | 20 |
| 4170 | 1.58 | 0.12 | 1.82 | 441 | 0.22 | 1.6 | 0.41 | 101 | 25 |
| 4180 | 1.03 | 0.13 | 0.88 | 443 | 0.11 | 0.77 | 0.28 | 74 | 27 |
| 4190 | 1.14 | 0.2 | 1.09 | 438 | 0.22 | 0.87 | 0.35 | 76 | 30 |
| 4200 | 3.43 | 0.07 | 4.95 | 437 | 0.37 | 4.58 | 0.75 | 133 | 21 |
| 4210 | 2.47 | 0.04 | 9.47 | 366 | 0.42 | 9.05 | 0.97 | 366 | 39 |
| 4220 | 1.66 | 0.18 | 1.54 | 440 | 0.27 | 1.27 | 0.71 | 76 | 42 |
| 4230 | 1.52 | 0.18 | 1.59 | 441 | 0.28 | 1.31 | 0.52 | 86 | 34 |
| 4240 | 0.86 | 0.13 | 0.79 | 443 | 0.1 | 0.69 | 0.28 | 80 | 32 |
| 4250 | 0.94 | 0.23 | 1.09 | 441 | 0.25 | 0.84 | 0.28 | 89 | 29 |
| 4260 | 3.14 | 0.19 | 4.93 | 439 | 0.94 | 3.99 | 0.54 | 127 | 17 |
| 4270 | 2.27 | 0.13 | 3.32 | 441 | 0.42 | 2.9 | 0.46 | 127 | 20 |
| 4280 | 1.39 | 0.16 | 1.14 | 445 | 0.18 | 0.96 | 0.54 | 69 | 38 |
| 4290 | 1.25 | 0.18 | 1 | 444 | 0.18 | 0.82 | 0.73 | 65 | 58 |
| 4300 | 0.98 | 0.17 | 0.72 | 441 | 0.12 | 0.6 | 0.44 | 61 | 44 |
| 4310 | 2 | 0.13 | 2 | 439 | 0.27 | 1.73 | 0.41 | 86 | 20 |
| 4320 | 1.13 | 0.16 | 0.86 | 444 | 0.14 | 0.72 | 0.49 | 63 | 43 |
| 4330 | 1.58 | 0.13 | 1.41 | 442 | 0.19 | 1.22 | 0.46 | 77 | 29 |
| 4340 | 1.3 | 0.12 | 1.15 | 443 | 0.14 | 1.01 | 0.4 | 77 | 30 |
| 4350 | 0.96 | 0.12 | 0.75 | 438 | 0.09 | 0.66 | 0.33 | 68 | 34 |
| 4360 | 2.8 | 0.08 | 2.95 | 440 | 0.25 | 2.7 | 0.46 | 96 | 16 |
| 4370 | 1.91 | 0.09 | 1.72 | 440 | 0.15 | 1.57 | 0.49 | 82 | 25 |
| 4380 | 3.3 | 0.1 | 3.44 | 439 | 0.35 | 3.09 | 0.64 | 93 | 19 |
| 4390 | 2.25 | 0.08 | 2.08 | 439 | 0.17 | 1.91 | 0.46 | 84 | 20 |
| 4400 | 1.21 | 0.09 | 0.99 | 443 | 0.09 | 0.9 | 0.41 | 74 | 33 |
| 4410 | 1.54 | 0.22 | 1.79 | 435 | 0.39 | 1.4 | 0.49 | 90 | 31 |
| 4420 | 1.57 | 0.1 | 1.55 | 441 | 0.16 | 1.39 | 0.43 | 88 | 27 |
| 4430 | 1.85 | 0.09 | 1.72 | 443 | 0.15 | 1.57 | 0.52 | 84 | 28 |
| 4440 | 0.87 | 0.12 | 0.67 | 440 | 0.08 | 0.59 | 0.31 | 67 | 35 |
| 4450 | 1.9 | 0.12 | 1.63 | 442 | 0.19 | 1.44 | 0.46 | 75 | 24 |
| 4460 | 1.04 | 0.11 | 0.8 | 442 | 0.09 | 0.71 | 0.35 | 68 | 33 |
| 4470 | 2.48 | 0.17 | 2.8 | 441 | 0.47 | 2.33 | 0.6 | 93 | 24 |
| 4480 | 0.69 | 0.17 | 0.52 | 441 | 0.09 | 0.43 | 0.31 | 62 | 44 |
| 4490 | 0.85 | 0.18 | 0.66 | 439 | 0.12 | 0.54 | 0.37 | 63 | 43 |

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|---|---|---|---|---|---|---|---|---|---|
| 4500 | 0.7 | 0.16 | 0.55 | 436 | 0.09 | 0.46 | 0.37 | 65 | 52 |
| 4510 | 1.11 | 0.24 | 0.95 | 441 | 0.23 | 0.72 | 0.37 | 64 | 33 |
| 4520 | 1.01 | 0.19 | 0.85 | 443 | 0.16 | 0.69 | 0.4 | 68 | 39 |
| 4530 | 1.61 | 0.12 | 1.81 | 441 | 0.22 | 1.59 | 0.44 | 98 | 27 |
| 4540 | 0.6 | 0.16 | 0.51 | 441 | 0.08 | 0.43 | 0.38 | 71 | 63 |
| 4550 | 1.27 | 0.09 | 1.05 | 442 | 0.09 | 0.96 | 0.33 | 75 | 25 |
| 4560 | 1.03 | 0.13 | 0.79 | 454 | 0.1 | 0.69 | 0.33 | 66 | 32 |
| 4570 | 0.73 | 0.2 | 0.64 | 442 | 0.13 | 0.51 | 0.33 | 69 | 45 |
| 4580 | 0.6 | 0.13 | 0.39 | 441 | 0.05 | 0.34 | 0.28 | 56 | 46 |
| 4590 | 0.95 | 0.1 | 0.73 | 447 | 0.07 | 0.66 | 0.37 | 69 | 38 |
| 4600 | 1.53 | 0.09 | 1.44 | 445 | 0.13 | 1.31 | 0.48 | 85 | 31 |
| 4610 | 2.14 | 0.11 | 2.15 | 442 | 0.23 | 1.92 | 0.51 | 89 | 23 |
| 4620 | 0.95 | 0.23 | 0.95 | 441 | 0.22 | 0.73 | 0.4 | 76 | 42 |
| 4630 | 1.89 | 0.11 | 1.89 | 447 | 0.21 | 1.68 | 0.46 | 88 | 24 |
| 4640 | 1.58 | 0.14 | 1.57 | 446 | 0.22 | 1.35 | 0.52 | 85 | 32 |
| 4650 | 1.76 | 0.1 | 1.72 | 446 | 0.17 | 1.55 | 0.46 | 88 | 26 |
| 4660 | 1.62 | 0.12 | 1.56 | 440 | 0.18 | 1.38 | 0.4 | 85 | 24 |
| 4670 | 5.89 | 0.06 | 6.66 | 449 | 0.41 | 6.25 | 0.83 | 106 | 14 |
| 4680 | 1.45 | 0.14 | 1.09 | 448 | 0.15 | 0.94 | 0.45 | 64 | 31 |
| 4690 | 6.31 | 0.07 | 12.4 | 439 | 0.89 | 11.51 | 0.88 | 182 | 13 |
| 4700 | 2.01 | 0.13 | 1.87 | 446 | 0.25 | 1.62 | 0.65 | 80 | 32 |
| 4710 | 1.45 | 0.26 | 1.44 | 442 | 0.38 | 1.06 | 0.59 | 73 | 40 |
| 4720 | 0.86 | 0.24 | 0.89 | 438 | 0.21 | 0.68 | 0.32 | 79 | 37 |
| 4730 | 1.03 | 0.27 | 1 | 447 | 0.27 | 0.73 | 0.33 | 70 | 32 |
| 4740 | 1.26 | 0.46 | 2.05 | 441 | 0.95 | 1.1 | 0.34 | 87 | 26 |
| 4750 | 2.12 | 0.25 | 2.65 | 443 | 0.66 | 1.99 | 0.39 | 93 | 18 |
| 4760 | 1.63 | 0.29 | 2.23 | 439 | 0.64 | 1.59 | 0.42 | 97 | 25 |
| 4770 | 0.94 | 0.42 | 1.11 | 445 | 0.47 | 0.64 | 0.28 | 68 | 29 |
| 4780 | 1.17 | 0.21 | 1.12 | 445 | 0.23 | 0.89 | 0.31 | 76 | 26 |
| 4790 | 0.95 | 0.27 | 0.96 | 443 | 0.26 | 0.7 | 0.33 | 73 | 34 |
| 4800 | 1.28 | 0.26 | 1.76 | 437 | 0.46 | 1.3 | 0.35 | 101 | 27 |
| 4810 | 9.16 | 0.45 | 28.98 | 428 | 12.92 | 16.06 | 4.44 | 175 | 48 |
| 4810 | 10.79 | 0.34 | 49.06 | 430 | 16.62 | 32.44 | 1.5 | 300 | 13 |
| 4820 | 5.21 | 0.44 | 22.91 | 424 | 9.97 | 12.94 | 1.24 | 248 | 23 |
| 4830 | 1.02 | 0.6 | 2.73 | 435 | 1.65 | 1.08 | 0.64 | 105 | 62 |
| 4840 | 0.36 | 0.67 | 0.6 | 391 | 0.4 | 0.2 | 0.3 | 55 | 83 |
| 4860 | 0.73 | 0.49 | 1.12 | 438 | 0.55 | 0.57 | 0.29 | 78 | 39 |
| 4870 | 0.88 | 0.67 | 1.93 | 441 | 1.3 | 0.63 | 0.27 | 71 | 30 |
| 4880 | 1.18 | 0.41 | 1.47 | 441 | 0.61 | 0.86 | 0.37 | 72 | 31 |
| 4890 | 1.2 | 0.44 | 1.59 | 440 | 0.7 | 0.89 | 0.42 | 74 | 35 |
| 4900 | 0.54 | 0.48 | 0.69 | 440 | 0.33 | 0.36 | 0.38 | 66 | 70 |
| 4910 | 0.51 | 0.53 | 1.42 | 341 | 0.75 | 0.67 | 0.4 | 131 | 78 |
| 4920 | 1.11 | 0.32 | 1.47 | 441 | 0.47 | 1 | 0.55 | 90 | 49 |
| 4930 | 0.55 | 0.6 | 1.07 | 440 | 0.64 | 0.43 | 0.31 | 78 | 56 |
| 4940 | 1.59 | 0.19 | 1.8 | 442 | 0.35 | 1.45 | 0.34 | 91 | 21 |
| 4950 | 0.5 | 0.47 | 0.64 | 440 | 0.3 | 0.34 | 0.36 | 68 | 72 |
| 4960 | 1.18 | 0.36 | 1.43 | 441 | 0.52 | 0.91 | 0.48 | 77 | 40 |
| 4970 | 2.32 | 0.35 | 4.23 | 441 | 1.46 | 2.77 | 0.5 | 119 | 21 |
| 4980 | 0.83 | 0.35 | 0.89 | 443 | 0.31 | 0.58 | 0.25 | 69 | 30 |
| 4990 | 0.49 | 0.42 | 0.55 | 417 | 0.23 | 0.32 | 0.23 | 65 | 46 |
| 5000 | 0.52 | 0.31 | 0.54 | 440 | 0.17 | 0.37 | 0.2 | 71 | 38 |

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|---|---|---|---|---|---|---|---|---|---|
| 5010 | 0.46 | 0.47 | 0.85 | 393 | 0.4 | 0.45 | 0.18 | 97 | 39 |
| 5020 | 0.93 | 0.31 | 0.99 | 449 | 0.31 | 0.68 | 0.29 | 73 | 31 |
| 5030 | 0.39 | 0.45 | 0.49 | 441 | 0.22 | 0.27 | 0.27 | 69 | 69 |
| 5040 | 0.98 | 0.29 | 0.94 | 448 | 0.27 | 0.67 | 0.25 | 68 | 25 |
| 5050 | 0.86 | 0.26 | 0.86 | 445 | 0.22 | 0.64 | 0.44 | 74 | 51 |
| 5060 | 1.86 | 0.19 | 2.2 | 446 | 0.42 | 1.78 | 0.61 | 95 | 32 |
| 5070 | 0.34 | 0.4 | 0.25 | 443 | 0.1 | 0.15 | 0.35 | 44 | 102 |
| 5080 | 0.54 | 0.28 | 0.61 | 447 | 0.17 | 0.44 | 0.23 | 81 | 42 |
| 5090 | 0.58 | 0.2 | 0.45 | 446 | 0.09 | 0.36 | 0.3 | 62 | 51 |
| 5100 | 0.74 | 0.26 | 0.68 | 453 | 0.18 | 0.5 | 0.24 | 67 | 32 |
| 5110 | 0.63 | 0.36 | 0.9 | 440 | 0.32 | 0.58 | 0.21 | 92 | 33 |
| 5120 | 0.81 | 0.37 | 1.11 | 443 | 0.41 | 0.7 | 0.36 | 86 | 44 |
| 5130 | 1.94 | 0.18 | 2.34 | 453 | 0.42 | 1.92 | 0.31 | 98 | 15 |
| 5140 | 1.98 | 0.23 | 1.77 | 458 | 0.41 | 1.36 | 0.51 | 68 | 25 |
| 5150 | 1.27 | 0.15 | 1.5 | 439 | 0.23 | 1.27 | 0.64 | 100 | 50 |
| 5160 | 1.67 | 0.14 | 1.9 | 446 | 0.26 | 1.64 | 0.42 | 98 | 25 |
| 5180 | 1.21 | 0.17 | 1.27 | 445 | 0.22 | 1.05 | 0.33 | 86 | 27 |
| 5190 | 0.92 | 0.23 | 0.83 | 444 | 0.19 | 0.64 | 0.37 | 69 | 40 |
| 5200 | 1.1 | 0.23 | 1.15 | 445 | 0.27 | 0.88 | 0.38 | 80 | 34 |
| 5210 | 0.62 | 0.4 | 0.89 | 445 | 0.36 | 0.53 | 0.39 | 85 | 62 |
| 5220 | 0.73 | 0.25 | 0.72 | 449 | 0.18 | 0.54 | 0.38 | 73 | 52 |
| 5230 | 2.54 | 0.19 | 3.89 | 442 | 0.74 | 3.15 | 0.68 | 124 | 26 |
| 5240 | 1.29 | 0.18 | 1.14 | 450 | 0.2 | 0.94 | 0.89 | 72 | 68 |
| 5250 | 4.55 | 0.05 | 12.9 | 440 | 0.64 | 12.26 | 0.46 | 269 | 10 |
| 5260 | 1.05 | 0.23 | 1.08 | 445 | 0.25 | 0.83 | 0.55 | 79 | 52 |
| 5270 | 1.39 | 0.17 | 1.57 | 445 | 0.27 | 1.3 | 0.56 | 93 | 40 |
| 5280 | 1.17 | 0.14 | 1.51 | 447 | 0.21 | 1.3 | 0.32 | 111 | 27 |
| 5290 | 3.22 | 0.19 | 5.66 | 448 | 1.09 | 4.57 | 0.44 | 141 | 13 |
| 5300 | 1.53 | 0.15 | 1.7 | 448 | 0.26 | 1.44 | 0.45 | 94 | 29 |
| 5310 | 1.21 | 0.25 | 1.55 | 449 | 0.38 | 1.17 | 0.37 | 96 | 30 |
| 5320 | 1.06 | 0.2 | 1.23 | 448 | 0.25 | 0.98 | 0.38 | 92 | 35 |
| 5330 | 2.03 | 0.13 | 3.01 | 449 | 0.39 | 2.62 | 0.44 | 129 | 21 |
| 5340 | 7.98 | 0.07 | 28.64 | 442 | 2 | 26.64 | 0.9 | 333 | 11 |
| 5350 | 1.7 | 0.1 | 2.48 | 454 | 0.24 | 2.24 | 0.53 | 131 | 31 |
| 5360 | 1.95 | 0.13 | 2.39 | 446 | 0.32 | 2.07 | 0.49 | 106 | 25 |
| 5370 | 0.96 | 0.15 | 0.93 | 447 | 0.14 | 0.79 | 0.43 | 82 | 44 |
| 5380 | 0.85 | 0.22 | 0.86 | 447 | 0.19 | 0.67 | 0.49 | 78 | 57 |
| 5390 | 1.09 | 0.23 | 1.93 | 448 | 0.45 | 1.48 | 0.41 | 135 | 37 |
| 5400 | 0.8 | 0.16 | 0.96 | 449 | 0.15 | 0.81 | 0.44 | 101 | 55 |
| 5410 | 0.8 | 0.16 | 0.86 | 450 | 0.14 | 0.72 | 0.34 | 90 | 42 |
| 5420 | 0.94 | 0.18 | 1.13 | 451 | 0.2 | 0.93 | 0.34 | 98 | 36 |
| 5430 | 1.2 | 0.16 | 1.34 | 450 | 0.21 | 1.13 | 0.33 | 94 | 27 |
| 5440 | 1.12 | 0.16 | 1.22 | 448 | 0.19 | 1.03 | 0.35 | 91 | 31 |
| 5450 | 0.92 | 0.15 | 1.05 | 447 | 0.16 | 0.89 | 0.35 | 96 | 38 |
| 5460 | 0.68 | 0.14 | 0.79 | 451 | 0.11 | 0.68 | 0.23 | 100 | 33 |
| 5470 | 3.31 | 0.1 | 4.28 | 448 | 0.41 | 3.87 | 0.61 | 116 | 18 |
| 5480 | 2.35 | 0.12 | 2.95 | 454 | 0.34 | 2.61 | 0.63 | 111 | 26 |
| 5490 | 3.26 | 0.09 | 4.8 | 456 | 0.43 | 4.37 | 0.6 | 134 | 18 |
| 5500 | 1.11 | 0.28 | 1.78 | 450 | 0.49 | 1.29 | 1.66 | 116 | 149 |
| 5510 | 0.75 | 0.3 | 1.07 | 448 | 0.32 | 0.75 | 0.56 | 100 | 74 |
| 5520 | 0.65 | 0.49 | 1.7 | 346 | 0.83 | 0.87 | 0.7 | 133 | 107 |

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|---|---|---|---|---|---|---|---|---|---|
| 5530 | 1.19 | 0.43 | 1.97 | 441 | 0.84 | 1.13 | 0.7 | 94 | 58 |
| 5540 | 4.12 | 0.07 | 6 | 452 | 0.44 | 5.56 | 0.75 | 134 | 18 |
| 5550 | 0.46 | 0.2 | 0.5 | 449 | 0.1 | 0.4 | 0.46 | 86 | 100 |
| 5560 | 0.69 | 0.19 | 0.7 | 455 | 0.13 | 0.57 | 0.39 | 82 | 56 |
| 5570 | 1.49 | 0.11 | 1.45 | 453 | 0.16 | 1.29 | 0.68 | 86 | 45 |
| 5580 | 1.07 | 0.15 | 1.12 | 454 | 0.17 | 0.95 | 0.77 | 88 | 71 |
| 5590 | 0.41 | 0.21 | 0.42 | 449 | 0.09 | 0.33 | 0.34 | 80 | 82 |
| 5600 | 0.95 | 0.39 | 1.76 | 445 | 0.68 | 1.08 | 0.7 | 113 | 73 |
| 5610 | 0.48 | 0.3 | 0.5 | 449 | 0.15 | 0.35 | 0.39 | 72 | 81 |
| 5620 | 2.54 | 0.17 | 2.38 | 454 | 0.4 | 1.98 | 0.89 | 77 | 35 |
| 5630 | 1.33 | 0.22 | 1.33 | 452 | 0.29 | 1.04 | 0.77 | 78 | 57 |
| 5640 | 1.11 | 0.22 | 0.93 | 453 | 0.2 | 0.73 | 0.72 | 65 | 64 |
| 5650 | 17.16 | 0.05 | 46.79 | 451 | 2.26 | 44.53 | 1.97 | 259 | 11 |
| 5650 | 10.24 | 0.06 | 48.59 | 445 | 2.77 | 45.82 | 1.45 | 447 | 14 |
| 5660 | 2.9 | 0.09 | 4.47 | 451 | 0.38 | 4.09 | 0.83 | 141 | 28 |
| 5670 | 1.09 | 0.1 | 1.15 | 451 | 0.11 | 1.04 | 0.65 | 95 | 59 |
| 5680 | 0.94 | 0.16 | 0.94 | 453 | 0.15 | 0.79 | 0.45 | 84 | 47 |
| 5690 | 4.67 | 0.38 | 8.79 | 443 | 3.35 | 5.44 | 1.53 | 116 | 32 |
| 5700 | 0.85 | 0.11 | 0.89 | 454 | 0.1 | 0.79 | 0.56 | 92 | 65 |
| 5710 | 0.89 | 0.09 | 0.85 | 453 | 0.08 | 0.77 | 0.5 | 86 | 56 |
| 5720 | 0.86 | 0.14 | 0.78 | 452 | 0.11 | 0.67 | 0.59 | 77 | 68 |
| 5730 | 0.84 | 0.1 | 0.8 | 454 | 0.08 | 0.72 | 0.45 | 85 | 53 |
| 5740 | 6.44 | 0.06 | 12.89 | 449 | 0.77 | 12.12 | 0.84 | 188 | 13 |
| 5750 | 2.2 | 0.08 | 2.62 | 458 | 0.2 | 2.42 | 0.76 | 110 | 34 |
| 5760 | 1.98 | 0.09 | 2.16 | 456 | 0.2 | 1.96 | 0.57 | 98 | 28 |
| 5770 | 1.58 | 0.1 | 1.67 | 454 | 0.16 | 1.51 | 0.49 | 95 | 31 |
| 5780 | 1.44 | 0.09 | 1.36 | 458 | 0.12 | 1.24 | 0.41 | 86 | 28 |
| 5790 | 2.16 | 0.09 | 2.81 | 455 | 0.24 | 2.57 | 0.39 | 118 | 18 |
| 5800 | 2.87 | 0.06 | 3.67 | 458 | 0.22 | 3.45 | 0.42 | 120 | 14 |
| 5810 | 2.07 | 0.08 | 2.6 | 453 | 0.21 | 2.39 | 0.63 | 115 | 30 |
| 5820 | 1.67 | 0.11 | 1.81 | 453 | 0.2 | 1.61 | 0.75 | 96 | 44 |
| 5830 | 1.05 | 0.09 | 1.42 | 449 | 0.13 | 1.29 | 0.46 | 122 | 43 |
| 5840 | 1.31 | 0.08 | 1.36 | 456 | 0.11 | 1.25 | 0.34 | 95 | 25 |
| 5850 | 1.25 | 0.09 | 1.25 | 452 | 0.11 | 1.14 | 0.33 | 91 | 26 |
| 5860 | 1.42 | 0.07 | 1.45 | 454 | 0.1 | 1.35 | 0.52 | 95 | 36 |
| 5870 | 2.16 | 0.08 | 3.1 | 454 | 0.25 | 2.85 | 0.52 | 131 | 24 |
| 5880 | 5.32 | 0.07 | 12.08 | 448 | 0.87 | 11.21 | 0.4 | 210 | 7 |
| 5890 | 2.77 | 0.06 | 5.25 | 452 | 0.32 | 4.93 | 0.51 | 177 | 18 |
| 5900 | 2.16 | 0.07 | 3.95 | 453 | 0.29 | 3.66 | 0.47 | 169 | 21 |
| 5910 | 10.43 | 0.07 | 48.84 | 445 | 3.18 | 45.66 | 1.27 | 437 | 12 |
| 5920 | 9.88 | 0.06 | 41.4 | 445 | 2.33 | 39.07 | 1.09 | 395 | 11 |
| 5930 | 6.05 | 0.04 | 16.66 | 448 | 0.74 | 15.92 | 0.9 | 263 | 14 |
| 5940 | 5.4 | 0.06 | 13.26 | 448 | 0.79 | 12.47 | 0.82 | 230 | 15 |
| 5950 | 2.12 | 0.1 | 2.61 | 449 | 0.27 | 2.34 | 0.76 | 110 | 35 |
| 5960 | 2.71 | 0.08 | 4.85 | 452 | 0.39 | 4.46 | 0.49 | 164 | 18 |
| 5970 | 3.26 | 0.07 | 6.06 | 450 | 0.4 | 5.66 | 0.58 | 173 | 17 |
| 5980 | 1.93 | 0.07 | 3.39 | 454 | 0.25 | 3.14 | 0.51 | 162 | 26 |
| 5990 | 8.27 | 0.05 | 32.21 | 446 | 1.69 | 30.52 | 0.74 | 369 | 8 |
| 6000 | 1.69 | 0.11 | 2.2 | 453 | 0.24 | 1.96 | 0.56 | 115 | 33 |
| 6010 | 1.39 | 0.09 | 2.02 | 455 | 0.19 | 1.83 | 0.43 | 131 | 30 |
| 6020 | 1.6 | 0.08 | 2.37 | 457 | 0.2 | 2.17 | 0.39 | 135 | 24 |

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|---|---|---|---|---|---|---|---|---|---|
| 6030 | 1.94 | 0.11 | 2.74 | 454 | 0.3 | 2.44 | 0.43 | 125 | 22 |
| 6040 | 0.82 | 0.12 | 0.86 | 458 | 0.1 | 0.76 | 0.29 | 92 | 35 |
| 6050 | 1.78 | 0.09 | 2.2 | 456 | 0.19 | 2.01 | 0.46 | 112 | 25 |
| 6060 | 1.68 | 0.12 | 1.86 | 455 | 0.22 | 1.64 | 0.45 | 97 | 26 |
| 6070 | 1.39 | 0.14 | 2.18 | 454 | 0.3 | 1.88 | 0.26 | 135 | 18 |
| 6080 | 0.79 | 0.16 | 0.88 | 456 | 0.14 | 0.74 | 0.39 | 93 | 49 |
| 6090 | 0.81 | 0.13 | 0.87 | 457 | 0.11 | 0.76 | 0.5 | 93 | 61 |
| 6100 | 3.16 | 0.08 | 5.93 | 448 | 0.49 | 5.44 | 0.46 | 172 | 14 |
| 6110 | 1.5 | 0.1 | 2.5 | 453 | 0.25 | 2.25 | 0.45 | 150 | 30 |
| 6120 | 0.77 | 0.14 | 0.86 | 453 | 0.12 | 0.74 | 0.39 | 96 | 50 |
| 6130 | 0.91 | 0.13 | 1.21 | 454 | 0.16 | 1.05 | 0.32 | 115 | 35 |
| 6140 | 1.64 | 0.1 | 2.57 | 453 | 0.26 | 2.31 | 0.35 | 140 | 21 |
| 6150 | 1.5 | 0.1 | 1.95 | 454 | 0.19 | 1.76 | 0.37 | 117 | 24 |
| 6160 | 0.69 | 0.14 | 0.59 | 455 | 0.08 | 0.51 | 0.39 | 73 | 56 |
| 6170 | 0.63 | 0.12 | 0.6 | 457 | 0.07 | 0.53 | 0.35 | 84 | 55 |
| 6180 | 0.62 | 0.13 | 0.61 | 456 | 0.08 | 0.53 | 0.34 | 85 | 54 |
| 6190 | 0.64 | 0.13 | 0.86 | 454 | 0.11 | 0.75 | 0.34 | 117 | 53 |
| 6200 | 0.68 | 0.12 | 0.75 | 459 | 0.09 | 0.66 | 0.4 | 97 | 58 |
| 6200.1 | 0.53 | 0.16 | 0.51 | 462 | 0.08 | 0.43 | 0.57 | 81 | 107 |
| 6210 | 1.24 | 0.09 | 1.84 | 453 | 0.17 | 1.67 | 0.17 | 134 | 13 |
| 6210.1 | 1.1 | 0.14 | 1.12 | 460 | 0.16 | 0.96 | 0.56 | 87 | 50 |
| 6220 | 4.02 | 0.08 | 10.35 | 449 | 0.81 | 9.54 | 0.43 | 237 | 10 |
| 6220.1 | 4.86 | 0.07 | 10.51 | 458 | 0.78 | 9.73 | 0.61 | 200 | 12 |
| 6230 | 1.12 | 0.12 | 1.38 | 455 | 0.17 | 1.21 | 0.49 | 108 | 43 |
| 6230.1 | 0.99 | 0.1 | 1.26 | 460 | 0.12 | 1.14 | 0.63 | 115 | 63 |
| 6240 | 1.42 | 0.1 | 1.9 | 454 | 0.19 | 1.71 | 0.34 | 120 | 23 |
| 6240.1 | 1.26 | 0.09 | 1.5 | 464 | 0.14 | 1.36 | 0.75 | 107 | 59 |
| 6250 | 1.25 | 0.11 | 1.79 | 456 | 0.2 | 1.59 | 0.26 | 127 | 20 |
| 6250.1 | 0.49 | 0.13 | 0.52 | 459 | 0.07 | 0.45 | 0.47 | 91 | 95 |
| 6260 | 0.66 | 0.14 | 0.72 | 456 | 0.1 | 0.62 | 0.34 | 93 | 51 |
| 6260.1 | 0.59 | 0.17 | 0.47 | 465 | 0.08 | 0.39 | 0.5 | 66 | 84 |
| 6270 | 1.27 | 0.11 | 1.52 | 455 | 0.17 | 1.35 | 0.37 | 106 | 29 |
| 6270.1 | 1.58 | 0.08 | 1.96 | 462 | 0.15 | 1.81 | 0.54 | 114 | 34 |
| 6280 | 0.58 | 0.11 | 0.7 | 456 | 0.08 | 0.62 | 0.26 | 106 | 44 |
| 6280.1 | 0.64 | 0.1 | 0.58 | 466 | 0.06 | 0.52 | 0.35 | 81 | 54 |
| 6290 | 5.11 | 0.06 | 15.91 | 447 | 0.88 | 15.03 | 0.36 | 294 | 7 |
| 6290.1 | 0.35 | 0.17 | 0.3 | 466 | 0.05 | 0.25 | 0.34 | 71 | 97 |
| 6300 | 0.98 | 0.11 | 1.06 | 457 | 0.12 | 0.94 | 0.64 | 95 | 65 |
| 6300.1 | 0.69 | 0.12 | 0.67 | 462 | 0.08 | 0.59 | 0.49 | 85 | 71 |
| 6310 | 0.66 | 0.13 | 0.6 | 459 | 0.08 | 0.52 | 0.22 | 78 | 33 |
| 6310.1 | 0.3 | 0.24 | 0.17 | 477 | 0.04 | 0.13 | 0.17 | 43 | 56 |
| 6320 | 0.37 | 0.14 | 0.44 | 459 | 0.06 | 0.38 | 0.21 | 102 | 56 |
| 6330 | 0.41 | 0.13 | 0.47 | 454 | 0.06 | 0.41 | 0.28 | 100 | 68 |
| 6330.1 | 0.22 | 0.29 | 0.21 | 470 | 0.06 | 0.15 | 0.54 | 68 | 245 |
| 6340 | 0.38 | 0.15 | 0.27 | 459 | 0.04 | 0.23 | 0.22 | 60 | 57 |
| 6340.1 | 0.37 | 0.11 | 0.27 | 467 | 0.03 | 0.24 | 0.22 | 64 | 59 |
| 6350 | 0.31 | 0.05 | 0.19 | 459 | 0.01 | 0.18 | 0.16 | 58 | 51 |
| 6360 | 1.12 | 0.08 | 1.06 | 455 | 0.09 | 0.97 | 0.33 | 86 | 29 |
| 6360.1 | 0.49 | 0.15 | 0.39 | 465 | 0.06 | 0.33 | 0.71 | 67 | 144 |
| 6370 | 0.88 | 0.11 | 0.92 | 457 | 0.1 | 0.82 | 0.39 | 93 | 44 |
| 6370.1 | 0.44 | 0.14 | 0.28 | 467 | 0.04 | 0.24 | 1.03 | 54 | 234 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6380 | 0.62 | 0.08 | 0.6 | 458 | 0.05 | 0.55 | 0.16 | 88 | 25 |
| 6380.1 | 0.39 | 0.13 | 0.32 | 465 | 0.04 | 0.28 | 0.23 | 71 | 58 |
| 6390 | 0.68 | 0.08 | 0.77 | 455 | 0.06 | 0.71 | 0.08 | 104 | 11 |
| 6390.1 | 0.5 | 0.08 | 0.48 | 464 | 0.04 | 0.44 | 0.32 | 88 | 64 |
| 6400 | 0.48 | 0.07 | 0.46 | 458 | 0.03 | 0.43 | 0.18 | 89 | 37 |
| 6410 | 0.65 | 0.12 | 0.75 | 457 | 0.09 | 0.66 | 0.22 | 101 | 33 |
| 6410.1 | 0.31 | 0.23 | 0.31 | 464 | 0.07 | 0.24 | 0.22 | 77 | 70 |
| 6420 | 0.59 | 0.1 | 0.6 | 457 | 0.06 | 0.54 | 0.11 | 91 | 18 |
| 6420.1 | 0.84 | 0.13 | 0.93 | 419 | 0.12 | 0.81 | 0.53 | 96 | 63 |
| 6430 | 0.56 | 0.09 | 0.57 | 460 | 0.05 | 0.52 | 0.22 | 92 | 39 |
| 6430.1 | 0.24 | 0.22 | 0.18 | 469 | 0.04 | 0.14 | 0.45 | 58 | 187 |
| 6440 | 0.54 | 0.12 | 0.5 | 458 | 0.06 | 0.44 | 0.26 | 81 | 48 |
| 6440.1 | 0.81 | 0.07 | 1.04 | 458 | 0.07 | 0.97 | 0.25 | 119 | 30 |
| 6450 | 0.41 | 0.09 | 0.43 | 455 | 0.04 | 0.39 | 0.11 | 95 | 26 |
| 6450.5 | 0.56 | 0.11 | 0.45 | 464 | 0.05 | 0.4 | 0.5 | 71 | 89 |
| 6460 | 0.68 | 0.08 | 0.75 | 455 | 0.06 | 0.69 | 0.12 | 101 | 17 |
| 6460.1 | 0.29 | 0.18 | 0.17 | 467 | 0.03 | 0.14 | 0.27 | 48 | 93 |
| 6470 | 0.31 | 0.11 | 0.37 | 456 | 0.04 | 0.33 | 0.02 | 106 | 6 |
| 6470.1 | 0.31 | 0.1 | 0.29 | 466 | 0.03 | 0.26 | 0.43 | 83 | 138 |
| 6480 | 0.14 | 0.11 | 0.09 | 472 | 0.01 | 0.08 | 0.13 | 57 | 92 |
| 6480.1 | 0.1 | 0.25 | 0.04 | 448 | 0.01 | 0.03 | 0.12 | 30 | 120 |
| 6490 | 0.18 | 0.11 | 0.09 | 464 | 0.01 | 0.08 | 0.05 | 44 | 27 |
| 6490.1 | 0.12 | 0.33 | 0.03 | 0 | 0.01 | 0.02 | 0.24 | 16 | 200 |
| 6500 | 0.54 | 0.14 | 0.5 | 463 | 0.07 | 0.43 | 0.09 | 79 | 16 |
| 6500.1 | 0.3 | 0.14 | 0.28 | 464 | 0.04 | 0.24 | 0.17 | 80 | 56 |
| 6510 | 0.31 | 0.36 | 0.44 | 330 | 0.16 | 0.28 | 0.2 | 90 | 64 |
| 6520 | 0.3 | 0.11 | 0.36 | 468 | 0.04 | 0.32 | 0.22 | 106 | 73 |
| 6530 | 0.12 | 0.33 | 0.12 | 432 | 0.04 | 0.08 | 0.18 | 66 | 150 |
| 6540 | 0.15 | 0.2 | 0.1 | 366 | 0.02 | 0.08 | 0.32 | 53 | 213 |
| 6560 | 0.16 | 0.07 | 0.14 | 484 | 0.01 | 0.13 | 0.12 | 81 | 75 |
| 6570 | 0.15 | 0.07 | 0.15 | 468 | 0.01 | 0.14 | 0.11 | 93 | 73 |
| 6580 | 0.23 | 0.07 | 0.28 | 470 | 0.02 | 0.26 | 0.11 | 113 | 47 |
| 6590 | 0.15 | 0.1 | 0.1 | 467 | 0.01 | 0.09 | 0.12 | 59 | 80 |
| 6600 | 0.24 | 0.14 | 0.14 | 464 | 0.02 | 0.12 | 0.23 | 50 | 95 |
| 6610 | 0.24 | 0.15 | 0.2 | 460 | 0.03 | 0.17 | 0.1 | 70 | 41 |
| 6620 | 0.22 | 0.22 | 0.09 | 451 | 0.02 | 0.07 | 0.33 | 31 | 150 |
| 6630 | 0.21 | 0.25 | 0.16 | 469 | 0.04 | 0.12 | 0.11 | 57 | 52 |
| 6640 | 0.11 | 0.25 | 0.04 | 432 | 0.01 | 0.03 | 0.09 | 27 | 81 |
| 6650 | 0.16 | 0.25 | 0.08 | 443 | 0.02 | 0.06 | 0.1 | 37 | 62 |
| 6660 | 0.15 | 0.13 | 0.08 | 458 | 0.01 | 0.07 | 0.17 | 46 | 113 |
| 6670 | 0.14 | 0 | 0.07 | 458 | 0 | 0.07 | 0.13 | 50 | 92 |
| 6680 | 0.21 | 0.09 | 0.11 | 454 | 0.01 | 0.1 | 0.13 | 47 | 61 |
| 6690 | 0.13 | 0.25 | 0.08 | 386 | 0.02 | 0.06 | 0.11 | 46 | 84 |
| 6700 | 0.11 | 0.25 | 0.04 | 353 | 0.01 | 0.03 | 0.13 | 27 | 118 |
| 6710 | 0.94 | 0.07 | 1.52 | 446 | 0.1 | 1.42 | 0.14 | 151 | 14 |
| 6720 | 0.09 | 0.43 | 0.07 | 329 | 0.03 | 0.04 | 0.13 | 44 | 144 |
| 6730 | 0.07 | 0.58 | 0.12 | 332 | 0.07 | 0.05 | 0.08 | 71 | 114 |
| 6740 | 0.1 | 0.29 | 0.07 | 352 | 0.02 | 0.05 | 0.16 | 50 | 160 |
| 6750 | 0.11 | 0.11 | 0.09 | 469 | 0.01 | 0.08 | 0.15 | 72 | 136 |
| 6760 | 0.48 | 0.07 | 0.54 | 464 | 0.04 | 0.5 | 0.2 | 104 | 41 |
| 6770 | 0.13 | 0.29 | 0.07 | 416 | 0.02 | 0.05 | 0.14 | 38 | 107 |

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|---|---|---|---|---|---|---|---|---|---|
| 6780 | 0.1 | 0.25 | 0.04 | 375 | 0.01 | 0.03 | 0.11 | 30 | 110 |
| 6790 | 0.13 | 0 | 0.01 | 0 | 0 | 0.01 | 0.08 | 7 | 61 |
| 6800 | 0.16 | 0.22 | 0.09 | 454 | 0.02 | 0.07 | 0.09 | 43 | 56 |
| 6810 | 0.08 | 0.57 | 0.07 | 311 | 0.04 | 0.03 | 0.1 | 37 | 125 |
| 6820 | 0.12 | 0.55 | 0.38 | 406 | 0.21 | 0.17 | 0.18 | 141 | 150 |
| 6830 | 0.13 | 0.4 | 0.1 | 355 | 0.04 | 0.06 | 0.14 | 46 | 107 |
| 6840 | 0.09 | 0.4 | 0.05 | 306 | 0.02 | 0.03 | 0.16 | 33 | 177 |
| 6850 | 0.05 | 0.5 | 0.02 | 0 | 0.01 | 0.01 | 0.13 | 20 | 260 |
| 6860 | 0.08 | 0 | 0.01 | 0 | 0 | 0.01 | 0.13 | 12 | 162 |
| 6870 | 0.1 | 0.2 | 0.05 | 353 | 0.01 | 0.04 | 0.16 | 40 | 160 |
| 6880 | 0.09 | 0.25 | 0.04 | 342 | 0.01 | 0.03 | 0.15 | 33 | 166 |
| 6890 | 0.15 | 0.11 | 0.09 | 461 | 0.01 | 0.08 | 0.27 | 53 | 180 |
| 6900 | 0.07 | 0.5 | 0.04 | 421 | 0.02 | 0.02 | 0.15 | 28 | 214 |
| 6910 | 0.11 | 0.43 | 0.14 | 344 | 0.06 | 0.08 | 0.3 | 72 | 272 |
| 6920 | 0.23 | 0.38 | 0.34 | 477 | 0.13 | 0.21 | 0.2 | 91 | 86 |
| 6930 | 0.08 | 0.38 | 0.08 | 363 | 0.03 | 0.05 | 0.24 | 62 | 300 |
| 6940 | 0.1 | 0.38 | 0.08 | 344 | 0.03 | 0.05 | 0.28 | 50 | 280 |
| 6950 | 0.06 | 0.33 | 0.03 | 352 | 0.01 | 0.02 | 0.22 | 33 | 366 |
| 6960 | 0.03 | 0.6 | 0.05 | 0 | 0.03 | 0.02 | 0.11 | 66 | 366 |
| 6970 | 0.42 | 0.15 | 0.27 | 485 | 0.04 | 0.23 | 0.19 | 54 | 45 |
| 6980 | 0.1 | 0.25 | 0.04 | 313 | 0.01 | 0.03 | 0.22 | 30 | 220 |
| 6990 | 0.06 | 0 | 0.01 | 0 | 0 | 0.01 | 0.08 | 16 | 133 |
| 7000 | 0.07 | 0 | 0.01 | 0 | 0 | 0.01 | 0.2 | 14 | 285 |
| 7010 | 0.12 | 0.32 | 0.25 | 410 | 0.08 | 0.17 | 0.27 | 141 | 225 |
| 7020 | 0.14 | 0.5 | 0.06 | 347 | 0.03 | 0.03 | 0.15 | 21 | 107 |
| 7030 | 0.18 | 0.27 | 0.11 | 353 | 0.03 | 0.08 | 0.15 | 44 | 83 |
| 7040 | 0.14 | 0 | 0.01 | 0 | 0 | 0.01 | 0.13 | 7 | 92 |
| 7050 | 0.12 | 0.4 | 0.05 | 0 | 0.02 | 0.03 | 0.26 | 25 | 216 |
| 7060 | 0.17 | 0.25 | 0.04 | 356 | 0.01 | 0.03 | 0.2 | 17 | 117 |
| 7070 | 0.13 | 0.13 | 0.08 | 433 | 0.01 | 0.07 | 0.22 | 53 | 169 |
| 7080 | 0.13 | 0.25 | 0.08 | 307 | 0.02 | 0.06 | 0.23 | 46 | 176 |
| 7090 | 0.13 | 0.2 | 0.05 | 377 | 0.01 | 0.04 | 0.15 | 30 | 115 |
| 7100 | 0.13 | 0.25 | 0.04 | 303 | 0.01 | 0.03 | 0.17 | 23 | 130 |
| 7120 | 0.16 | 0.35 | 0.23 | 336 | 0.08 | 0.15 | 0.22 | 93 | 137 |
| 7140 | 0.15 | 0 | 0.01 | 324 | 0 | 0.01 | 0.13 | 6 | 86 |
| 7160 | 0.1 | 0.5 | 0.02 | 309 | 0.01 | 0.01 | 0.27 | 10 | 270 |
| 7180 | 0.13 | 0.33 | 0.06 | 335 | 0.02 | 0.04 | 0.23 | 30 | 176 |
| 7200 | 0.12 | 0 | 0.01 | 366 | 0 | 0.01 | 0.2 | 8 | 166 |
| 7220 | 0.12 | 0.38 | 0.08 | 421 | 0.03 | 0.05 | 0.16 | 41 | 133 |
| 7240 | 0.11 | 0.17 | 0.06 | 324 | 0.01 | 0.05 | 0.64 | 45 | 581 |
| 7260 | 0.09 | 1 | 0.01 | 0 | 0.01 | 0 | 0.32 | 0 | 355 |
| 7290 | 0.09 | 1 | 0.01 | 0 | 0.01 | 0 | 0.15 | 0 | 166 |
| 7300 | 0.24 | 0.33 | 0.12 | 425 | 0.04 | 0.08 | 0.31 | 33 | 129 |
| 7310 | 0.16 | 0.36 | 0.11 | 335 | 0.04 | 0.07 | 0.17 | 43 | 106 |
| 7320 | 0.19 | 0.2 | 0.1 | 355 | 0.02 | 0.08 | 0.28 | 42 | 147 |
| 7390 | 1.75 | 0.04 | 3.21 | 454 | 0.14 | 3.07 | 0.29 | 175 | 16 |
| 7400 | 0.18 | 0.2 | 0.05 | 366 | 0.01 | 0.04 | 0.2 | 22 | 111 |
| 7410 | 0.18 | 0.12 | 0.17 | 385 | 0.02 | 0.15 | 0.16 | 83 | 88 |
| 7420 | 0.2 | 0.5 | 0.06 | 307 | 0.03 | 0.03 | 0.21 | 15 | 105 |
| 7460 | 0.18 | 0.31 | 0.32 | 330 | 0.1 | 0.22 | 0.15 | 122 | 83 |
| 7480 | 0.17 | 0.38 | 0.08 | 425 | 0.03 | 0.05 | 0.18 | 29 | 105 |

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|---|---|---|---|---|---|---|---|---|---|
| 7500 | 0.13 | 0.21 | 0.14 | 482 | 0.03 | 0.11 | 0.16 | 61 | 88 |
| 7520 | 0.18 | 0.3 | 0.2 | 423 | 0.06 | 0.14 | 0.35 | 77 | 194 |
| 7540 | 0.12 | 1 | 0.01 | 0 | 0.01 | 0 | 0.17 | 0 | 141 |
| 7560 | 0.29 | 0.28 | 0.54 | 335 | 0.15 | 0.39 | 0.21 | 134 | 72 |
| 7570 | 0.15 | 1 | 0.02 | 0 | 0.02 | 0 | 0.16 | 0 | 106 |
| 7620 | 0.1 | 0.6 | 0.1 | 374 | 0.06 | 0.04 | 0.09 | 40 | 90 |
| 7640 | 0.17 | 0.22 | 0.09 | 329 | 0.02 | 0.07 | 0.43 | 41 | 252 |
| 7650 | 0.18 | 0.75 | 0.04 | 351 | 0.03 | 0.01 | 0.09 | 5 | 49 |
| 7660 | 0.37 | 0.13 | 0.32 | 459 | 0.04 | 0.28 | 0.3 | 75 | 81 |
| 7680 | 0.16 | 0.75 | 0.04 | 402 | 0.03 | 0.01 | 0.12 | 6 | 75 |
| 7800 | 0.52 | 0.3 | 2.64 | 333 | 0.79 | 1.85 | 0.45 | 355 | 86 |
| 7820 | 0.19 | 0.3 | 0.1 | 348 | 0.03 | 0.07 | 0.12 | 36 | 63 |
| 7830 | 0.2 | 0.67 | 0.06 | 0 | 0.04 | 0.02 | 0.1 | 10 | 50 |
| 7840 | 0.15 | 0.29 | 0.07 | 302 | 0.02 | 0.05 | 0.12 | 33 | 80 |
| 7850 | 0.26 | 0.33 | 0.03 | 437 | 0.01 | 0.02 | 0.13 | 7 | 50 |
| 7860 | 0.41 | 0.08 | 0.36 | 467 | 0.03 | 0.33 | 0.16 | 80 | 39 |
| 7870 | 0.14 | 0.38 | 0.08 | 410 | 0.03 | 0.05 | 0.13 | 35 | 92 |
| 7880 | 0.14 | 0.1 | 0.1 | 472 | 0.01 | 0.09 | 0.07 | 64 | 50 |
| 7890 | 0.14 | 0 | 0.02 | 421 | 0 | 0.02 | 0.23 | 14 | 164 |

Table V.4 Rock-Eval/TOC data for Cable Head E-95.

| DEPTH (m) | TOC | PI | S1+S2 | TMAX | S1 | S2 | S3 | OI | HI |
|---|---|---|---|---|---|---|---|---|---|
| 1520 | 0.05 | 0.11 | 0.09 | 430 | 0.01 | 0.08 | 0.13 | 260 | 160 |
| 1525 | 0.15 | 0.3 | 0.1 | 393 | 0.03 | 0.07 | 0.15 | 100 | 46 |
| 1530 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.04 | 66 | 16 |
| 1535 | 0.0 | 0 | 0.01 | | 0 | 0.01 | 0.07 | 140 | 20 |
| 1540 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 60 | 20 |
| 1545 | 0.25 | 0.5 | 0.1 | 348 | 0.05 | 0.05 | 0.1 | 40 | 20 |
| 1550 | 0.13 | 0 | 0.01 | | 0 | 0.01 | 0.08 | 61 | 7 |
| 1555 | 0.12 | 0 | 0.01 | 346 | 0 | 0.01 | 0.13 | 108 | 8 |
| 1560 | 0.07 | 0 | 0.01 | | 0 | 0.01 | 0.1 | 142 | 14 |
| 1565 | 0.12 | 0 | 0.01 | | 0 | 0.01 | 0.11 | 91 | 8 |
| 1570 | 0.17 | 0.67 | 0.03 | | 0.02 | 0.01 | 0.12 | 70 | 5 |
| 1575 | 0.16 | 1 | 0.02 | | 0.02 | 0 | 0.12 | 75 | 0 |
| 1580 | 0.12 | 0 | 0.02 | | 0 | 0.02 | 0.16 | 133 | 16 |
| 1585 | 0.14 | 0.33 | 0.03 | 336 | 0.01 | 0.02 | 0.18 | 128 | 14 |
| 1590 | 0.19 | 0.33 | 0.06 | 428 | 0.02 | 0.04 | 0.17 | 89 | 21 |
| 1595 | 0.22 | 0.19 | 0.21 | 388 | 0.04 | 0.17 | 0.23 | 104 | 77 |
| 1600 | 0.43 | 0.32 | 0.34 | 394 | 0.11 | 0.23 | 0.31 | 72 | 53 |
| 1605 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.11 | 183 | 16 |
| 1610 | 0.12 | 0.63 | 0.08 | | 0.05 | 0.03 | 0.13 | 108 | 25 |
| 1615 | 0.06 | 1 | 0.01 | | 0.01 | 0 | 0.11 | 183 | 0 |
| 1620 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.04 | 133 | 33 |
| 1625 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.11 | 220 | 20 |
| 1630 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.08 | 133 | 16 |
| 1635 | 0.07 | 0 | 0.01 | | 0 | 0.01 | 0.07 | 100 | 14 |
| 1640 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 150 | 25 |
| 1645 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.08 | 133 | 16 |
| 1650 | 0.05 | 0.4 | 0.05 | 355 | 0.02 | 0.03 | 0.09 | 180 | 60 |
| 1655 | 0.03 | 0.25 | 0.04 | 450 | 0.01 | 0.03 | 0.06 | 200 | 100 |

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|---|---|---|---|---|---|---|---|---|---|
| 1660 | 0.04 | 1 | 0.01 | | 0.01 | 0 | 0.09 | 225 | 0 |
| 1665 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 120 | 20 |
| 1670 | 0.09 | 1 | 0.03 | | 0.03 | 0 | 0.06 | 66 | 0 |
| 1675 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.09 | 150 | 16 |
| 1680 | 0.18 | 0.25 | 0.08 | 373 | 0.02 | 0.06 | 0.21 | 116 | 33 |
| 1685 | 0.34 | 0.16 | 0.31 | 367 | 0.05 | 0.26 | 0.34 | 100 | 76 |
| 1690 | 0.72 | 0.47 | 3.59 | 378 | 1.69 | 1.9 | 0.63 | 87 | 263 |
| 1695 | 0.81 | 0.49 | 4.98 | 376 | 2.42 | 2.56 | 0.44 | 54 | 316 |
| 1700 | 0.06 | 1 | 0.01 | | 0.01 | 0 | 0.14 | 233 | 0 |
| 1705 | 0.09 | 1 | 0.01 | | 0.01 | 0 | 0.1 | 111 | 0 |
| 1710 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 200 | 33 |
| 1715 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 150 | 25 |
| 1720 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.04 | 66 | 16 |
| 1725 | 1 | 0.08 | 1.33 | 440 | 0.11 | 1.22 | 0.07 | 6 | 122 |
| 1730 | 0.11 | 0.13 | 0.08 | 447 | 0.01 | 0.07 | 0.11 | 100 | 63 |
| 1735 | 0.1 | 0 | 0.05 | 441 | 0 | 0.05 | 0.09 | 90 | 50 |
| 1740 | 0.01 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 100 | 100 |
| 1745 | 0.1 | 0.24 | 0.17 | 395 | 0.04 | 0.13 | 0.05 | 50 | 130 |
| 1750 | 0.08 | 0 | 0.09 | 445 | 0 | 0.09 | 0.05 | 62 | 112 |
| 1755 | 0.04 | 0.4 | 0.05 | 448 | 0.02 | 0.03 | 0.05 | 125 | 75 |
| 1760 | 0.05 | 0 | 0.01 | 365 | 0 | 0.01 | 0.03 | 60 | 20 |
| 1765 | 0.07 | 0.2 | 0.05 | 313 | 0.01 | 0.04 | 0.04 | 57 | 57 |
| 1770 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 60 | 20 |
| 1775 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 25 | 25 |
| 1780 | 0.03 | 0.5 | 0.02 | | 0.01 | 0.01 | 0.02 | 66 | 33 |
| 1785 | 0.05 | 0.5 | 0.02 | 325 | 0.01 | 0.01 | 0.07 | 140 | 20 |
| 1790 | 0.04 | 0.25 | 0.04 | | 0.01 | 0.03 | 0.1 | 250 | 75 |
| 1795 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 150 | 50 |
| 1800 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 50 | 50 |
| 1305 | 0.07 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 85 | 14 |
| 1810 | 0.11 | 0.17 | 0.06 | 436 | 0.01 | 0.05 | 0.09 | 81 | 45 |
| 1815 | 0.12 | 0 | 0.06 | 444 | 0 | 0.06 | 0.04 | 33 | 50 |
| 1820 | 0.09 | 0.17 | 0.06 | 436 | 0.01 | 0.05 | 0.05 | 55 | 55 |
| 1825 | 0.07 | 0.2 | 0.05 | 448 | 0.01 | 0.04 | 0.05 | 71 | 57 |
| 1830 | 0.05 | 0.5 | 0.02 | 333 | 0.01 | 0.01 | 0.09 | 180 | 20 |
| 1835 | 0.07 | 0.25 | 0.04 | 438 | 0.01 | 0.03 | 0.06 | 85 | 42 |
| 1840 | 0.07 | 0.1 | 0.1 | 435 | 0.01 | 0.09 | 0.06 | 85 | 128 |
| 1845 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.07 | 174 | 25 |
| 1850 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.02 | 66 | 33 |
| 1855 | 0.08 | 0.09 | 0.11 | 424 | 0.01 | 0.1 | 0.07 | 87 | 125 |
| 1860 | 0.16 | 0 | 0.07 | 426 | 0 | 0.07 | 0.16 | 100 | 43 |
| 1865 | 0.1 | 0.2 | 0.05 | 376 | 0.01 | 0.04 | 0.08 | 80 | 40 |
| 1870 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.05 | 83 | 16 |
| 1875 | 0.1 | 0.25 | 0.08 | 416 | 0.02 | 0.06 | 0.08 | 80 | 60 |
| 1880 | 0.06 | 0 | 0.03 | 339 | 0 | 0.03 | 0.09 | 150 | 50 |
| 1885 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.05 | 125 | 25 |
| 1890 | 0.02 | 0.33 | 0.03 | 347 | 0.01 | 0.02 | 0.03 | 150 | 100 |
| 1895 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 150 | 50 |
| 1900 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.05 | 166 | 33 |
| 1905 | 0.04 | 0.5 | 0.02 | 301 | 0.01 | 0.01 | 0.03 | 75 | 25 |
| 1910 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.05 | 100 | 20 |

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|---|---|---|---|---|---|---|---|---|---|
| 1915 | 0.1 | 0 | 0.02 | 356 | 0 | 0.02 | 0.01 | 10 | 20 |
| 1920 | 0.01 | 0.5 | 0.02 | | 0.01 | 0.01 | 0.01 | 100 | 100 |
| 1925 | 0.09 | 0.11 | 0.09 | 376 | 0.01 | 0.08 | 0.05 | 55 | 88 |
| 1930 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 200 | 33 |
| 1935 | 0.03 | 0.4 | 0.05 | | 0.02 | 0.03 | 0.03 | 100 | 100 |
| 1940 | 0.02 | 0.5 | 0.02 | 314 | 0.01 | 0.01 | 0.02 | 100 | 50 |
| 1945 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.02 | 66 | 33 |
| 1950 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 33 | 33 |
| 1955 | 0.09 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 33 | 11 |
| 1960 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.05 | 125 | 25 |
| 1965 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.04 | 100 | 25 |
| 1970 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 75 | 25 |
| 1975 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 50 | 50 |
| 1980 | 0.05 | 0 | 0.03 | 344 | 0 | 0.03 | 0.06 | 120 | 60 |
| 1985 | 0.04 | 0.2 | 0.05 | | 0.01 | 0.04 | 0.05 | 125 | 100 |
| 1990 | 0.02 | 1 | 0.01 | | 0.01 | 0 | 0.02 | 100 | 0 |
| 1995 | 0.03 | 0 | 0.01 | 319 | 0 | 0.01 | 0.04 | 133 | 33 |
| 2000 | 0.03 | 0.33 | 0.06 | 357 | 0.02 | 0.04 | 0.01 | 33 | 133 |
| 2005 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.02 | 100 | 50 |
| 2010 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.03 | 75 | 25 |
| 2015 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 33 | 33 |
| 2020 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 33 | 33 |
| 2025 | 0.01 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 100 | 100 |
| 2030 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 25 | 25 |
| 2035 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.04 | 80 | 20 |
| 2040 | 0.01 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 100 | 100 |
| 2045 | 0.05 | 0 | 0.01 | | 0 | 0.01 | 0.06 | 120 | 20 |
| 2050 | 0.08 | 0.33 | 0.09 | 332 | 0.03 | 0.06 | 0.06 | 75 | 75 |
| 2060 | 0.11 | 0 | 0.03 | 376 | 0 | 0.03 | 0.07 | 63 | 27 |
| 2065 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.09 | 150 | 16 |
| 2070 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 25 | 25 |
| 2075 | 0.02 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 50 | 50 |
| 2080 | 0.06 | 0 | 0.01 | | 0 | 0.01 | 0.02 | 33 | 16 |
| 2085 | 0.08 | 0.4 | 0.05 | 420 | 0.02 | 0.03 | 0.08 | 100 | 37 |
| 2090 | 0.11 | 0.67 | 0.03 | 336 | 0.02 | 0.01 | 0.05 | 45 | 9 |
| 2095 | 0.09 | 1 | 0.01 | | 0.01 | 0 | 0.05 | 55 | 0 |
| 2100 | 0.38 | 0.18 | 1.6 | 380 | 0.29 | 1.31 | 0.46 | 121 | 344 |
| 2105 | 0.17 | 0.08 | 0.4 | 428 | 0.03 | 0.37 | 0.2 | 117 | 217 |
| 2110 | 0.23 | 0.11 | 0.18 | 470 | 0.02 | 0.16 | 0.12 | 52 | 69 |
| 2115 | 0.09 | 0 | 0.02 | 384 | 0 | 0.02 | 0.04 | 44 | 22 |
| 2120 | 0.34 | 0.07 | 0.27 | 475 | 0.02 | 0.25 | 0.07 | 20 | 73 |
| 2125 | 0.27 | 0.04 | 0.27 | 464 | 0.01 | 0.26 | 0.07 | 25 | 96 |
| 2130 | 0.41 | 0.03 | 0.32 | 461 | 0.01 | 0.31 | 0.06 | 14 | 75 |
| 2135 | 0.16 | 0.14 | 0.14 | 457 | 0.02 | 0.12 | 0.12 | 75 | 75 |
| 2140 | 0.2 | 0.07 | 0.15 | 459 | 0.01 | 0.14 | 0.1 | 50 | 70 |
| 2145 | 0.59 | 0 | 0.04 | 418 | 0 | 0.04 | 0.11 | 18 | 6 |
| 2150 | 0.7 | 0 | 0.15 | 481 | 0 | 0.15 | 0.1 | 14 | 21 |
| 2155 | 0.86 | 1 | 0.01 | | 0.01 | 0 | 0.16 | 18 | 0 |
| 2160 | 0.25 | 0.2 | 0.1 | 362 | 0.02 | 0.08 | 0.06 | 24 | 32 |
| 2165 | 0.22 | 0.07 | 0.15 | 467 | 0.01 | 0.14 | 0.03 | 13 | 63 |
| 2170 | 0.84 | 0.07 | 0.28 | 533 | 0.02 | 0.26 | 0.02 | 2 | 30 |

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|---|---|---|---|---|---|---|---|---|---|
| 2175 | 0.25 | 0.13 | 0.08 | 498 | 0.01 | 0.07 | 0.08 | 32 | 27 |
| 2180 | 0.15 | 0 | 0.03 | 427 | 0 | 0.03 | 0.04 | 26 | 20 |
| 2185 | 0.27 | 0.04 | 0.23 | 456 | 0.01 | 0.22 | 0.05 | 18 | 81 |
| 2190 | 0.37 | 0.03 | 0.35 | 472 | 0.01 | 0.34 | 0.06 | 16 | 91 |
| 2190 | 0.35 | 0.03 | 0.32 | 482 | 0.01 | 0.31 | 0.06 | 17 | 88 |
| 2195 | 0.26 | 0.09 | 0.22 | 478 | 0.02 | 0.2 | 0.1 | 38 | 76 |
| 2200 | 0.41 | 0.04 | 0.28 | 479 | 0.01 | 0.27 | 0.08 | 19 | 65 |
| 2205 | 0.14 | 0.09 | 0.11 | 456 | 0.01 | 0.1 | 0.1 | 71 | 71 |
| 2210 | 0.14 | 0 | 0.07 | 434 | 0 | 0.07 | 0.07 | 50 | 50 |
| 2215 | 0.03 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 33 | 33 |
| 2220 | 0.01 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 100 | 100 |
| 2225 | 0.29 | 0 | 0.18 | 479 | 0 | 0.18 | 0.07 | 24 | 62 |
| 2230 | 0.25 | 0.08 | 0.12 | 478 | 0.01 | 0.11 | 0.13 | 52 | 44 |
| 2230 | 0.19 | 0 | 0.05 | 422 | 0 | 0.05 | 0.13 | 68 | 26 |
| 2235 | 0.17 | 0 | 0.05 | 480 | 0 | 0.05 | 0.08 | 47 | 29 |
| 2235 | 0.27 | 0.07 | 0.27 | 491 | 0.02 | 0.25 | 0.1 | 37 | 92 |
| 2240 | 0.65 | 0 | 0.31 | 496 | 0 | 0.31 | 0.09 | 13 | 47 |
| 2245 | 0.16 | 0 | 0.03 | 423 | 0 | 0.03 | 0.06 | 37 | 18 |
| 2250 | 0.04 | 0 | 0.01 | | 0 | 0.01 | 0.01 | 25 | 25 |
| 2255 | 0.22 | 0.27 | 0.11 | 484 | 0.03 | 0.08 | 0.01 | 4 | 36 |
| 2260 | 2.96 | 0.07 | 4.97 | 463 | 0.33 | 4.64 | 0.23 | 7 | 156 |
| 2265 | 0.66 | 0.08 | 0.63 | 468 | 0.05 | 0.58 | 0.27 | 40 | 87 |
| 2270 | 6.75 | 0.04 | 18.48 | 457 | 0.72 | 17.76 | 0.35 | 5 | 263 |
| 2275 | 0.48 | 0.08 | 0.36 | 474 | 0.03 | 0.33 | 0.48 | 100 | 68 |
| 2280 | 0.56 | 0.06 | 0.52 | 473 | 0.03 | 0.49 | 0.4 | 71 | 87 |
| 2285 | 0.35 | 0.06 | 0.34 | 469 | 0.02 | 0.32 | 0.17 | 48 | 91 |
| 2290 | 0.48 | 0.05 | 0.43 | 468 | 0.02 | 0.41 | 0.14 | 29 | 85 |
| 2295 | 0.69 | 0.07 | 0.74 | 466 | 0.05 | 0.69 | 0.12 | 17 | 99 |
| 2300 | 0.47 | 0.07 | 0.43 | 470 | 0.03 | 0.4 | 0.09 | 19 | 85 |
| 2305 | 2.96 | 0.06 | 5.24 | 465 | 0.31 | 4.93 | 0.27 | 9 | 166 |
| 2310 | 1.95 | 0.07 | 2.07 | 468 | 0.15 | 1.92 | 0.3 | 15 | 98 |
| 2315 | 5.86 | 0.04 | 15.77 | 459 | 0.63 | 15.14 | 0.25 | 4 | 258 |
| 2320 | 0.21 | 0.2 | 0.1 | 494 | 0.02 | 0.08 | 0.4 | 190 | 38 |
| 2325 | 0.63 | 0.06 | 0.64 | 469 | 0.04 | 0.6 | 0.25 | 39 | 95 |
| 2330 | 2 | 0.07 | 2.73 | 469 | 0.19 | 2.54 | 0.21 | 10 | 127 |
| 2335 | 2.04 | 0.07 | 2.64 | 467 | 0.19 | 2.45 | 0.21 | 10 | 120 |
| 2340 | 4.43 | 0.05 | 8.27 | 463 | 0.42 | 7.85 | 0.42 | 9 | 177 |
| 2345 | 0.67 | 0.06 | 0.68 | 473 | 0.04 | 0.64 | 0.4 | 59 | 95 |
| 2350 | 0.8 | 0.06 | 0.78 | 469 | 0.05 | 0.73 | 0.27 | 33 | 91 |
| 2355 | 1.25 | 0.08 | 1.24 | 471 | 0.1 | 1.14 | 0.23 | 18 | 91 |
| 2360 | 4.45 | 0.06 | 7.45 | 466 | 0.45 | 7 | 0.32 | 7 | 157 |
| 2365 | 0.25 | 0.17 | 0.12 | 489 | 0.02 | 0.1 | 0.21 | 84 | 40 |
| 2370 | 2.73 | 0.06 | 3.39 | 470 | 0.21 | 3.18 | 0.26 | 9 | 116 |
| 2375 | 4.53 | 0.04 | 8.91 | 467 | 0.35 | 8.56 | 0.35 | 7 | 188 |
| 2380 | 2.83 | 0.05 | 4.22 | 469 | 0.21 | 4.01 | 0.41 | 14 | 141 |
| 2385 | 2.08 | 0.06 | 3.11 | 469 | 0.2 | 2.91 | 0.73 | 35 | 139 |
| 2390 | 1.7 | 0.06 | 1.88 | 471 | 0.11 | 1.77 | 0.35 | 20 | 104 |
| 2395 | 1.11 | 0.07 | 1.35 | 472 | 0.1 | 1.25 | 0.22 | 19 | 112 |
| 2400 | 3.68 | 0.05 | 6.64 | 468 | 0.3 | 6.34 | 0.3 | 8 | 172 |
| 2405 | 0.66 | 0.1 | 0.63 | 474 | 0.06 | 0.57 | 0.31 | 46 | 86 |
| 2410 | 1.33 | 0.08 | 1.36 | 472 | 0.11 | 1.25 | 0.27 | 20 | 93 |

| 2415 | 0.75 | 0.08 | 0.77 | 475 | 0.06 | 0.71 | 0.17 | 22 | 94 |
|---|---|---|---|---|---|---|---|---|---|
| 2420 | 0.61 | 0.05 | 0.61 | 474 | 0.03 | 0.58 | 0.13 | 21 | 95 |
| 2425 | 0.33 | 0.08 | 0.24 | 474 | 0.02 | 0.22 | 0.16 | 48 | 66 |
| 2430 | 0.81 | 0.08 | 0.79 | 476 | 0.06 | 0.73 | 0.17 | 20 | 90 |
| 2435 | 0.48 | 0.05 | 0.38 | 471 | 0.02 | 0.36 | 0.17 | 35 | 75 |
| 2440 | 0.18 | 0.23 | 0.22 | 411 | 0.05 | 0.17 | 0.23 | 127 | 94 |
| 2445 | 0.16 | 0.31 | 0.16 | 381 | 0.05 | 0.11 | 0.1 | 62 | 68 |
| 2450 | 0.15 | 0.5 | 0.04 |  | 0.02 | 0.02 | 0.11 | 73 | 13 |
| 2455 | 0.82 | 0.1 | 0.78 | 461 | 0.08 | 0.7 | 0.16 | 19 | 85 |
| 2460 | 0.17 | 0.33 | 0.06 | 467 | 0.02 | 0.04 | 0.19 | 111 | 23 |
| 2465 | 0.12 | 0 | 0.01 |  | 0 | 0.01 | 0.21 | 175 | 8 |
| 2470 | 0.75 | 0.13 | 0.69 | 471 | 0.09 | 0.6 | 0.15 | 20 | 80 |
| 2475 | 0.3 | 0.25 | 0.12 | 480 | 0.03 | 0.09 | 0.23 | 76 | 30 |
| 2480 | 0.17 | 0.25 | 0.08 | 455 | 0.02 | 0.06 | 0.23 | 135 | 35 |
| 2485 | 0.17 | 0.31 | 0.13 | 397 | 0.04 | 0.09 | 0.14 | 82 | 52 |
| 2490 | 0.99 | 0.09 | 0.87 | 470 | 0.08 | 0.79 | 0.19 | 19 | 79 |
| 2495 | 1.67 | 0.11 | 1.36 | 474 | 0.15 | 1.21 | 0.23 | 13 | 72 |
| 2500 | 3.42 | 0.07 | 3.52 | 479 | 0.24 | 3.28 | 0.39 | 11 | 95 |
| 2505 | . | 0.11 | 0.89 | 478 | 0.1 | 0.79 | 0.38 | 38 | 79 |
| 2510 | 1.52 | 0.13 | 1.14 | 487 | 0.15 | 0.99 | 0.28 | 18 | 65 |
| 2510 | 26.84 | 0.05 | 43.55 | 479 | 2.21 | 41.34 | 1.15 | 4 | 154 |
| 2510 | 24.65 | 0.06 | 36.66 | 481 | 2.1 | 34.56 | 1.4 | 5 | 140 |
| 2510 | 46.98 | 0.06 | 74.72 | 480 | 4.18 | 70.54 | 0.01 | 0 | 150 |
| 2515 | 5.94 | 0.04 | 11.47 | 476 | 0.51 | 10.96 | 0.68 | 11 | 184 |
| 2520 | 0.45 | 0.11 | 0.35 | 485 | 0.04 | 0.31 | 0.35 | 77 | 68 |
| 2525 | 0.62 | 0.1 | 0.58 | 489 | 0.06 | 0.52 | 0.27 | 43 | 83 |
| 2530 | 1.47 | 0.06 | 1.43 | 480 | 0.09 | 1.34 | 0.21 | 14 | 91 |
| 2535 | 2.15 | 0.07 | 2.01 | 478 | 0.15 | 1.86 | 0.22 | 10 | 86 |
| 2540 | 0.98 | 0.09 | 0.8 | 482 | 0.07 | 0.73 | 0.17 | 17 | 74 |
| 2545 | 1.35 | 0.09 | 1.28 | 469 | 0.12 | 1.16 | 0.16 | 11 | 85 |
| 2550 | 4.37 | 0.07 | 6.22 | 475 | 0.43 | 5.79 | 0.41 | 9 | 132 |
| 2555 | 0.75 | 0.1 | 0.6 | 479 | 0.06 | 0.54 | 0.29 | 38 | 72 |
| 2560 | 4.77 | 0.05 | 6.24 | 477 | 0.34 | 5.9 | 0.36 | 7 | 123 |
| 2565 | 1.26 | 0.09 | 1.11 | 483 | 0.1 | 1.01 | 0.33 | 26 | 80 |
| 2570 | 2.11 | 0.08 | 2.22 | 476 | 0.17 | 2.05 | 0.25 | 11 | 97 |
| 2575 | 2.2 | 0.09 | 2.47 | 475 | 0.21 | 2.26 | 0.11 | 5 | 102 |
| 2580 | 2.32 | 0.07 | 2.47 | 477 | 0.18 | 2.29 | 0.13 | 5 | 98 |
| 2585 | 2.11 | 0.07 | 2.28 | 476 | 0.17 | 2.11 | 0.09 | 4 | 100 |
| 2590 | 0.71 | 0.14 | 0.73 | 487 | 0.1 | 0.63 | 0.04 | 5 | 88 |
| 2595 | 1.41 | 0.1 | 1.37 | 485 | 0.14 | 1.23 | 0.11 | 7 | 87 |
| 2600 | 0.46 | 0.14 | 0.36 | 487 | 0.05 | 0.31 | 0.06 | 13 | 67 |
| 2605 | 0.34 | 0.15 | 0.27 | 488 | 0.04 | 0.23 | 0.03 | 8 | 67 |
| 2610 | 1.21 | 0.09 | 1.2 | 480 | 0.11 | 1.09 | 0.32 | 26 | 90 |
| 2615 | 1.06 | 0.09 | 0.94 | 486 | 0.08 | 0.86 | 0.25 | 23 | 81 |
| 2620 | 0.2 | 0.27 | 0.15 | 503 | 0.04 | 0.11 | 0.02 | 10 | 55 |
| 2625 | 0.13 | 0.36 | 0.11 | 368 | 0.04 | 0.07 | 0.12 | 92 | 53 |
| 2630 | 0.1 | 0.5 | 0.02 | 360 | 0.01 | 0.01 | 0.07 | 70 | 10 |
| 2635 | 0.63 | 0.2 | 0.44 | 479 | 0.09 | 0.35 | 0.11 | 17 | 55 |
| 2640 | 0.37 | 0.23 | 0.26 | 498 | 0.06 | 0.2 | 0.28 | 75 | 54 |
| 2645 | 0.37 | 0.41 | 0.17 | 502 | 0.07 | 0.1 | 0.1 | 27 | 27 |
| 2650 | 0.16 | 0.56 | 0.09 | 438 | 0.05 | 0.04 | 0.07 | 43 | 25 |

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|---|---|---|---|---|---|---|---|---|---|
| 2655 | 0.27 | 0.25 | 0.12 | 486 | 0.03 | 0.09 | 0.19 | 70 | 33 |
| 2660 | 0.27 | 0.21 | 0.14 | 504 | 0.03 | 0.11 | 0.03 | 11 | 40 |
| 2665 | 0.16 | 0.6 | 0.05 | 414 | 0.03 | 0.02 | 0.06 | 37 | 12 |
| 2670 | 0.14 | 0.4 | 0.05 | 402 | 0.02 | 0.03 | 0.05 | 35 | 21 |
| 2675 | 0.28 | 0.17 | 0.18 | 494 | 0.03 | 0.15 | 0.02 | 7 | 53 |
| 2680 | 0.17 | 0.5 | 0.02 | 405 | 0.01 | 0.01 | 0.11 | 64 | 5 |
| 2685 | 0.33 | 0.31 | 0.16 | 503 | 0.05 | 0.11 | 0.06 | 18 | 33 |
| 2690 | 0.48 | 0.2 | 0.3 | 488 | 0.06 | 0.24 | 0.32 | 66 | 50 |
| 2695 | 0.87 | 0.14 | 0.57 | 489 | 0.08 | 0.49 | 0.36 | 41 | 56 |
| 2700 | 0.45 | 0.26 | 0.23 | 489 | 0.06 | 0.17 | 0.36 | 80 | 37 |
| 2705 | 0.44 | 0.23 | 0.3 | 490 | 0.07 | 0.23 | 0.31 | 70 | 52 |
| 2710 | 0.41 | 0.2 | 0.3 | 491 | 0.06 | 0.24 | 0.29 | 70 | 58 |
| 2715 | 0.25 | 0.22 | 0.18 | 494 | 0.04 | 0.14 | 0.17 | 68 | 55 |
| 2720 | 0.21 | 0.08 | 0.12 | 486 | 0.01 | 0.11 | 0.21 | 100 | 52 |
| 2725 | 0.19 | 0.21 | 0.14 | 501 | 0.03 | 0.11 | 0.01 | 5 | 57 |
| 2730 | 0.51 | 0.1 | 0.41 | 495 | 0.04 | 0.37 | 0.01 | 1 | 72 |
| 2735 | 0.25 | 0.17 | 0.12 | 510 | 0.02 | 0.1 | 0.01 | 4 | 40 |
| 2740 | 0.13 | 0.25 | 0.04 | 469 | 0.01 | 0.03 | 0.01 | 7 | 23 |
| 2745 | 0.3 | 0.13 | 0.23 | 448 | 0.03 | 0.2 | 0.01 | 3 | 66 |

Table V.5 Rock-Eval/TOC data for East Point E-49.

| DEPTH (F) | TOC | Pi | S1+S2 | TMAX | S1 | S2 | S3 | HI | OI |
|---|---|---|---|---|---|---|---|---|---|
| 3120 | 0.04 | 0.74 | 0.19 | 345 | 0.14 | 0.05 | 0.39 | 125 | 975 |
| 3150 | 0.04 | 0.67 | 0.24 | 334 | 0.16 | 0.08 | 0.45 | 200 | 1125 |
| 3180 | 0.05 | 0.62 | 0.29 | 337 | 0.18 | 0.11 | 0.39 | 220 | 780 |
| 3210 | 0.06 | 0.63 | 0.35 | 336 | 0.22 | 0.13 | 0.49 | 216 | 816 |
| 3240 | 0.05 | 0.62 | 0.34 | 333 | 0.21 | 0.13 | 0.48 | 260 | 960 |
| 3300 | 0.16 | 0.78 | 1.21 | 324 | 0.94 | 0.27 | 0.46 | 168 | 287 |
| 3330 | 0.12 | 0.68 | 0.84 | 325 | 0.57 | 0.27 | 0.49 | 225 | 408 |
| 3360 | 0.07 | 0.77 | 0.47 | 324 | 0.36 | 0.11 | 0.41 | 157 | 585 |
| 3390 | 0.08 | 0.76 | 0.59 | 325 | 0.45 | 0.14 | 0.34 | 175 | 425 |
| 3420 | 0.04 | 0.75 | 0.28 | 327 | 0.21 | 0.07 | 0.28 | 175 | 700 |
| 3450 | 0.38 | 0.73 | 0.91 | 325 | 0.66 | 0.25 | 0.33 | 65 | 86 |
| 3480 | 0.13 | 0.7 | 0.37 | 329 | 0.26 | 0.11 | 0.33 | 84 | 253 |
| 3510 | 0.17 | 0.67 | 0.7 | 328 | 0.47 | 0.23 | 0.46 | 135 | 270 |
| 3540 | 0.25 | 0.66 | 0.99 | 326 | 0.65 | 0.34 | 0.76 | 136 | 304 |
| 3570 | 0.2 | 0.66 | 0.95 | 328 | 0.63 | 0.32 | 0.64 | 160 | 320 |
| 3600 | 0.24 | 0.65 | 0.99 | 333 | 0.64 | 0.35 | 0.59 | 145 | 245 |
| 3630 | 0.16 | 0.65 | 0.82 | 335 | 0.53 | 0.29 | 0.63 | 181 | 393 |
| 3660 | 0.11 | 0.7 | 0.5 | 326 | 0.35 | 0.15 | 0.44 | 136 | 400 |
| 3690 | 0.13 | 0.73 | 0.62 | 328 | 0.45 | 0.17 | 0.33 | 130 | 253 |
| 3720 | 0.16 | 0.72 | 0.58 | 335 | 0.42 | 0.16 | 0.29 | 100 | 181 |
| 3750 | 0.17 | 0.75 | 0.75 | 330 | 0.56 | 0.19 | 0.38 | 111 | 223 |
| 3780 | 0.16 | 0.72 | 0.69 | 324 | 0.5 | 0.19 | 0.57 | 118 | 356 |
| 3810 | 0.14 | 0.52 | 0.21 | 340 | 0.11 | 0.1 | 0.57 | 71 | 407 |
| 3840 | 0.12 | 0.6 | 0.2 | 338 | 0.12 | 0.08 | 0.5 | 66 | 416 |
| 3870 | 0.12 | 0.55 | 0.2 | 344 | 0.11 | 0.09 | 0.5 | 75 | 416 |
| 3900 | 0.11 | 0.58 | 0.12 | 308 | 0.07 | 0.05 | 0.52 | 45 | 472 |
| 3930 | 0.28 | 0.48 | 0.94 | 335 | 0.45 | 0.49 | 0.65 | 175 | 232 |
| 3960 | 0.18 | 0.62 | 0.77 | 330 | 0.48 | 0.29 | 0.46 | 161 | 255 |

| 3990 | 0.1 | 0.56 | 0.18 | 343 | 0.1 | 0.08 | 0.56 | 80 | 560 |
|---|---|---|---|---|---|---|---|---|---|
| 4020 | 0.11 | 0.56 | 0.18 | 343 | 0.1 | 0.08 | 0.61 | 72 | 554 |
| 4050 | 0.08 | 0.54 | 0.13 | 310 | 0.07 | 0.06 | 0.56 | 75 | 700 |
| 4090 | 0.11 | 0.54 | 0.13 | 0 | 0.07 | 0.06 | 0.55 | 54 | 500 |
| 4110 | 0.1 | 0.5 | 0.16 | 337 | 0.08 | 0.08 | 0.55 | 80 | 550 |
| 4140 | 0.14 | 0.52 | 0.25 | 347 | 0.13 | 0.12 | 0.46 | 85 | 328 |
| 4170 | 0.03 | 0.8 | 0.05 | 339 | 0.04 | 0.01 | 0.23 | 33 | 766 |
| 4200 | 0.1 | 0.5 | 0.14 | 338 | 0.07 | 0.07 | 0.6 | 70 | 600 |
| 4230 | 0.13 | 0.48 | 0.21 | 342 | 0.1 | 0.11 | 0.51 | 84 | 392 |
| 4260 | 0.09 | 0.56 | 0.18 | 338 | 0.1 | 0.08 | 0.42 | 88 | 466 |
| 4290 | 0.16 | 0.46 | 0.41 | 335 | 0.19 | 0.22 | 0.46 | 137 | 287 |
| 4320 | 0.15 | 0.55 | 0.22 | 347 | 0.12 | 0.1 | 0.47 | 66 | 313 |
| 4350 | 0.17 | 0.55 | 0.56 | 333 | 0.31 | 0.25 | 0.43 | 147 | 252 |
| 4380 | 0.12 | 0.52 | 0.25 | 338 | 0.13 | 0.12 | 0.51 | 100 | 425 |
| 4410 | 0.1 | 0.6 | 0.15 | 339 | 0.09 | 0.06 | 0.53 | 60 | 529 |
| 4440 | 0.67 | 0.67 | 4.88 | 326 | 3.27 | 1.61 | 0.77 | 240 | 114 |
| 4470 | 0.13 | 0.53 | 0.32 | 342 | 0.17 | 0.15 | 0.5 | 115 | 384 |
| 4500 | 0.25 | 0.59 | 1.16 | 336 | 0.69 | 0.47 | 0.6 | 188 | 240 |
| 4520 | 0.16 | 0.64 | 0.67 | 333 | 0.43 | 0.24 | 0.44 | 150 | 275 |
| 4540 | 0.08 | 0.67 | 0.24 | 308 | 0.16 | 0.08 | 0.41 | 100 | 512 |
| 4550 | 0.17 | 0.56 | 0.75 | 335 | 0.42 | 0.33 | 0.5 | 194 | 294 |
| 4570 | 0.11 | 0.61 | 0.33 | 335 | 0.2 | 0.13 | 0.48 | 118 | 436 |
| 4590 | 0.11 | 0.5 | 0.26 | 337 | 0.13 | 0.13 | 0.51 | 118 | 463 |
| 4610 | 0.14 | 0.57 | 0.61 | 335 | 0.35 | 0.26 | 0.37 | 185 | 264 |
| 4630 | 0.1 | 0.52 | 0.23 | 337 | 0.12 | 0.11 | 0.53 | 110 | 529 |
| 4640 | 0.09 | 0.59 | 0.29 | 339 | 0.17 | 0.12 | 0.51 | 133 | 566 |
| 4670 | 0.11 | 0.54 | 0.26 | 336 | 0.14 | 0.12 | 0.57 | 109 | 518 |
| 4690 | 0.12 | 0.56 | 0.25 | 334 | 0.14 | 0.11 | 0.58 | 91 | 483 |
| 4700 | 0.38 | 0.61 | 2.19 | 329 | 1.33 | 0.86 | 0.51 | 226 | 134 |
| 4710 | 0.19 | 0.55 | 0.65 | 333 | 0.36 | 0.29 | 0.5 | 152 | 263 |
| 4730 | 0.2 | 0.61 | 0.61 | 333 | 0.37 | 0.24 | 0.38 | 120 | 190 |
| 4770 | 0.13 | 0.58 | 0.43 | 338 | 0.25 | 0.18 | 0.32 | 138 | 246 |
| 4790 | 0.16 | 0.5 | 0.38 | 339 | 0.19 | 0.19 | 0.62 | 118 | 387 |
| 4810 | 0.11 | 0.63 | 0.41 | 337 | 0.26 | 0.15 | 0.47 | 136 | 427 |
| 4830 | 0.32 | 0.56 | 1.63 | 332 | 0.92 | 0.71 | 0.5 | 221 | 156 |
| 4850 | 0.12 | 0.48 | 0.31 | 337 | 0.15 | 0.16 | 0.5 | 133 | 416 |
| 4870 | 0.17 | 0.55 | 0.94 | 338 | 0.52 | 0.42 | 0.35 | 247 | 205 |
| 4890 | 0.23 | 0.57 | 0.93 | 334 | 0.53 | 0.4 | 0.53 | 173 | 230 |
| 4910 | 0.55 | 0.69 | 4.13 | 327 | 2.84 | 1.29 | 0.99 | 234 | 180 |
| 4930 | 0.39 | 0.48 | 1.85 | 343 | 0.89 | 0.96 | 0.9 | 246 | 230 |
| 4950 | 0.08 | 0.59 | 0.27 | 341 | 0.16 | 0.11 | 0.34 | 137 | 425 |
| 4960 | 0.14 | 0.57 | 0.46 | 341 | 0.26 | 0.2 | 0.53 | 142 | 378 |
| 4980 | 0.12 | 0.53 | 0.32 | 344 | 0.17 | 0.15 | 0.57 | 125 | 475 |
| 5000 | 0.16 | 0.5 | 0.34 | 345 | 0.17 | 0.17 | 0.61 | 106 | 381 |
| 5020 | 0.34 | 0.46 | 0.41 | 343 | 0.19 | 0.22 | 0.55 | 64 | 161 |
| 5030 | 0.12 | 0.5 | 0.14 | 329 | 0.07 | 0.07 | 0.45 | 58 | 375 |
| 5040 | 0.16 | 0.55 | 0.31 | 344 | 0.17 | 0.14 | 0.45 | 87 | 281 |
| 5070 | 0.15 | 0.52 | 0.21 | 343 | 0.11 | 0.1 | 0.48 | 66 | 320 |
| 5100 | 0.14 | 0.42 | 0.33 | 349 | 0.14 | 0.19 | 0.48 | 135 | 342 |
| 5120 | 0.16 | 0.45 | 0.49 | 345 | 0.22 | 0.27 | 0.62 | 168 | 387 |
| 5140 | 0.09 | 0.53 | 0.15 | 345 | 0.08 | 0.07 | 0.49 | 77 | 544 |

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|---|---|---|---|---|---|---|---|---|---|
| 5160 | 0.14 | 0.54 | 0.24 | 346 | 0.13 | 0.11 | 0.42 | 78 | 300 |
| 5170 | 0.38 | 0.38 | 0.39 | 405 | 0.15 | 0.24 | 0.45 | 63 | 118 |
| 5190 | 0.45 | 0.43 | 0.53 | 354 | 0.23 | 0.3 | 0.59 | 66 | 131 |
| 5230 | 0.15 | 0.54 | 0.24 | 354 | 0.13 | 0.11 | 0.29 | 73 | 193 |
| 5260 | 0.37 | 0.45 | 0.71 | 359 | 0.32 | 0.39 | 0.29 | 105 | 78 |
| 5290 | 0.18 | 0.6 | 0.52 | 343 | 0.31 | 0.21 | 0.23 | 116 | 127 |
| 5320 | 0.15 | 0.51 | 0.41 | 346 | 0.21 | 0.2 | 0.36 | 133 | 239 |
| 5350 | 0.12 | 0.61 | 0.23 | 344 | 0.14 | 0.09 | 0.35 | 75 | 291 |
| 5380 | 0.64 | 0.49 | 0.61 | 385 | 0.3 | 0.31 | 0.26 | 48 | 40 |
| 5410 | 0.09 | 0.5 | 0.1 | 318 | 0.05 | 0.05 | 0.45 | 55 | 499 |
| 5440 | 0.1 | 0.5 | 0.16 | 351 | 0.08 | 0.08 | 0.35 | 80 | 350 |
| 5490 | 0.18 | 0.45 | 0.22 | 342 | 0.1 | 0.12 | 0.33 | 66 | 183 |
| 5520 | 0.29 | 0.52 | 0.5 | 345 | 0.26 | 0.24 | 0.4 | 82 | 137 |
| 5550 | 0.18 | 0.51 | 0.74 | 348 | 0.38 | 0.36 | 0.45 | 199 | 249 |
| 5580 | 0.2 | 0.62 | 0.74 | 349 | 0.46 | 0.28 | 0.37 | 140 | 185 |
| 5610 | 0.63 | 0.75 | 4.92 | 335 | 3.68 | 1.24 | 0.85 | 196 | 134 |
| 5640 | 0.48 | 0.72 | 3.85 | 334 | 2.79 | 1.06 | 0.66 | 220 | 137 |
| 5670 | 0.39 | 0.69 | 2.51 | 334 | 1.74 | 0.77 | 0.49 | 197 | 125 |
| 5700 | 0.16 | 0.55 | 0.6 | 334 | 0.33 | 0.27 | 0.51 | 168 | 318 |
| 5730 | 0.09 | 0.5 | 0.24 | 341 | 0.12 | 0.12 | 0.45 | 133 | 499 |
| 5760 | 0.1 | 0.6 | 0.5 | 333 | 0.3 | 0.2 | 0.33 | 200 | 330 |
| 5790 | 0.21 | 0.57 | 0.74 | 334 | 0.42 | 0.32 | 0.37 | 152 | 176 |
| 5820 | 0.13 | 0.5 | 0.46 | 339 | 0.23 | 0.23 | 0.35 | 176 | 269 |
| 5850 | 0.09 | 0.48 | 0.23 | 341 | 0.11 | 0.12 | 0.42 | 133 | 466 |
| 5870 | 0.08 | 0.42 | 0.19 | 346 | 0.08 | 0.11 | 0.41 | 137 | 512 |
| 5900 | 0.13 | 0.56 | 0.59 | 345 | 0.33 | 0.26 | 0.32 | 200 | 246 |
| 5920 | 0.06 | 0.43 | 0.14 | 350 | 0.06 | 0.08 | 0.37 | 133 | 616 |
| 5960 | 0.07 | 0.48 | 0.27 | 346 | 0.13 | 0.14 | 0.26 | 200 | 371 |
| 5990 | 0.07 | 0.44 | 0.25 | 347 | 0.11 | 0.14 | 0.31 | 200 | 442 |
| 6020 | 0.08 | 0.52 | 0.33 | 342 | 0.17 | 0.16 | 0.26 | 200 | 325 |
| 6050 | 0.43 | 0.51 | 2.38 | 336 | 1.22 | 1.16 | 0.33 | 269 | 76 |
| 6070 | 0.1 | 0.4 | 0.42 | 340 | 0.17 | 0.25 | 0.25 | 250 | 250 |
| 6080 | 0.84 | 0.52 | 1.16 | 399 | 0.6 | 0.56 | 0.36 | 66 | 42 |
| 6090 | 0.08 | 0.45 | 0.11 | 350 | 0.05 | 0.06 | 0.32 | 75 | 400 |
| 6100 | 0.13 | 0.56 | 0.18 | 379 | 0.1 | 0.08 | 0.39 | 61 | 300 |
| 6110 | 0.09 | 0.59 | 0.22 | 345 | 0.13 | 0.09 | 0.29 | 99 | 322 |
| 6120 | 0.07 | 0.47 | 0.15 | 344 | 0.07 | 0.08 | 0.24 | 114 | 342 |
| 6130 | 0.03 | 0.5 | 0.06 | 0 | 0.03 | 0.03 | 0.23 | 100 | 766 |
| 6140 | 0.06 | 0.58 | 0.12 | 0 | 0.07 | 0.05 | 0.25 | 83 | 416 |
| 6150 | 0.07 | 0.54 | 0.13 | 0 | 0.07 | 0.06 | 0.31 | 85 | 442 |
| 6170 | 0.07 | 0.47 | 0.17 | 311 | 0.08 | 0.09 | 0.24 | 128 | 342 |
| 6180 | 0.09 | 0.43 | 0.14 | 0 | 0.06 | 0.08 | 0.25 | 88 | 277 |
| 6190 | 0.13 | 0.41 | 0.56 | 343 | 0.23 | 0.33 | 0.34 | 253 | 261 |
| 6200 | 0.07 | 0.5 | 0.24 | 346 | 0.12 | 0.12 | 0.34 | 171 | 485 |
| 6210 | 0.05 | 0.53 | 0.15 | 345 | 0.08 | 0.07 | 0.29 | 140 | 580 |
| 6220 | 0.03 | 0.56 | 0.09 | 0 | 0.05 | 0.04 | 0.27 | 133 | 900 |
| 6230 | 0.04 | 0.5 | 0.12 | 301 | 0.06 | 0.06 | 0.29 | 150 | 725 |
| 6240 | 0.15 | 0.65 | 0.23 | 326 | 0.15 | 0.08 | 0.23 | 53 | 153 |
| 6250 | 0.04 | 0.6 | 0.15 | 343 | 0.09 | 0.06 | 0.31 | 150 | 775 |
| 6270 | 0.05 | 0.55 | 0.11 | 384 | 0.06 | 0.05 | 0.27 | 100 | 540 |
| 6280 | 0.11 | 0.48 | 0.25 | 341 | 0.12 | 0.13 | 0.52 | 118 | 472 |

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|---|---|---|---|---|---|---|---|---|---|
| 6290 | 0.07 | 0.5 | 0.14 | 309 | 0.07 | 0.07 | 0.56 | 100 | 800 |
| 6300 | 0.07 | 0.48 | 0.21 | 346 | 0.1 | 0.11 | 0.47 | 157 | 671 |
| 6310 | 0.06 | 0.55 | 0.2 | 347 | 0.11 | 0.09 | 0.37 | 150 | 616 |
| 6320 | 0.07 | 0.56 | 0.25 | 350 | 0.14 | 0.11 | 0.35 | 157 | 500 |
| 6330 | 0.08 | 0.59 | 0.32 | 341 | 0.19 | 0.13 | 0.36 | 162 | 450 |
| 6340 | 0.06 | 0.56 | 0.18 | 338 | 0.1 | 0.08 | 0.29 | 133 | 483 |
| 6350 | 0.07 | 0.56 | 0.25 | 343 | 0.14 | 0.11 | 0.32 | 157 | 457 |
| 6360 | 0.18 | 0.55 | 1.02 | 342 | 0.56 | 0.46 | 0.36 | 255 | 199 |
| 6370 | 0.06 | 0.6 | 0.25 | 353 | 0.15 | 0.1 | 0.35 | 166 | 583 |
| 6380 | 0.1 | 0.58 | 0.26 | 347 | 0.15 | 0.11 | 0.33 | 110 | 330 |
| 6390 | 0.07 | 0.55 | 0.2 | 345 | 0.11 | 0.09 | 0.41 | 128 | 585 |
| 6400 | 0.18 | 0.51 | 0.73 | 351 | 0.37 | 0.36 | 0.63 | 199 | 350 |
| 6410 | 0.05 | 0.65 | 0.23 | 356 | 0.15 | 0.08 | 0.34 | 160 | 680 |
| 6420 | 2.15 | 0.76 | 20.48 | 414 | 15.54 | 4.94 | 1.19 | 229 | 55 |
| 6430 | 0.09 | 0.4 | 0.42 | 353 | 0.17 | 0.25 | 0.3 | 277 | 333 |
| 6440 | 0.08 | 0.5 | 0.2 | 348 | 0.1 | 0.1 | 0.46 | 125 | 575 |
| 6450 | 0.06 | 0.47 | 0.19 | 349 | 0.09 | 0.1 | 0.54 | 166 | 900 |
| 6460 | 0.06 | 0.45 | 0.2 | 353 | 0.09 | 0.11 | 0.35 | 183 | 583 |
| 6470 | 0.09 | 0.54 | 0.24 | 346 | 0.13 | 0.11 | 0.43 | 122 | 477 |
| 6480 | 0.12 | 0.55 | 0.42 | 340 | 0.23 | 0.19 | 0.39 | 158 | 325 |
| 6490 | 0.07 | 0.44 | 0.27 | 349 | 0.12 | 0.15 | 0.52 | 214 | 742 |
| 6500 | 0.09 | 0.53 | 0.43 | 347 | 0.23 | 0.2 | 0.41 | 222 | 455 |
| 6510 | 0.07 | 0.73 | 0.3 | 337 | 0.22 | 0.08 | 0.38 | 114 | 542 |
| 6520 | 0.08 | 0.59 | 0.27 | 347 | 0.16 | 0.11 | 0.29 | 137 | 362 |
| 6530 | 1.29 | 0.72 | 9.5 | 323 | 6.86 | 2.64 | 1.33 | 204 | 103 |
| 6540 | 0.15 | 0.5 | 0.54 | 346 | 0.27 | 0.27 | 0.47 | 180 | 313 |
| 6550 | 0.07 | 0.58 | 0.24 | 347 | 0.14 | 0.1 | 0.35 | 142 | 500 |
| 6560 | 0.09 | 0.52 | 0.31 | 347 | 0.16 | 0.15 | 0.3 | 166 | 333 |
| 6570 | 0.17 | 0.68 | 0.87 | 336 | 0.59 | 0.28 | 0.41 | 164 | 241 |
| 6580 | 0.08 | 0.48 | 0.21 | 349 | 0.1 | 0.11 | 0.31 | 137 | 387 |
| 6590 | 0.1 | 0.52 | 0.33 | 348 | 0.17 | 0.16 | 0.4 | 160 | 400 |
| 6600 | 0.1 | 0.64 | 0.45 | 345 | 0.29 | 0.16 | 0.35 | 160 | 350 |
| 6610 | 0.16 | 0.74 | 0.8 | 338 | 0.59 | 0.21 | 0.36 | 131 | 225 |
| 6620 | 0.37 | 0.73 | 2.31 | 329 | 1.69 | 0.62 | 0.37 | 167 | 100 |
| 6630 | 0.21 | 0.64 | 0.45 | 355 | 0.29 | 0.16 | 0.6 | 76 | 285 |
| 6640 | 0.26 | 0.78 | 1.3 | 336 | 1.01 | 0.29 | 0.34 | 111 | 130 |
| 6650 | 0.16 | 0.83 | 0.88 | 345 | 0.73 | 0.15 | 0.51 | 93 | 318 |
| 6660 | 0.3 | 0.52 | 0.56 | 401 | 0.29 | 0.27 | 0.48 | 90 | 160 |
| 6670 | 0.22 | 0.66 | 0.95 | 344 | 0.63 | 0.32 | 0.49 | 145 | 222 |
| 6680 | 0.15 | 0.53 | 0.64 | 345 | 0.34 | 0.3 | 0.37 | 200 | 246 |
| 6690 | 0.27 | 0.81 | 1.94 | 338 | 1.57 | 0.37 | 0.61 | 137 | 225 |
| 6700 | 1.52 | 0.85 | 15.2 | 341 | 12.85 | 2.35 | 0.66 | 154 | 43 |
| 6710 | 1.14 | 0.83 | 10.89 | 330 | 9.04 | 1.85 | 0.86 | 162 | 75 |
| 6720 | 1.51 | 0.83 | 15.09 | 336 | 12.5 | 2.59 | 0.68 | 171 | 45 |
| 6730 | 1.36 | 0.82 | 13.48 | 334 | 10.99 | 2.49 | 0.69 | 183 | 50 |
| 6750 | 1.56 | 0.83 | 15.6 | 342 | 13.01 | 2.59 | 0.58 | 166 | 37 |
| 6760 | 1.79 | 0.87 | 18.76 | 346 | 16.4 | 2.36 | 0.71 | 131 | 39 |
| 6770 | 1.4 | 0.85 | 13.97 | 348 | 11.94 | 2.03 | 0.88 | 145 | 62 |
| 6780 | 0.65 | 0.86 | 5.89 | 333 | 5.08 | 0.81 | 0.59 | 124 | 90 |
| 6790 | 1.58 | 0.8 | 14.98 | 396 | 11.98 | 3 | 0.99 | 189 | 62 |
| 6800 | 1.33 | 0.82 | 12.59 | 333 | 10.37 | 2.22 | 0.91 | 166 | 68 |

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|---|---|---|---|---|---|---|---|---|---|
| 6810 | 1.57 | 0.83 | 15.09 | 338 | 12.5 | 2.59 | 0.69 | 164 | 43 |
| 6820 | 0.89 | 0.71 | 7.18 | 338 | 5.11 | 2.07 | 0.8 | 232 | 89 |
| 6830 | 0.88 | 0.74 | 7.51 | 334 | 5.57 | 1.94 | 0.76 | 220 | 86 |
| 6840 | 1.22 | 0.8 | 11.79 | 341 | 9.47 | 2.32 | 0.55 | 190 | 45 |
| 6850 | 0.43 | 0.79 | 3.42 | 328 | 2.7 | 0.72 | 0.72 | 167 | 167 |
| 6860 | 0.7 | 0.8 | 6.23 | 329 | 4.96 | 1.27 | 0.79 | 181 | 112 |
| 6870 | 1.49 | 0.84 | 14.46 | 336 | 12.08 | 2.38 | 0.84 | 159 | 56 |
| 6880 | 1.25 | 0.81 | 11.85 | 338 | 9.64 | 2.21 | 0.87 | 176 | 69 |
| 6890 | 0.72 | 0.77 | 6.18 | 333 | 4.74 | 1.44 | 0.59 | 199 | 81 |
| 6900 | 0.35 | 0.66 | 2.4 | 328 | 1.58 | 0.82 | 0.38 | 234 | 108 |
| 6910 | 0.69 | 0.64 | 5.14 | 345 | 3.29 | 1.85 | 0.9 | 268 | 130 |
| 6920 | 0.43 | 0.73 | 3.23 | 329 | 2.35 | 0.88 | 0.44 | 204 | 102 |
| 6930 | 0.43 | 0.74 | 3.37 | 327 | 2.5 | 0.87 | 0.52 | 202 | 120 |
| 6940 | 0.33 | 0.73 | 2.34 | 330 | 1.7 | 0.64 | 0.39 | 193 | 118 |
| 6950 | 0.19 | 0.66 | 1.15 | 327 | 0.76 | 0.39 | 0.36 | 205 | 189 |
| 6960 | 0.41 | 0.69 | 2.97 | 330 | 2.05 | 0.92 | 0.4 | 224 | 97 |
| 6970 | 0.25 | 0.7 | 1.56 | 330 | 1.09 | 0.47 | 0.33 | 188 | 132 |
| 6980 | 0.4 | 0.74 | 3.09 | 323 | 2.3 | 0.79 | 0.32 | 197 | 80 |
| 6990 | 0.34 | 0.7 | 2.23 | 331 | 1.57 | 0.66 | 0.46 | 194 | 135 |
| 7000 | 0.25 | 0.7 | 1.32 | 332 | 0.92 | 0.4 | 0.44 | 160 | 176 |
| 7010 | 0.18 | 0.58 | 0.31 | 344 | 0.18 | 0.13 | 0.48 | 72 | 266 |
| 7020 | 0.71 | 0.76 | 5.96 | 331 | 4.51 | 1.45 | 0.67 | 204 | 94 |
| 7030 | 0.32 | 0.71 | 2.08 | 330 | 1.48 | 0.6 | 0.57 | 187 | 178 |
| 7040 | 1.29 | 0.64 | 3.24 | 331 | 2.08 | 1.16 | 1.15 | 89 | 89 |
| 7050 | 0.21 | 0.58 | 1.03 | 333 | 0.6 | 0.43 | 0.3 | 204 | 142 |
| 7060 | 0.71 | 0.67 | 5.28 | 329 | 3.53 | 1.75 | 0.74 | 246 | 104 |
| 7070 | 0.18 | 0.57 | 0.88 | 332 | 0.5 | 0.38 | 0.36 | 211 | 199 |
| 7080 | 0.28 | 0.64 | 1.77 | 320 | 1.14 | 0.63 | 0.43 | 225 | 153 |
| 7090 | 0.17 | 0.61 | 0.41 | 335 | 0.25 | 0.16 | 0.36 | 94 | 211 |
| 7100 | 0.15 | 0.58 | 0.59 | 327 | 0.34 | 0.25 | 0.34 | 166 | 226 |
| 7110 | 0.12 | 0.65 | 0.31 | 340 | 0.2 | 0.11 | 0.33 | 91 | 275 |
| 7120 | 0.16 | 0.63 | 0.68 | 331 | 0.43 | 0.25 | 0.39 | 156 | 243 |
| 7130 | 0.1 | 0.51 | 0.39 | 336 | 0.2 | 0.19 | 0.29 | 190 | 290 |
| 7150 | 0.12 | 0.7 | 0.57 | 336 | 0.4 | 0.17 | 0.29 | 141 | 241 |
| 7160 | 0.28 | 0.57 | 1.44 | 338 | 0.82 | 0.62 | 0.65 | 221 | 232 |
| 7170 | 0.17 | 0.54 | 0.84 | 331 | 0.45 | 0.39 | 0.26 | 229 | 152 |
| 7180 | 0.18 | 0.58 | 0.86 | 325 | 0.5 | 0.36 | 0.23 | 199 | 127 |
| 7190 | 0.15 | 0.57 | 0.61 | 331 | 0.35 | 0.26 | 0.23 | 173 | 153 |
| 7200 | 0.13 | 0.42 | 0.24 | 396 | 0.1 | 0.14 | 0.18 | 107 | 138 |
| 7210 | 0.18 | 0.49 | 0.43 | 333 | 0.21 | 0.22 | 0.19 | 122 | 105 |
| 7220 | 0.2 | 0.41 | 0.37 | 401 | 0.15 | 0.22 | 0.24 | 110 | 120 |
| 7230 | 0.16 | 0.52 | 0.48 | 334 | 0.25 | 0.23 | 0.25 | 143 | 156 |
| 7240 | 0.24 | 0.41 | 1.09 | 335 | 0.45 | 0.64 | 0.21 | 266 | 87 |
| 7250 | 0.15 | 0.43 | 0.54 | 341 | 0.23 | 0.31 | 0.27 | 206 | 180 |
| 7260 | 0.13 | 0.66 | 0.5 | 337 | 0.33 | 0.17 | 0.43 | 130 | 330 |
| 7270 | 0.15 | 0.71 | 0.73 | 327 | 0.52 | 0.21 | 0.35 | 140 | 233 |
| 7280 | 0.1 | 0.48 | 0.29 | 338 | 0.14 | 0.15 | 0.31 | 150 | 310 |
| 7290 | 0.09 | 0.55 | 0.31 | 336 | 0.17 | 0.14 | 0.28 | 155 | 311 |
| 7300 | 0.13 | 0.7 | 0.61 | 334 | 0.43 | 0.18 | 0.4 | 138 | 307 |
| 7310 | 0.07 | 0.47 | 0.15 | 349 | 0.07 | 0.08 | 0.29 | 114 | 414 |
| 7320 | 0.15 | 0.52 | 0.5 | 337 | 0.26 | 0.24 | 0.33 | 160 | 219 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 7330 | 0.21 | 0.46 | 0.35 | 333 | 0.16 | 0.19 | 0.73 | 90 | 347 |
| 7340 | 0.12 | 0.39 | 0.31 | 343 | 0.12 | 0.19 | 0.25 | 158 | 208 |
| 7350 | 0.23 | 0.51 | 0.37 | 341 | 0.19 | 0.18 | 0.46 | 78 | 200 |
| 7360 | 0.26 | 0.58 | 0.57 | 337 | 0.33 | 0.24 | 0.43 | 92 | 165 |
| 7370 | 0.26 | 0.47 | 0.36 | 379 | 0.17 | 0.19 | 0.38 | 73 | 146 |
| 7380 | 0.26 | 0.36 | 0.33 | 447 | 0.12 | 0.21 | 0.33 | 80 | 126 |
| 7390 | 0.14 | 0.53 | 0.4 | 327 | 0.21 | 0.19 | 0.3 | 135 | 214 |
| 7400 | 0.15 | 0.58 | 0.26 | 379 | 0.15 | 0.11 | 0.41 | 73 | 273 |
| 7420 | 0.93 | 0.65 | 7.08 | 329 | 4.62 | 2.46 | 1.09 | 264 | 117 |
| 7430 | 0.12 | 0.39 | 0.38 | 331 | 0.15 | 0.23 | 0.35 | 191 | 291 |
| 7440 | 0.21 | 0.38 | 0.4 | 335 | 0.15 | 0.25 | 0.26 | 119 | 123 |
| 7450 | 0.22 | 0.33 | 0.24 | 393 | 0.08 | 0.16 | 0.29 | 72 | 131 |
| 7460 | 0.24 | 0.46 | 0.39 | 339 | 0.18 | 0.21 | 0.39 | 87 | 162 |
| 7470 | 0.44 | 0.4 | 0.9 | 402 | 0.36 | 0.54 | 0.38 | 122 | 86 |
| 7480 | 0.61 | 0.5 | 1.27 | 399 | 0.63 | 0.64 | 0.52 | 104 | 85 |
| 7490 | 1.21 | 0.22 | 1.5 | 461 | 0.33 | 1.17 | 0.7 | 96 | 57 |
| 7500 | 0.38 | 0.35 | 0.57 | 415 | 0.2 | 0.37 | 0.72 | 97 | 189 |
| 7510 | 1.15 | 0.13 | 1.6 | 465 | 0.21 | 1.39 | 0.63 | 120 | 54 |
| 7520 | 0.36 | 0.42 | 0.57 | 402 | 0.24 | 0.33 | 0.57 | 91 | 158 |
| 7530 | 0.5 | 0.31 | 0.59 | 471 | 0.18 | 0.41 | 0.54 | 82 | 108 |
| 7540 | 0.26 | 0.45 | 0.31 | 420 | 0.14 | 0.17 | 0.56 | 65 | 215 |
| 7550 | 0.16 | 0.52 | 0.31 | 337 | 0.16 | 0.15 | 0.33 | 93 | 206 |
| 7560 | 0.24 | 0.32 | 0.31 | 462 | 0.1 | 0.21 | 0.45 | 87 | 187 |
| 7570 | 0.19 | 0.42 | 0.26 | 415 | 0.11 | 0.15 | 0.63 | 78 | 331 |
| 7580 | 0.2 | 0.5 | 0.3 | 399 | 0.15 | 0.15 | 0.66 | 75 | 330 |
| 7590 | 0.48 | 0.22 | 0.69 | 467 | 0.15 | 0.54 | 0.52 | 112 | 108 |
| 7600 | 0.39 | 0.62 | 1.57 | 327 | 0.98 | 0.59 | 0.49 | 151 | 125 |
| 7610 | 0.73 | 0.22 | 0.97 | 466 | 0.21 | 0.76 | 0.46 | 104 | 63 |
| 7620 | 1.88 | 0.1 | 3.67 | 457 | 0.36 | 3.31 | 0.6 | 176 | 31 |
| 7630 | 1.65 | 0.3 | 2.22 | 462 | 0.67 | 1.55 | 0.66 | 93 | 40 |
| 7640 | 0.65 | 0.35 | 1.04 | 468 | 0.36 | 0.68 | 0.62 | 104 | 95 |
| 7650 | 0.84 | 0.45 | 1.5 | 463 | 0.67 | 0.83 | 0.79 | 98 | 94 |
| 7660 | 0.44 | 0.46 | 0.83 | 463 | 0.38 | 0.45 | 0.56 | 102 | 127 |
| 7670 | 1.14 | 0.25 | 1.45 | 471 | 0.36 | 1.09 | 0.59 | 95 | 51 |
| 7680 | 0.73 | 0.48 | 1.26 | 416 | 0.61 | 0.65 | 0.75 | 89 | 102 |
| 7690 | 0.55 | 0.29 | 0.7 | 475 | 0.2 | 0.5 | 0.65 | 90 | 118 |
| 7700 | 2.21 | 0.6 | 8 | 452 | 4.79 | 3.21 | 1.1 | 145 | 49 |
| 7710 | 1.24 | 0.41 | 2.02 | 469 | 0.82 | 1.2 | 0.98 | 96 | 79 |
| 7720 | 1.76 | 0.72 | 14.68 | 369 | 10.52 | 4.16 | 1 | 236 | 56 |
| 7730 | 1.08 | 0.66 | 7.9 | 340 | 5.2 | 2.7 | 0.72 | 249 | 66 |
| 7740 | 0.69 | 0.66 | 4.84 | 336 | 3.21 | 1.63 | 1.38 | 236 | 200 |
| 7750 | 0.5 | 0.59 | 2.81 | 331 | 1.67 | 1.14 | 0.78 | 228 | 156 |
| 7760 | 2.73 | 0.21 | 5.02 | 464 | 1.07 | 3.95 | 0.77 | 144 | 28 |
| 7770 | 1.79 | 0.66 | 13.98 | 363 | 9.22 | 4.76 | 0.87 | 265 | 48 |
| 7780 | 1.37 | 0.66 | 11.22 | 362 | 7.37 | 3.85 | 0.66 | 281 | 48 |
| 7790 | 0.6 | 0.6 | 2.06 | 331 | 1.24 | 0.82 | 0.82 | 136 | 136 |
| 7800 | 1.09 | 0.35 | 2.21 | 426 | 0.77 | 1.44 | 0.73 | 132 | 66 |
| 7810 | 0.99 | 0.71 | 6.37 | 351 | 4.51 | 1.86 | 0.67 | 187 | 67 |
| 7820 | 0.51 | 0.64 | 1.59 | 328 | 1.01 | 0.58 | 0.61 | 113 | 119 |
| 7830 | 0.4 | 0.63 | 1.72 | 342 | 1.08 | 0.64 | 0.46 | 160 | 115 |
| 7850 | 1.15 | 0.26 | 1.75 | 469 | 0.46 | 1.29 | 0.66 | 112 | 57 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 7870 | 0.91 | 0.5 | 1.65 | 468 | 0.83 | 0.82 | 0.98 | 90 | 107 |
| 7880 | 0.65 | 0.56 | 1.21 | 470 | 0.68 | 0.53 | 0.78 | 81 | 120 |
| 7890 | 0.71 | 0.5 | 1.22 | 412 | 0.61 | 0.61 | 0.93 | 85 | 130 |
| 7920 | 0.46 | 0.51 | 0.78 | 467 | 0.4 | 0.38 | 0.52 | 82 | 113 |
| 7950 | 0.45 | 0.42 | 0.76 | 471 | 0.32 | 0.44 | 0.6 | 97 | 133 |
| 7980 | 0.41 | 0.59 | 1.04 | 399 | 0.61 | 0.43 | 0.51 | 104 | 124 |
| 8010 | 0.67 | 0.34 | 0.9 | 470 | 0.31 | 0.59 | 0.91 | 88 | 135 |
| 8040 | 1.07 | 0.23 | 1.38 | 441 | 0.32 | 1.06 | 0.82 | 99 | 76 |
| 8070 | 0.65 | 0.3 | 0.83 | 476 | 0.25 | 0.58 | 0.93 | 89 | 143 |
| 8100 | 0.29 | 0.43 | 0.42 | 421 | 0.18 | 0.24 | 0.74 | 82 | 255 |
| 8130 | 1.22 | 0.11 | 1.23 | 461 | 0.14 | 1.09 | 0.82 | 89 | 67 |
| 8170 | 1.31 | 0.19 | 1.53 | 468 | 0.29 | 1.24 | 1.07 | 94 | 81 |
| 8200 | 0.47 | 0.32 | 0.6 | 471 | 0.19 | 0.41 | 0.65 | 87 | 138 |

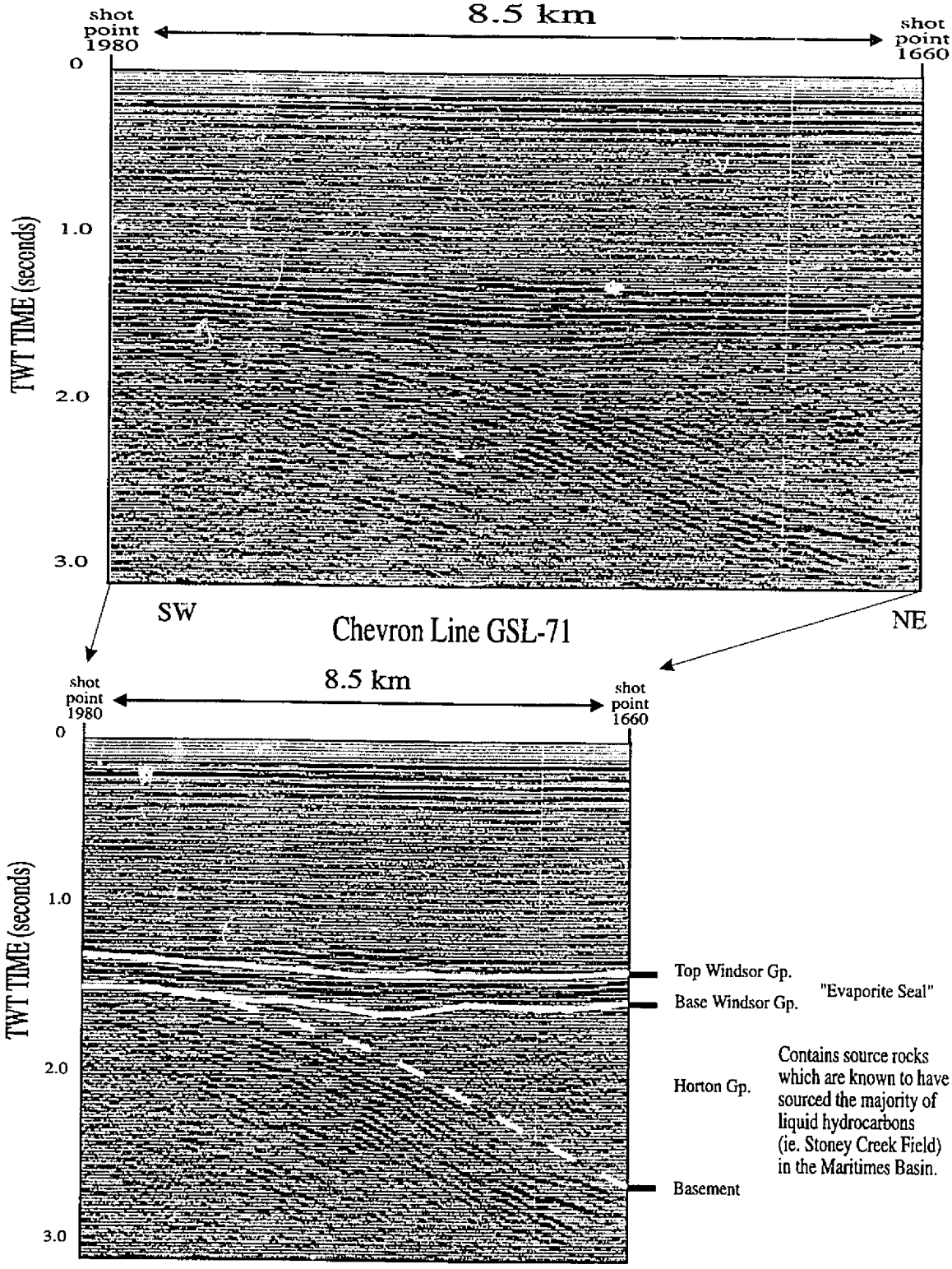



Figure VI.1 (Top) Uninterpreted record Chevron G.S.L. Line 71 (line E, Fig. 2.11). (Bottom) Interpreted showing the CMB Play Type 1 -- subsalt. Source and reservoir rocks are provided by the Horton Group and a seal is provided by the onlapping Windsor Group evaporites.

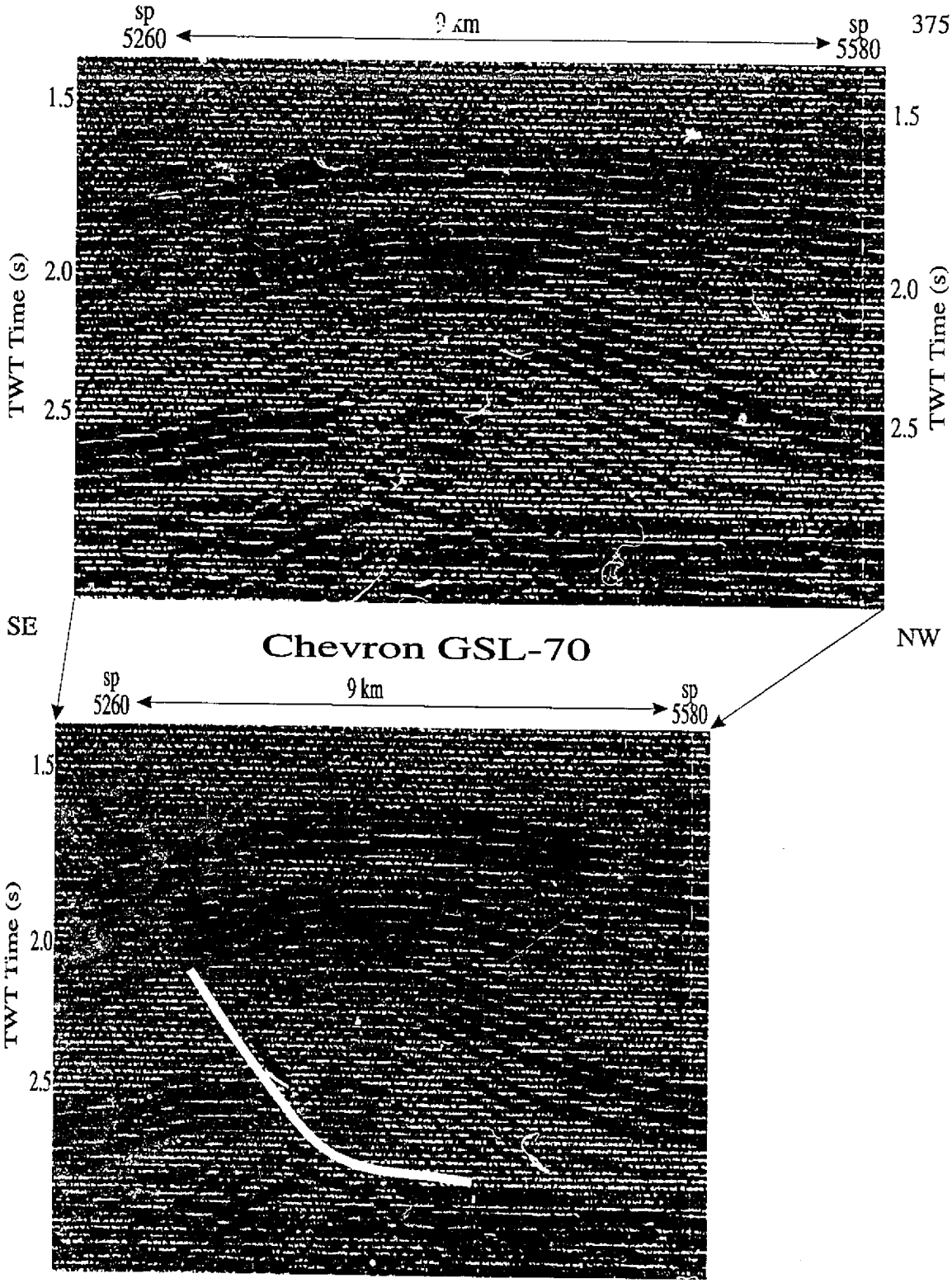



Figure VI.1 (Top) Uninterpreted record Chevron G.S.L. Line 71 (line E, Fig. 2.11). (Bottom) Interpreted showing the CMB Play Type 3 -- fault related. See Figure 5.10C for a schematic interpretation.

# APPENDIX VII: CMB THERMAL MODELLING RESULTS

Table VII.1 List of results from CMB modelling Scenario A (preferred model) and B: Increased Heat Flow and Additional Overburden.

| Well | A Overburden (m) | B Overburden (m) |
|---|---|---|
| Beaton Point F-70 | 600 | 250 |
| Birchgrove No.11800 | 1800 | 1400 |
| Bradelle L-49 | 1000 | 600 |
| Brion Island No.1 | 950 | 550 |
| Cable Head E-95 | 700 | 400 |
| East Point E-49 | 0 | 0 |
| NSDME M-1 | 1550 | 1100 |
| NSDME M-2A | 1200 | 700 |
| Middlesex No.1 | 2400 | 1800 |
| Naufrage No.1 | 1000 | 550 |
| North Sydney F-24 | 1000 | 550 |
| North Sydney P-05 | 1800 | 1100 |
| St. Paul P-91 | 1700 | 1100 |
| Tyrone No.1 | 600 | 200 |

Table VII.2 List of organic maturation timing results from CMB modelling Scenarios A, B, C2, and D1, comparing the timing of Horton Group, Bird Rock Formation and Green Gables Formation organic maturations for several CMB wells. All values are in Ma and indicate the time when the top of each succession reached the top of a particular maturation zone (the bold values indicate when the bottom of a succession reached the top of a particular maturation zone). E = Early Mature (0.7 $\%R_{0max}$); M = Mid Mature (1.0 $\%R_{0max}$); L = Late Mature (1.3 $\%R_{0max}$); G = Main Gas Generation Zone (2.5 $\%R_{0max}$); IM = Immature; OV = Overmature. Note if organic matter reaches the top of Main Gas Generation Zone it is likely overmature.

| Well | Scenario D1 | | | | Scenario C2 | | | | Scenario A | | | | Scenario B | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | E | M | L | G | E | M | L | G | E | M | L | G | E | M | L | G |
| Horton Group source rocks | | | | | | | | | | | | | | | | |
| Birch Grove No.1 | 285 | 282 | 279 | 271 | 313 | 310 | 309 | 308 | 306 | 284 | 281 | 277 | 307 | 285 | 281 | 278 |
| Bradelle L-49 | 300 | 287 | 281 | 279 | 315 | 311 | 309 | 307 | 312 | 310 | 302 | 294 | 312 | 311 | 306 | 299 |
| North Sydney F-24 | 286 | 282 | 277 | | 308 | 304 | 294 | 285 | 305 | 299 | 290 | 278 | 306 | 297 | 282 | 272 |
| North Sydney P-05 | 285 | 282 | 278 | | 308 | 305 | 299 | 291 | 305 | 291 | 282 | 278 | 305 | 294 | 282 | 273 |
| St. Paul P-91 | 304 | 285 | 282 | 281 | 319 | 313 | 311 | 309 | 313 | 311 | 298 | 285 | 315 | 311 | 303 | 291 |
| Bird Rock Fm. source rocks | | | | | | | | | | | | | | | | |
| Bradelle L-49 | 286 | 282 | 269 | | 300 | 294 | 287 | 248 | 298 | 289 | 280 | 280 | 298 | 291 | 281 | 283 |
| Brion Island No.1 | 284 | 279 | | | 305 | 292 | | | 302 | 284 | | | 303 | 288 | | |
| NSDME M-1 | 282 | 271 | | | 306 | 295 | | | 302 | 279 | | | 304 | 281 | | |
| NSDME M-2A | 283 | 273 | | | 305 | 294 | | | 304 | 279 | | | 305 | 283 | | |
| St. Paul P-91 | 285 | 282 | 279 | 270 | 290 | | | | 286 | 282 | 277 | 272 | 287 | 282 | | |
| Tyrone No.1 | 295 | 287 | 282 | 280 | 299 | 292 | 286 | 200 | 305 | 300 | 292 | 287 | 306 | 302 | 294 | 290 |
| Green Gables Fm. source rocks | | | | | | | | | | | | | | | | |
| Beaton Point F-70 | 279 | | | | 270 | | | | 278 | | | | 279 | | | |
| Birchgrove No.1 | 282 | 279 | | | IM | | | | 281 | 277 | | | 281 | | | |
| Bradelle L-49 | 284 | 280 | | | 293 | 287 | | | 290 | 283 | | | 292 | 284 | | |
| Brion Island No.1 | 281 | | | | 270 | | | | 282 | | | | 282 | | | |
| Cable Head E-95 | 290 | 284 | 280 | 277 | 305 | 301 | 294 | 291 | 304 | 296 | 288 | 283 | 304 | 298 | 291 | 287 |
| East Point E-49 | 287 | 281 | | | 304 | 285 | | | OV | | | | | | | |
| NSDME M-1 | 280 | | | | 281 | | | | 281 | | | | 281 | | | |
| NSDME M-2A | 281 | | | | 294 | | | | 286 | | | | 290 | | | |
| Middlesex No.1 | 281 | 265 | | | 288 | | | | 283 | 277 | | | 284 | 276 | | |
| Naufrage No.1 | 289 | 284 | 280 | 268 | 301 | 295 | 288 | 276 | 300 | 293 | 284 | 276 | 300 | 294 | 287 | 279 |
| North Sydney F-24 | 283 | 280 | | | 292 | 251 | | | 295 | 287 | | | 288 | 272 | | |
| North Sydney P-05 | 283 | 280 | | | 294 | 279 | | | 286 | 282 | | | 287 | 280 | | |
| Tyrone No.1 | 291 | 284 | 281 | 276 | 305 | 300 | 292 | 289 | 299 | 292 | 285 | 269 | 300 | 294 | 288 | 279 |

Table VII.3 List of results from CMB modelling Scenario C1 and C2: Minimal Overburden Model. Values represent the required paleogeothermal gradients and initial heat flow values needed to match predicted maturity values with measured maturity values. Values in bold indicate the best fits between modelled and measured maturity values.

| Well | C1 Paleogeothermal Gradient ($^0$C/km) | C2 Steady-State Heat Flow (mWm$^{-2}$) |
|---|---|---|
| Beaton Point F-70 | **45** | **80** |
| Birchgrove No.1 | >150 | >300 |
| Bradelle L-49 | **65** | 100 |
| Brion Island No.1 | 63 | **95** |
| Cable Head E-95 | 70 | 90 |
| East Point E-49 | **45** | **75** |
| NSDME M-1 | 85 | 120 |
| NSDME M-2A | 60 | 100 |
| Middlesex No.1 | 100 | 160 |
| Naufrage No.1 | 50 | **90** |
| North Sydney F-24 | 100 | 110 |
| North Sydney P-05 | 95 | **140** |
| St. Paul P-91 | **75** | 120 |
| Tyrone No.1 | 45 | 90 |

Table VII.4 Results from CMB modelling Scenario D: Additional Overburden Model with constant paleogeothermal gradients. Values represent the amount of overburden required to match predicted maturity values with measured maturity values. Values in bold indicate the best fits between modelled and measured maturity values. N/P = not possible

| Well | D1 25°C/km (m) | D2 35°C/km (m) | D3 45°C/km (m) | D4 55°C/km (m) |
|---|---|---|---|---|
| Beaton Point F-70 | 1700 | 850 | **100** | 0 |
| Birch Grove No.1 | 4100 | **2700** | 2000 | 1550 |
| Bradelle L-49 | **2900** | 1700 | 900 | 450 |
| Brion Island No.1 | 2500 | 1325 | **725** | 250 |
| Cable Head F-95 | 3400 | 1850 | **900** | 300 |
| East Point E-49 | 2700 | 1550 | **0** | N/P |
| NSDME M-1 | 2400 | **1400** | 925 | 575 |
| NSDME M-2A | 2200 | **1100** | 575 | 215 |
| Middlesex No.1 | 2800 | 1800 | 1300 | 900 |
| Naufrage No.1 | **3100** | 1400 | 500 | 0 |
| North Sydney F-24 | **3400** | 2050 | 1350 | 800 |
| North Sydney P-05 | **3500** | 2200 | 1450 | 1000 |
| St. Paul P-91 | 4400 | 2800 | 1800 | 1100 |
| Tyrone No.1 | **3050** | 1200 | 0 | N/P |

# BIBLIOGRAPHY


AGSO (Australian Geological Survey Organization), 1996. An Australian Phanerozoic timescale. *Edited by* G. Young and J. Laurie. Oxford University Press, 288p.

Alberty, M.W. 1992. Wireline methods. *In* Development geology reference manual. *Edited by D.M.* Thompson and A.M. Woods. American Association of Petroleum Geologists, Methods in Exploration Series, No.10, pp. 141-194.

Allen, T.L. 1995. A study of carbonate rocks from the late Visean to Namurian Mabou Group, Cape Breton Island, Nova Scotia. B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Allen, G.P. and Posamentier, H.W. 1993. Sequence stratigraphy and facies models of an incised valley fill: the Gironde estuary, France. Journal of Sedimentary Petrology, 63: 378-391.

Allen, P.A., and Allen, J.R. 1990. Basin analysis - principles and applications. Blackwell Scientific Publications, Oxford, 451p.

Amano, K. and Taira, A. 1992. Two phase uplift of higher Himalayas since 17Ma. Geology, 20: 391-394.

Archer, A.W., and Greb, S.F. 1995. An Amazon-scale drainage system in the Early Pennsylvanian of central North America. The Journal of Geology, 103: 611-628.

Archer, A.W., Calder, J.H., Gibling, M.R., Naylor, R.D., Reid, D.R., and Wightman, W.G. 1995. Invertebrate trace fossils and agglutinated foraminifera as indicators of marine influence within the clastic section at Joggins, Nova Scotia, Canada. Canadian Journal of Earth Science, 32: 2027-2039.

Arditto, P.A. 1991. A sequence stratigraphic analsys of the Late Permian succession in the Southern Coalfield, Sydney Basin, New South Wales. Australian Journal of Earth Sciences, 38: 125-137.

Arkle, T.Jr. 1974. Stratigraphy of the Pennsylvanian and Permian systems of the Central Appalachians. *In* Carboniferous of the Southeastern United States. *Edited by G.* Brigs. Geological Society of America, Special Paper 148, pp. 5-29.

Baldwin, B., and Butler, C.O. 1985. Compaction curves. American Association of Petroleum Geologists Bulletin, 69: 622-626.

Ball, F.D., Sullivan, R.M., and Peach, A.R. 1981. Carboniferous drilling project. New Brunswick Department of Natural Resouces, Mineral Resources Branch, Report of Investigation No. 18, 109p.

Barr, S.M., White, C.E., and Webster, T. 1996. Devonian and Carboniferous stratigraphy in the Guysborough - Loch Lomand area, Nova Scotia. Atlantic Geoscience Society, Annual General Meeting and Collquium, Program and Abtracts, pp. 8-9.

Barr, S.M., Brisebois, D., and MacDonald, A.S. 1985. Carboniferous volcanic rocks of the Magdalene Islands, Gulf of St. Lawrence. Canadian Journal of Earth Sciences, 22: 1679-1688.

Barr, S.M., and Raeside, R.P. 1986. Pre-Carboniferous tectono-stratigraphic subdivisions of Cape Breton Island, Nova Scotia. Maritime Sediments and Atlantic Geology, 22: 252-263.

Barss, M.S. 1983. Palynological analyses of samples from Texaco Shell et al. Blue H-28. Geological Survey of Canada, Internal Report, EPGS-PAL.7-83MSB, 1p.

Barss, M.S. 1968, Samples submitted for age correlation from a borehole near Sand Lake, Cape Breton Co., Nova Scotia. Geological Survey of Canada, Internal Report, CRS-Report 4-68, 1p.

Barss, M.S. 1967, Report to R.D. Howie on sample submitted for age determination from Blanchard #1 borehole, New Brunswick, drilled by Hudsons Bay Oil and Gas Co. Geological Survey of Canada, Internal Report, Coal Research Section Report 4-67 MSB, 1p.

Barss, M.S. 1960, Report on sample submitted by Dr. V. Prest, for age determination. Geological Survey of Canada, Internal Report, Coal Research Section Report #117, 1p.

Barss, M.S., Bujak, J.P., and Williams, G.L. 1979. Palynological zonation and correlation of sixty-seven wells, eastern Canada. Geological Survey of Canada, Paper 78-24, 103p.

Bateman, J.A. 1995. Mineralogic and geochemical traits of the Egret Member oil source rock (Kimmeridgian), Jeanne D'Arc Basin, offshore Newfoundland, Canada. M.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Baum, G.R., and Vail, P.R. 1988. Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic Basins. *In* Sea-level research: An integrated approach. *Edited by* C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner. Society of Economic Paleontologists and Mineralogists, Special Publication 42, pp. 309-327.

Beaubouef, R.T., McLaughlin, P.P., Bohacs, K.M., and Devlin, W.J. 1995. Sequence stratigraphy of coal-bearing strata, upper Cretaceous, Washakie Basin, SW Wyoming. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.7A.

Beaumont, C., Quinlan, G.M., and Hamilton, J. 1987. The Alleghanian orogeny and its relationship to the evolution of the eastern interior, North America. *In* Sedimentary basins and basin forming mechanisms. *Edited by* C. Beaumont and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 425-445.

Beerbower, J.R. 1969. Interpretation of cyclic permo-Carboniferous deposition in alluvial plain sediments in West Virginia. Geological Society of America Bulletin, 80: 1843-1848.

Beerbower, J.R. 1964. Cyclothems and cyclic depositional mechanisms in alluvial plain sedimentation. Kansas Geological Survey Bulletin, 169: 31-42.

Bell, W.A. 1958. Possibilites for occurrence of petroleum reservoirs in Nova Scotia. Nova Scotia Department of Mines Paper, 177p.

Bell, W.A. 1948. Early Carboniferous strata of St. Georges Bay area, Newfoundland. Geological Survey of Canada, Bulletin No. 10, 45p.

Bell, W.A. 1944. Carboniferous rock and fossil floras of northern Nova Scotia. Geological Survey of Canada, Memoir 238, 119p.

Bell, W.A. 1929. Horton Winsdor District, Nova Scotia. Geological Survey of Canada, Memoir 155, 268p.

Bell, W.A. 1927. Outline of Carboniferous stratigraphy and geologic history of the Maritime Provinces of Canada. Royal Society of Canada Transactions, Section IV, pp. 75-108.

Bell, W.A. 1926. Carboniferous formations of Northumberland Strait, Nova Scotia. Geological Survey of Canda, Summary Report, 1924, Part C, pp. 142-180.

Bell, J.S., and Howie, R.D. 1990. Paleozoic geology. *In* Geology of the continental margin of eastern Canada. *Edited by* M.J. Keen and G.L. Williams. Geological Survey of Canada, Geology of Canada, No. 2, pp.143-165.

Belt, E.S. 1984. Origin of Late Dinantian cyclothems, East Fife, Scotland. 9'me Congres International de Stratigraphie et du Geologie du Carbonifere, Washington and Champaign-Urbana, 1979, Compte Rendu, 3: 570-588.

Belt, E.S. 1969. Newfoundland carboniferous stratigraphy and its relation to the Maritimes and Ireland. *In* Symposium on the North Atlantic - geology and continental drift. *Edited by* M. Kay. American Association of Petroleum Geologists, Memoir 12, pp. 734-753.

Belt, E.S. 1968a. Carboniferous continental sedimentation, Atlantic provinces, Canada. *In* Late Paleozoic and Mesozoic continental sedimentation, northeastern North America. *Edited by* G.deV. Lkein. Geological Association of America, Special Paper 106, pp. 126-176.

Belt, E.S. 1968b. Post-Acadian rifts and related facies, Eastern Canada. *In* Studies of Appalachian geology, northern Maritimes. *Edited by* E.A. Zen, W.S. White, J.B. Hadley and J.B. Thompson. New York, Wiley, pp. 95-117.

Belt, E.S. 1964. Revision of Nova Scotia Middle Carboniferous units. American Journal of Science, 262: 653-673.

Belt, E.S. 1965. Stratigraphy and paleogeography of Mabou group and related Middle Carboniferous facies, Nova Scotia, Canada. Geological Society of America Bulletin, 76: 777-802.

Besly, B.M., Burley, S.D., and Turner, P. 1993. Carboniferous "Barren Red Bed" play of the Silver Pit area, Southern North. *In* Proceedings, 4th Conference on Petroleum Geology of Northwest Europe. Geological Society, London, pp. 727-740.

Bhattacharya, J.P., and Walker, R.G. 1992. Deltas. *In* Facies models: response to sea level change. *Edited by* R.G. Walker and N.P. James. Geological Association of Canada, pp. 157-177.

Blackwell, D.D., and Steele, J.L. 1989. Thermal conductivity of sedimentary rocks: measurement and significance. *In* Thermal history of sedimentary basins - methods and case histories. *Edited by* N.D. Naeser and T.H. McCulloh. Springer-Verlag, New York, 319p.

Blair, T.C., and Bilodeau, W.L. 1988. Development of tectonic cyclothems in rift, pull-apart and foreland basins: Sedimentary response to episodic tectonism. Geology, 16: 517-520.

Blum, M.D. and Valastro, S., Jr. 1994. Late Quaternary sedimentation, lower Colorado River, Gulf Coastal Plain of Texas. Geological Society of America Bulletin, 106: 1002-1016.

Boehner, R.C., Ryan, R.J., and Carter, D.C. 1988. The Maritimes Basin: epieugeosyncline, taphrogeosyncline, horst-graben, wrench, rift, successor, aulacogen, pull-apart, transpression? -basins,

subbasins? - Just a problem of semantics?. Abstract. *In* Mines and Minerals Branch Report of Activities 1987, Part B. Nova Scotia Department of Mines and Energy, Report 88-1, p.278.

Boehner, R.C., Calder, J.H., Carter, D.C., Donahoe, H.V.Jr., Ferguson, L., Pickerill, R.K., and Ryan, R.J. 1986. Carboniferous-Jurassic sedimentation and tectonics: Minas, Cumberland and Moncton Basins, Nova Scotia and New Brunswick. *In* Basins of Eastern Canada and Worldwide Analogues Symposium, Halifax, Nova Scotia, August 1986. Atlantic Geoscience Society, Special Publication Number 4, pp. 4-21.

Boehner, R.C. 1984. Stratigraphy and depositional history of marine evaporites in the Windsor Group, Shubenacadie and Musquodoboit structural basins, Nova Scotia, Canada. 9th International Congress on Carboniferous Stratigraphy, IX-ICC, 3: 163-178.

Boyd, R., Williamson, P., and Haq, B.U. 1993. Seismic stratigraphy and passive-margin evolution of the southern Exmouth Plateau. *In* Sequence stratigraphy and facies associations. *Edited by* H.W. Posamentier, C.P. Summerhayes, B.U. Haq, and G.P. Allen. International Association of Sedimentologists, Special Publication No. 18, Blackwell Scientific Publications, pp. 581-603.

Bradley, D.S. 1982. Subsidence in Late Paleozoic basins in the northern Appalachians. Tectonics, 1: 107-123.

Brindley, G.W. 1961. Chlorite minerals. *In* The X-ray identification and crystal structure of clay minerals. *Edited by* G. Brown. Mineralogic Society, London, pp. 242-296.

Brooks, J., Cornford, C., and Archer, R. 1987. The role of hydrocarbon source rocks in petroleum exploration. *In* Marine petroleum source rocks. *Edited by* J. Brooks and R. Archer. Geological Society, Special Publication No. 26, pp. 17-46.

Brown, L.F., and Fisher, W.L. 1977. Seismic-stratigraphic interpretation of depositional systems: Examples from Brazilian rift and pull-apart basins. *In* Seismic stratigraphy-applications to hydrocarbon exploration. *Edited by* C.E. Payton. American Association of Petroleum Geologists, Memoir 26, pp. 213-248.

Browne, G.H., and Plint, A.G. 1994. Alternating braidplain and lacustrine deposition in a strike-slip setting: The Pennsylvanian Boss Point Formation of the Cumberland Basin, Maritime Canada. Journal of Sedimentary Research, B64: 40-59.

Burns, B.A., Heller, P., Paola, C., and Mariano, M. 1996. Fluvial response to cyclic changes in relative sea level and sediment supply: The Montserrat Conglomerate of northeast Spain. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.A21.

Calder, J.H. 1984. Sedimentology studies within the Springhill coalfield, Cumberland County, Nova Scotia. Nova Scotia Department of Mines and Energy, Report 84-1, pp. 1-6.

Calder, J.H., and Gibling, M.R. 1994. The Euramerican coal province: Controls on Late Paleozoic peat accumulation. Palaeogeography, Palaeoclimatology, Palaeoecology, 106: 1-21.

Cant, D.J. 1992. Subsurface facies analysis. *In* Facies models: response to sea level change. *Edited by* R.G. Walker and N.P. James. Geological Association of Canada, pp. 27-45.

Cecil, C.B., Stanton, R.W., Neuzil, S.G., Dulong, F.T., Ruppert, L.F., and Pierce, B.S. 1985. Paleoclimate controls on Late Paleozoic sedimentation and peat formation in the central Appalachian basin. International Journal of Coal Geology, 5: 195-230.

Cecil, C.B. 1990. Paleoclimate controls on stratigraphic repetition of chemical and siliclastic rocks. Geology, 18: 533-536.

Cercone, K.R. 1984. Thermal history of the Michigan basin. American Association Of Petroleum Geologists Bulletin, 68: 130-136.

Cercone, K.R. and Pollack, H.N. 1991. Thermal maturity of the Michigan Basin. *In* Early sedimentary evolution of the Michigan Basin. *Edited by* P.A. Catacosinos and P.A.Jr. Daniels. Geological Society of America, Special Paper 256,

Chandler, F.W., Waldron, J.W.F., Palmer, S., Giles, P.S., Gall, Q., Howells, K., and Durling, P. 1995. Geological map of the Stellarton Gap (NTS 11E/07, 09, 10 and 15). *In* Mines and Minerals Branch Report of Activities 1995. Nova Scotia Department of Mines and Energy, Report 95-2, p. 41.

Chevron Canada Resources, 1983. Well history. Irving Chevron Texaco Cable Head E-95.

Chevron Canada Resources, 1982. Well history. Irving Chevron Middlesex No.1.

Chowdhury, A.H., Fowler, M.G., and Noble, J.P.A. 1991. Petroleum geochemistry and geology of the Albert Formation, Moncton Subbasin, New Brunswick, Canada. Bulletin of Canadian Petroleum Geology, 39: 315-331.

Christiansen, F.G. 1989. Petroleum geology of north Greenland. *Gronlands Geol. Unders. Bull.*, 78: 1-92.

Church, K.D., and Gawthorpe, R.L. 1994. High resolution sequence stratigraphy of the late Namurian in the Widmerpool Gulf (East Midlands, UK). Marine and Petroleum Geology, 11: 528-544.

Claoe-Long, F.C., Jones, P.J., Roberts, J., and Maxwell, S. 1992. The numerical age of the Devonian-Carboniferous boundary. Geological Magazine, 129: 281-291.

Cluff, R. M., and Byrnes, A.P. 1990. Lopatin analysis of maturation and petroleum generation in the Illinois Basin. *In* Interior cratonic basins. *Edited by* M.W. Leighton, D.R. Kolata, D.F. Oltz, and J.J. Eidel. American Association of Petroleum Geologists, Memoir 51, pp. 425-454.

COGLA (Canada Oil and Gas Lands Administration), 1990. Offshore schedule of wells (1966-1990). Energy, Mines, and Resources Canada.

Connolly, W.M., and Stanton, R.J.Jr. 1992. Interbasinal cyclostratigraphic correlation of Milankovitch band transgressive-regressive cycles: Correlation of Desmoinesian-Missourian strata between southeastern Arizona and the midcontinent of North America. Geology, 20: 999-1002.

Crawford, T.L. 1995. Carbonates and associated sedimentary rocks of the Upper Visean to Namurian Mabou Group, Cape Breton Island, Nova Scotia: evidence for lacustrine deposition. Atlantic Geology, 31:167-182.

Damberger, 1971. Coalification pattern of the Illinois basin. Economic Geology, 66: 488-494.

Davies, S.J., McLean, D., and Oliver, D. 1995. Development of a sequence stratigraphic framework for an Upper Carboniferous basin - new concepts using spectral gamma-ray response and palynology. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.21A.

Debrabant, P., Fagel, N., Chamley, H., Bout, V., and Caulet, J. 1993. Neogene to Quaternary clay mineral fluxes in the Central Indian basin. Palaeogeography, Palaeoclimatology, Palaeoecology, 103: 117-131.

Dehler, S.A. and Keen, C.E. 1993. Effects of rifting and subsidence on thermal evolution of sediments in Canada's east coast basins. Canadian Journal of Earth Sciences, 30: 1782-1798.

Deming, D. 1994. Overburden rock, temperature and heat flow. *In* The petroleum system - from source to trap. *Edited by* L.B. Magoon and W.G. Dow. American Association of Petroleum Geologists, Memior 60, pp. 165-186.

Dolby, G. 1994. Palynological analyses of Carboniferous outcrop and core samples from the Natmap Program, 1993 feild season. Dolby and Associates, Unpublished report #9305, 92p.

Dolby, G. 1991. The palynology of the Morien Group, Sydney Basin, Cape Breton Island, Nova Scotia. Nova Scotia Department of Mines and Energy, Unpublished report, 23p.

Dolby, G. 1989a. Palnological analysis of samples from Port Hood and Chimney Corner coalfields, Cape Breton Island, and other miscellaneous samples. Nova Scotia Department of Mines and Energy, Unpublished report, 11p.

Dolby, G. 1989b. Palnology of samples from the Debert and Port Hood coalfields, Nova Scotia. Nova Scotia Department of Mines and Energy, Unpublished report, 8p.

Donaldson, A.C. 1974. Pennsylvanian sediments of the Central Appalachians. *In* Carboniferous of the southeastern United States. *Edited by* G. Brigs. Geological Society of America, Special Paper 148, pp. 47-78.

Donaldson, A.C., Renton, J.J., and Presley, M.W. 1985. Pennsylvanian deposystems and paleoclimates of the Appalachians. International Journal of Coal Geology, 5: 167-193.

Donaldson, A.C., and Shumaker, R.C. 1981. Late Paleozoic molasse of Central Appalachians. *In* Sedimentation and tectonics in alluvial basins. *Edited by* A.D. Miall. Geological Association of Canada, Special Paper 23, pp. 99-124.

Donohoe, H.V.Jr., and Wallace, P.I. 1980. Geological map of the Cobequid Highlands, Cumberland, Colchester and Pictou Counties. Nova Scotia Department of Mines and Energy, Open File Report 455.

Drozdzewski, G. 1989. The Ruhr coal basin (Germany): structural evolution of an autochthonous foreland basin. International Journal of Coal Geology, 23: 231-250.

Duff, P. McL. D., and Walton, E.K. 1973. Carboniferous sediments at Joggins, Nova Scotia. Seventh International Carboniferous Congress on Stratigraphy, 2: 365-379.

Durling, P. In press. A seismic reflection study of the Fountain Lake Group in the Scottsburn Anticline area, northern Nova Scotia. Geological Survey of Canada, Current Research 1996-D.

Durling, P., Harvey, P., and Howells, K. 1995. Geophysical evidence for thrust faulting in the Carboniferous Antigonish-Mabou subbasin, Nova Scotia. Atlantic Geology, 31: 183-196.

Durling, P., and Marillier, F. 1993a. Structural elements of the Magdalen Basin, Gulf of St. Lawrence, from seismic reflection data. Geological Survey of Canada, Current Research, Part D, Paper 93-1D, pp. 147-154.

Durling, P., and Marillier, F. 1993b. Tectonic setting of Middle Devonian to Lower Carboniferous rock in the Maritimes Basin. Atlantic Geology, 29: 199-217.

Durling, P.W., and Marillier, J.Y. 1990. Structural trends and basement rock subdivisions in the western Gulf of St. Lawrence, northern Appalachians. Atlantic Geology, 26: 79-95.

Eisbacher, G.H. 1969. Displacement and stress field along part of the Cobequid Fault, Nova Scotia. Canadian Journal of Earth Sciences, 6: 1095-1104.

Embry, A.F. 1995. Sequence boundaries and sequence hierarchies: problems and proposals. *In* Sequence stratigraphy on the Northwest European Margin. *Edited by* R.J. Steel et al. Norwegian Petroleum Society, Special Publication No. 5, Elsevier, Amsterdam, pp. 1-11.

Embry, A.F. 1993. Transgressive - regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago. Canadian Journal of Earth Sciences 30: 301-320.

Ettensohn F.R., and Chesnut, D.R.Jr. 1989. Nature and probable origin of the Mississippian-Pennsylvanian unconformity in the eastern United States. Onzieme International Congress on Carboniferous Stratigraphy and Geology, Compte Rendu, 4: 145-159.

Falvey, D.A., and Middleton, M.F. 1981. Passive continental margins: Evidence for a pre-breakup deep crustal metamorphic subsidence mechanism. Ocenologic Acta, SP, pp. 103-114.

Ferm, J.C. 1975. Pennsylvanian cyclothems of the Appalachian Plateau, a retrospective view. U.S. Geological Survey, Professional Paper 853, pp. 57-64.

Ferril, B.A., and Thomas, W.A. 1988. Acadian dextral transpression and synorogenic sedimentary successions in the Appalachians. Geology, 16: 604-608.

Fleming, J.M. 1970. Petroleum exploration in Newfoundland and Labrador. Newfoundland Department of Mines, Agriculture, and Resources, Mineral Resources Report 3, 118p.

Forbes, P.L., Ungerer, P., and Mudford, B.S. 1992. A two-dimensional model of overpressure development and gas accumulation in Venture Field, Eastern Canada. American Association of Petroleum Geologists Bulletin, 76: 318-338.

Fowler, M.G., Hamblin, A.P., MacDonald, D.J., and McMahon, P.G. 1993. Geological occurrence and geochemistry of some oil shows in Nova Scotia. Bulletin of Canadian Petroleum Geology, 41: 422-436.

Fralick, P.W., and Schenk, P.E. 1981. Molasse deposition and basin evolution in a wrench tectonic setting: The late Paleozoic, Eastern Cumberland Basin, Maritimes Canada. *In* Sedimentation and alluvial basins. *Edited by A.D.* Miall. Geological Association of Canada, Special Paper 23, pp. 77-97.

Gallagher, K., and Sambridge, M. 1992. The resolution of past heat flow in sedimentary basins from non-linear inversion of geochemical data: The smoothest model approach with synthetic examples. International Journal of Geophysics, 109: 78-95.

Galloway, W.E. 1989. Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists Bulletin 73: 125-142.

Galloway, W.E., and Brown, L.F.Jr. 1973. Depositional systems and shelf-slope relations on cratonic basin margin, Uppermost Pennsylvanian of north-central Texas. American Association of Petroleum Geologists Bulletin, 57: 1185-1218.

Geldsetzer, H.H.J. 1978. The Windsor Group in Atlantic Canada - an update. Geological Survey of Canada, Paper 78-1C, pp. 43-48.

Gerlach, J.B., and Cercone, K.R. 1993. Former Carboniferous overburden in the northern Appalachian Basin: A reconstruction based on vitrinite reflectance. Organic Geochemistry, 20: 223-232, ref # 8.

Gersib, G.S., and McCabe, P.J. 1981. Continental coal-bearing sediments of the Port Hood Formation (Carboniferous), Cape Linzee, Nova Scotia, Canada. *In* Recent and ancient nonmarine depositional environments: Models for exploration. *Edited by* F.G. Ethridge and R.M. Flores. Society of Economic Paleontologists and Mineralogists, Special Publication 31, pp. 95-108.

Gibling, M.R. 1995. Upper Paleozoic rocks, Nova Scotia. *In* Chapter 5 of Geology of the Appalachian-Caledonian orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, no. 6, pp. 455-492.

Gibling, M.R., and Bird, D.J. 1994. Late Carboniferous cyclothems and alluvial paleovalleys in the Sydney Basin, Nova Scotia. Geological Society of America Bulletin 106: 105-117.

Gibling, M.R., and Wightman, W.G. 1994. Palaeovalleys and protozoan assemblages in a Late Carboniferous cyclothem, Sydney Basin, Nova Scotia. Sedimentology, 41: 699-719.

Gibling, M.R., Marchioni, D.L., and Kalkreuth, W.D. 1994. Detrital and organic facies of Upper Carboniferous strata at Mabou Mines, western Cape Breton Island, Nova Scotia. *In* Current Research 1994-D, Geological Survey of Canada, pp. 51-56.

Gibling, M.R., Calder, J.H., and Naylor, R.D. 1992a. Carboniferous coal basins of Nova Scotia. Geological Association of Canada - Mineralogical Association of Canada Joint Annual Meeting 1992, Field Excursion C-1: Guidebook, 84p.

Gibling, M.R., Calder, J.H., Ryan, R., van De Poll, H.W., and Yeo, G.M. 1992b. Late Carboniferous and Early Permian drainage patterns in Atlantic Canada. Canadian Journal of Earth Sciences, 29: 338-352.

Gibling, M.R., and Kalkreuth, W.D. 1991. Petrology of selected carbonaceous limestones and shales in Late Carboniferous coal basins of Atlantic Canada. International Journal of Coal Geology, 17: 239-271.

Gibling, M.R., Zentilli, M., and McCready, R.G.L. 1989. Sulphur in Pennsylvanian coals of Atlantic Canada: Geologic and isotopic evidence for a bedrock evaporite source. International Journal of Coal Geology, 11: 81-104.

Gibling, M.R., Boehner, R.C., and Rust, B.R. 1987. The Sydney Basin of Atlantic Canada: An upper Paleozoic strike-slip basin in a collisional setting. *In* Sedimentary basins and basin forming mechanisms. *Edited by* C. Beaumont, and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 269-285.

Giles, P.S. 1996. Namurian and early Westphalian stratigraphy of western and southwestern Cape Breton Island. Atlantic Geoscience Society, Annual General Meeting and Collquium, Program and Abtracts, pp. 13-14.

Giles, P.S. 1981. Major transgressive-regressive cycles in Middle to Late Visean rocks of Nova Scotia. Nova Scotia Department of Mines and Energy, Paper 81-2, 27p.

Giles, P.S., Hein, F.J., and Allen, T.L. 1996. Bedrock geology of Port Hood - Lake Ainslie (11K04, 11K03, 11F13), Cape Breton Island, Nova Scotia. Geological Survey of Canada, Open File, 1:50000 map with marginal notes..

Giles, P.S., and Durling, P.W. 1993. The Visean Windsor Group of the Magdalen Basin, Eastern Canda, as imaged by seismic reflection data. Geologic Association of Canada/Mineralogical Association of Canada, Joint Annual Meeting, Program and Abstracts, p.A-35.

Glennie, K.W. 1984. Early Permian - Rotliegend. *In* Introduction to the petroleum geology of the North Sea. *Edited by* K.W. Glennie. Blackwell Scientific Publications, pp. 41-60.

Gonzalez-Bonorino, G. and Eyles, N. 1995. Inverse relation between ice extent and the late Paleozoic glacial record of Gondwana. Geology, 23: 1015-1018.

Grant, A.C. 1994. Aspects of seismic character and extent of Upper Carboniferous coal measures, Gulf of St. Lawrence and Sydney Basins. Palaeogeography, Palaeoclimatology, Palaeoecology, 106: 217-285.

Grant, A.C., and Moir, P.N. 1992. Observations on coalbed methane potential, Prince Edward Island. Geological Survey of Canada, Paper 92-1E, pp. 269-278.

Greb, S.F., and Chesnut D.R.Jr. 1996. Lower and Lower Middle Pennsylvanian fluvial to estuarine depositon, central Appalachian basin: Effects of eustacy, tectonics and climate. Geological Society of America Bulletin, 108: 303-317.

Gretener, P.E. 1981. Geothermics: Using temperature in hydrocarbon exploration. American Association of Petroleum Geologists, Education Course Note Series #17, 170p.

Grist, A.M., Ryan, R.J., and Zentilli, M. 1995. The thermal evolution and timing of hydrocarbon generation in the Maritimes Basin of eastern Canada: Evidence from apatite fission track data. Bulletin of Canadian Petroleum Geology, 43: 145-155.

Gulf Oil Canada, 1975. Well history, Gulf et al. Hastings No.1.

Gussow, W.C. 1953. Carboniferous stratigraphy and structural geology of New Brunswick, Canada. American Association of Petroleum Geologists Bulletin, 37: 1713-1816.

Hacquebard, P.A. 1986. The Gulf of St. Lawrence Carboniferous Basin; the largest coalfield of eastern Canada. Canadian Institute of Mining Bulletin, 79: 67-78.

Hacquebard, P.A. 1984. Coal rank changes in the Sydney and Pictou coalfields of Nova Scotia; cause and economic significance. Bulletin of Canadian Institute of Mining and Metallurgy, 77: 33-40.

Hacquebard, P.A. 1972. The Carboniferous of eastern Canada. 7th International Congress on Carboniferous Stratigraphy and Geology, Compte Rendu, 1: 63-90.

Hacquebard, P.A., and Cameron, A.R. 1989. Distribution and coalification patterns in Canadian bituminous and anthracite coals. International Journal of Coal Geology, 13: 207-260.

Hacquebard, P.A., Gillis, K.S., and Bromley, D.S. 1989. Re-evaluation of the coal resources of western Cape Breton Island. Nova Scotia Department of Mines and Energy, Paper 89-3, 47p.

Hacquebard, P.A., and Donaldson, J.R. 1970. Coal metamorphism and hydrocarbon potential in the Upper Paleozoic of the Atlantic Provinces, Canada. Canadian Journal of Earth Sciences, 7: 1139-1163.

Haites, T.B. 1952. Some geological aspects of the Inverness County coalfields in comparison with those of the Sydney Coalfield. 2nd Conference on the Orogin and Constitution of Coal, Crystal Cliffs, 1952. Nova Scotia Department of Mines and Energy Research Foundation, Halifax, pp. 112-135.

Hamblin, A.P., Fowler, M.G., Utting, Hawkins J., and Riediger, C.L. 1995. Sedimentology, palynology and source rock potential of Lower Carboniferous (Tournaisian) rocks, Couche area, Great Northern Peninsula, Newfoundland. Bulletin of Canadian Petroleum Geology, 43: 1-19.

Hamblin, A.P., and Rust, B.R. 1989. Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia. Basin Research, 2: 239-255.

Hamilton, D.S. 1995. Utility of coal seams as genetic stratigraphic sequence boundaries in nonmarine basins: An example from the Gunnedah Basin: Reply. American Association of Petroleum Geolgists Bulletin, 79: p.1182.

Hamilton, D.S., and Tadros, N.Z. 1994. Utility of coal seams as genetic stratigraphic sequence boundaries in nonmarine basins: An example from the Gunnedah Basin, Australia. American Association of Petroleum Geologists Bulletin, 78: 267-286.

Hampson, G. 1994. Controls on incised valley fills in a post-rift basin complex: Examples from the Upper Carboniferous, United Kingdom. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.162.

Harland, B.W., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G. 1989. A geologic time scale 1989. Cambridge University Press, Cambridge, 263p.

Haszeldine, R.S., and Anderton, R. 1980. A braidplain facies model for the Westphalian B coal measures of north-east England. Nature, 284: 51-53.

Hatcher, R.D., Jr., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., and Wiltschko, D.V. 1989. Alleghanian orogen. *In* The Geology of North America, Vol. F-2, The Appalachian-Ouachita Orogen in the United States. *Edited by* R.D. Hatcher, Jr., W.A. Thomas, and G.W. Viele. Geological Society of America, Boulder, Colorado, pp. 233-318.

Hayes, A.O., and Johnson, H. 1938. Geology of the Bay St. George Carboniferous area. Geological Survey of Newfoundland, Bulletin No. 12, 62p.

Helland-Hansen, W., and Gjelberg, J.G. 1994. Conceptual basis and variability in sequence stratigraphy: A different perspective. Sedimentary Geology, 92: 31-52.

Hendricks, M., Jamieson, R.A., Willet, S.D., and Zentilli, M. 1993. Burial and exhumation of the Long Range Inlier and its surroundings, western Newfoundland: Results of an apatite fission-track study. Canadian Journal of Earth Sciences, 30: 1594-1606.

Hess, J.C., and Lippolt, H.J. 1986. $^{40}Ar/^{39}Ar$ Ages of tonstein and tuff sanidines: New calibration points for the improvement of the Upper Carboniferous time scale. Chemical Geology, 59: 143-154.

Heward, A.P. 1978. Alluvial fan sequence and megasequence models: With examples from Westphalian D - Stephanian B coalfields, Northern Spain. *In* Fluvial Sedimentology. *Edited by* A.D. Miall. Canadian Society of Petroleum Geologists, Memoir 15, pp. 669-702.

Horne, J.C., Ferm, J.C., Caruccio, F.T., and Baganz, B.P. 1978. Depositional models in coal exploration and mine planning in Appalachian Region. American Association of Petroleum Geologists Bulletin, 62: 2379-2411.

Hower, J.C., Levine, R.R., Skehan, J.W., S.J., Daniels, E.J., Lewis, S.E., Davis, A., Gray, R., and Altaner, S.P. 1993. Appalachian anthracites. Organic-Geochemistry, 20: 619-642.

Howie, R.D. 1988. Upper Paleozoic evaporites of Southeastern Canada. Geological Survey of Canada Bulletin 380, 120p.

Howie, R.D. 1977. Geological studies and evaluation of MacDougall Core Hole 1A, Western Prince Edward Island. Geological Survey of Canada, Paper 77-20, 26p.

Howie, R.D. 1966. Stoney Creek gas and oil field, New Brunswick. American Association of Petroleum Geologists Memoir 9, 2: 1819-1832.

Howie, R.D., and Barss, M.S. 1975. Upper Paleozoic rocks of the Atlantic provinces, Gulf of St. Lawrence, and adjacent continental shelf. Geological Survey of Canada, Paper 74-30, 2: 35-50.

Huang, Z. and Williamson, M.A. 1996. Artificial neural network modelling as an aid to source rock characterization. Marine and Petroleum Gelogy, 13: 277-290.

Hudsons Bay Oil and Gas Co. Ltd. 1980a. Well history, Hudsons Bay et al. Beaton Point F-70.

Hudsons Bay Oil and Gas Co. Ltd. 1980b. Well history, Hudsons Bay et al East Point E-47.

Hudsons Bay Oil and Gas Co. Limited, 1973. Well history, Hudson Bay Fina et al. Green Gables No. 1.

Hudsons Bay Oil and Gas Co. Limited, 1970. Well history, Hudson Bay Fina East Point E-49.

Hudsons Bay Oil and Gas Co. Limited, 1974. Well history #2, Hudson Bay Fina East Point E-49.

Huertas, M.O., Ruiz, F.M., Palomo, I., and Chamley, H. 1995. Comparative mineralogic and geochemical clay sedimentation in the Betic Cordilleras and Basque-Cantabrian Basin areas at the Cretaceous-Tertiary boundary. Sedimentary Geology, 94: 209-227.

Hyde, R.S., Kalkreuth, W.D., and Utting, J. 1991. Coal petrology, palynology, and depositional environments of Upper Carboniferous Barachois Group (Westphalian A and C) coals of southwestern Newfoundland. Canadian Journal of Earth Sciences, 28: 1905-1924.

Hyde, R.S., Miller, H.G., Hiscott, R.N., and Wright, J.A. 1988. Basin architecture and thermal maturation in the strike-slip Deer Lake Basin, Carboniferous of Newfoundland. Basin Research, 1: 85-105.

Hymdman, R.D., Jessop, A.M., Judge, A.S., and Rankin, D.S. 1979. Heat flow in the Maritime provinces of Canada. Canadian Journal of Earth Sciences, 16: 1154-1165.

INRS-Petrole 1975a. Mineralogical, palynological and reflectometry study of SOQUIP et al. Naufrage No.1 well. Unpublished report, SOQUIP, SO2053 AD 06695 ad 218, 16p.

INRS-Petrole, 1975b. Organic matter and clay mineralogy study of the wells Bradelle L-49 and Brion Island No. 1. Unpublished report, SOQUIP, St. Laurent's Golf, 15p.

INRS-Petrole, 1975c. Organic matter and clay mineralogy study of the wells East Point, Green Gables No.1, Irishtown No.1, Northumberland Strait F-25. Unpublished report, SOQUIP, St. Laurent's Golf, 22p.

INRS-Petrole, 1973. Rapport preliminaire analyse palynologique Sondage Brion 1. Unpublished report, INRS-Petrole, 29.11.73-1-AA/hm, 7p.

International Stratigraphic Guide, 1979. *In* A guide to stratigraphic classification, terminology, and procedure [second edition]. *Edited by* A. Salvador. Geological Society of America Inc., Boulder, Colorado, 214p.

Irion, G., Muller, J., Nunes de Mello, J., and Junk, W.J. 1995. Quaternary geology of the Amazonian Lowland. Geo-Marine Letters, 15: 172-178.

Island Development Company, 1944, Well history, The Island Development Company, Hillsborough No.1.

Jenkins, W.A.M. 1984. Ordovician rocks in the Eastcan et al. Freydis B-87 and other wells offshore Atlantic Canada. Canadian Journal of Earth Sciences, 21: 864-868.

Jervey, M.T. 1992. Siliciclastic sequence development in foreland basin, with examples from the Western Canada foreland basin. *In* Foreland basins and foldbelts. *Edited by* R.W. Macqueen and D.A. Leckie. American Association of Petroleum Geologists, Memoir 55, pp. 47-80.

Jervey, M.T. 1988. Quantitative geological modelling of siliciclastic rock sequences and their seismic expression. *In* Sea-level research: An integrated approach. *Edited by* C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner. SEMP Special Publication 42, pp. 3-17.

Johnson, J.G., Klapper, G., and Sandberg, C.A. 1985. Devonian eustatic fluctuations in Euramerica. Geological Society of America Bulletin, 96: 567-587.

Johnson, D.D. 1995a. Modelling tectonic, climate, and eustatic effects on orogen/foreland basin systems. Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia.

Johnson, S.C. 1995b. A preliminary report on the stratigraphy of the Late Namurian to Stephanian fluviatile strata in southern New Brunswick. *In* Current Research 1995-E, Geological Survey of Canada, pp. 313-320.

Jordan, T.E., Flemmings, B.P., and Beer, J.A. 1988. Dating thrust-fault activity by use of foreland-basin strata. *In* New perspectives in basin analysis. *Edited by* K.L. Kleinspehn and C. Paola. New York, Springer-Verlag, pp. 307-330.

Joy, A.M. 1993. Comments on the pattern of post-rift subsidence in the Central and Northern North Sea Basins. *In* Tectonics and seismic sequence stratigraphy. *Edited by* G.D. Williams and A. Dobb. Geological Society, Special Publication No. 71, pp. 123-140.

Kalkreuth, W., and Macauley, G. 1987. Organic petrology and geochemical (Rock-eval) studies on oil shales and coals from the Pictou and Antigonish areas, Nova Scotia, Canada. Bulletin of Canadian Petroleum Geology, 35: 263-295.

Keen, C.E. 1983. Salt diapirs and thermal maturity: Scotian Basin. Bulletin of Canadian Petroleum Geology, 31: 101-108.

Keen, C.E., and Beamont, C. 1990. Geodynamics of rifted continental margins. *In* Geology of the continental margin of Eastern Canada. *Edited by* M.J. Keen and G.L. Williams. Geological Survey of Canada, Geology of Canada, no. 2, pp. 391-472.

Kelly, D.G. 1967. Some aspects of Carboniferous stratigraphy and depositional history in the Atlantic provinces. Geological Association of Canada, Special Paper 4, pp. 213-229.

Keppie, D.J. 1989. Northern Appalachian terranes and their accretionary history. Geological Society of America, Special Paper 230, pp. 159-192.

Keppie, J.D. 1982. The Minas Geofracture. *In* Major structural zones and faults of the northern Appalachians. *Edited by* P. Saint Jullien and J. Beland. Geological Association of Canada, Special Paper 24, pp. 263 - 280.

Keppie, J.D. 1977. Plate tectonic interpretation of Palaeozoic world maps (with emphasis on Circum-Atlantic orogens and southern Nova Scotia). Nova Scotia Department of Mines and Energy, Paper 77-3, pp. 1-45.

Kingston, D.R., Dishroon, C.P., and Williams, P.A. 1983. Global basin classification system. American Association of Petroleum Geologists Bulletin, 67: 2175-2193.

Klein, G.deV., and Kupperman, J.B., 1992. Pennsylvanian cyclothems: Methods of distinguishing tectonically induced changes in sea level form climatically induced changes. Geological Society of America Bulletin, 104: 166-175.

Knight, I. 1983. Geology of the Carboniferous Bay of St. George Sub - Basin, Western Newfoundland. Newfoundland Department of Mines and Energy, Memoir 1, 358p.

Landing, E., and Wardlaw, B.R. 1981. Atokan Conodonts from the Pennsylvanian outlier of the Michigan Basin. Journal of Paleontology, 55: 1251-1269.

Langdon, G.S. and Hall, J. 1994. Devonian-Carboniferous tectonics and basin deformation in the Cabot Strait area, Eastern Canada. American Association of Petroleum Geologists Bulletin, 78: 1748-1774.

Larue, D.K., Sprague, A.R., Patterson, P.E., and Van Wagoner, J.C. 1995. Multi-storey sandstone bodies, sequence stratigraphy, and fluvial reservoir connectivity. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.54A.

Leckie, D.A. and Smith, D.G. 1992. Regional setting, evolution, and depostional cycles of the Western Canada foreland basin. *In* Foreland basins and foldbelts. *Edited by* R.W. Macqueen and D.A. Leckie. American Association of Petroleum Geologists, Memoir 55, pp. 9-46.

Lefort, J.P. 1987. Appalachian - West African linkages. *In* Tectonothermal evolution of the West African orogens and circum-Atlantic terrrane linkages. International Geological Correlation Program. Project 233. Conference at Nouakchott. Mauritania. Abstracts with Programs. pp. 139-142.

LeGallais, C.J. 1983. Stratigraphy, sedimentology and basin evolution of the Pictou Group (Pennsylvanian), Oromocto Sub-basin, New Brunswick. M.Sc. thesis, McGill University, Montreal, Quebec.

Legarreta, L., Uliana, M.A., Larotonda, C.A. and Meconi, G.R. 1993. Approaches to nonmarine sequence stratigraphy – theoretical models and examples from Argentine Basins. *In* Proceedings, 7th IFP Exploration and Production Research Conference, Scarborough, April 15-17, 1992. Subsurface Reservoir Characterization from Outcrop Observations. *Edited by* R. Eshard, and B. Doligez, pp. 125-144.

Lerche, I. 1990. Basin analysis quantitative methods - volume 1. Academic Press, Inc., San Diego, California, 562p.

Lindsay, J.E. 1987. Sequence stratigraphy and depositional controls in Late Proterozoic - Early Cambrian sediments of Amadeus Basin, Central Australia. American Association of Petroleum Geologists Bulletin, 71: 1387-1403.

Lindsay, J.F. and Korsch, R.J. 1989. Interplay of tectonics and sea-level changes in basin evolution: and example from the intracratonic Amadeus Basin, central Australia. Basin Research, 2: 3-25.

Lopatin, N.V. 1971. Temperature and geologic time as factors in coalification: Akademiya Nauk SSSR Izvestiya, Seriya Geologicheskaya no. 3, pp. 95-106. ( English translation by N.H. Bostick, Illinois State Geological Survey, 1972).

Lyons, P.C., Tiffney, B., and Cameron, B. 1976. Early Pennsylvanian age of the Norfolk Basin, southwestern Massachusetts, based on plant megafossils. *In* Studies in New England Geology. *Edited by* P.C. Lyons and A.H. Brownlow. Geological Society of America Memoir 146, pp. 181-197.

Lyons, P.C. 1979. Biostratigraphy in the Pennsylvanian of Massachusettes and Rhode Island. *In* The Mississippian and Pennsylvanian (Carboniferous) systems in the United States-Massachusettes, Rhode Island, and Maine. *Edited by* J.W., S.J. Skehan, D.P. Murray, J.C. Hepburn, M.P. Billings, P.C. Lyons, and R.G. Doyle. U.S. Geological Survey Professional Paper, 1110-A-L, pp. A20-A24.

MacDonald, D.J. 1989. Petroleum activities update. Nova Scotia Department of Mines and Energy, Report of Activities 89-3, pp. 1-3.

Magnavita, L.P., and da Silva, H.T.F. 1995. Rift border system: The interplay between tectonics and sedimentation in the Reconcavo Basin, northeastern Brazil. American Association of Petroleum Geologists Bulletin, 79: 1590-1607.

Magoon, L.B., and Dow, W.G. 1994. The petroleum system. *In* The petroleum system - from source to trap. *Edited by* L.B. Magoon, and W.G. Dow. American Association of Petroleum Geologists, Memior 60, pp. 3-24.

Marillier, F., Keen, C.E., Stockmal, G.S., Quinlan, G., Williams, H., Colmann-Sadd, S.P., and O'Brien, S.J. 1989. Crustal structure and surface zonation of the Canadian Appalachians: Implications of deep seismic data. Canadian Journal of Earth Sciences, 26: 305-321.

Martel, A. T. 1990. Stratigraphy, fluviolacustrine sedimentology and cyclicity of the Late Devonian/Early Carboniferous Horton Bluff Formation, Nova Scotia, Canada. Doctorate thesis, Dalhousie University, Halifax, Nova Scotia.

Martel, A.T. 1987. Seismic stratigraphy and hydrocarbon potential of the strike-slip Sackville Sub-basin, New Brunswick. *In* Sedimentary basins and basin forming mechanisms. *Edited by* C. Beaumont, and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 319-334.

Martel, A.T. and Gibling, M.R. In press. Stratigraphy and tectonic history of the Upper Devonian to Lower Carboniferous Horton Bluff Formation, Nova Scotia. Atlantic Geology.

Martel, A.T., McGregor, D.C., and Utting, J. 1993. Stratigraphic significance of upper Devonian and lower Carboniferous miospores from the type area of the Horton Group, Nova Scotia. Canadian Journal of Earth Sciences, 30: 1091-1098.

Martel, A. T., and Gibling, M. R. 1991. Wave-dominated facies and tectonically controlled cyclicity in the Lower Carboniferous Horton Bluff Formation, Nova Scotia, Canada. Special Publication of the International Association of Sedimentologists 13, pp. 223-243.

Martinsen, O.J. and Sauar, B. 1994. Fluvial sheet sandstone development above a tectonically-controlled sequence boundary: Canyon Creek Member, Erickson Sandstone (Campanian), Rock Springs Uplift, Wyoming. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.206.

Martinsen, O.J., Martinsen, R.S., and Steidtmann, J.R. 1993. Mesaverde Group (Upper Cretaceous), Southeastern Wyoming: Allostatigraphy versus sequence stratigraphy in a tectonically active area. American Association of Petroleum Geologists Bulletin, 77: 1351-1373.

Masters, J. 1979. Deep basin gas trap, western Canada. American Association of Petroleum Geologists Bulletin, 63: 152-181.

Matte, P. 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. Tectonophysics, 196: 309-337.

McAlpine, K.D. 1990. Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne D'Arc Basin, Grand Banks of Newfoundland. Geological Survey of Canada, Paper 89-17, pp. 1-50.

McCamis, J.G. 1973. The Carboniferous Basin - land and gulf. Canadian Institute of Mining Bulletin, 65: 51-57.

McCutcheon, S.R., and Robinson, P.T. 1987. Geological constraints upon the genesis of the Maritimes Basin, Atlantic Canada. *In* Sedimentary basins and basin forming mechanisms. *Edited by C.* Beaumont and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 287-297.

Melvin, J. 1993. Evolving fluvial style in the Kekiktuk Formation (Mississippian), Endicott Field area, Alaska. Base level response to contemporaneous tectonism. American Association of Petroleum Geologists Bulletin, 77: 1723-1744.

Miall, A.D. 1984. Deltas. *In* Facies models, 2nd edition. *Edited by* R.G. Walker. Geoscience Canada Reprint Series 1, pp. 105-118.

Miller, P.E., and D'eon, G.J. 1987. Labrador shelf paleoenvironments. Geological Survey of Canada, Open File Report 1722, 186p.

Miller D.S., and Duddy, I.R. 1989. Early Cretaceous uplift and erosion of the northern Appalachian Basin, New York, based on apatite fission track analysis. Earth and Planetary Science Letters, 93: 35-49.

Mitchum, R.M.Jr., and Van Wagoner, J.C. 1991. High-frequency sequences and their stacking patterns: Sequence-stratigraphic evidence of high frequency eustatic cycles. Sedimentary Geology, 70: 131-160

Moir, P. 1986. Compilation and further analysis of Paleozoic lithologies from well sites on the Labrador Shelf. Geological Survey of Canada, Internal Report, EPGS-GEN.1-86PNM, 5p.

Moore, D. 1959. Role of deltas in the formation of some British Lower Carboniferous cyclothems. Journal of Geology, 67: 522-539.

Morse, D.G. 1994. Siliciclastic Reservoir Rocks. *In* The petroleum system - from source to trap. *Edited by* L.B. Magoon and W.G. Dow. American Association of Petroleum Geologists, Memoir 60, pp. 121-139.

Mossman, D.J. 1992. Carboniferous source rocks of the Canadian Atlantic margin. *In* Basins on the Atlantic seaboard: Petroleum geology, sedimentology and basin evolution. *Edited by* J. Parnell. Geological Society, Special Publication No. 62, pp. 25-34.

Mossman, D.J., and Place, C.H. 1989. Early Permian fossil vertebrate footprints and their stratigraphic setting in megacyclic sequence II red beds, Prim Point, Prince Edward Island. Canadian Journal of Earth Sciences, 26: 591-605.

Mukhopadhyay, P.K., Hatcher, P.G., and Calder, J.H. 1991. Hydrocarbon generation from deltaic and intermontane fluviodeltaic coal and coaly shale from the Tertiary of Texas and Carboniferous of Nova Scotia. Organic Geochemistry, 17: 765-783.

Murphy Oil Company Ltd. 1968. Well history, Murphy et al. Birch Grove No.1.

Murphy Oil Company Ltd. 1974. Well history, Murphy et al. North Sydney P-05.

Nance, R.D. 1987. Dextral transpression and Late Carboniferous sedimentation in the Fundy Coastal Zone of southern New Brunswick. *In* Sedimentary basins and basin forming mechanisms. *Edited by* C. Beaumont and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12: 363-377.

Naylor, R.D., Kalkreuth, W., Smith, W.D., and Yeo, G.M. 1989. Stratigraphy, sedimentology and depositional environments of the coal-bearing Stellarton Formation, Nova Scotia. Geological Survey of Canada, Paper 89-8, pp. 2-13.

Negroni, P., Reymond, A., and Espitalie, J. 1988. Geochemical and modelling studies of the Mauritania offshore. Organic Geochemistry, 13: 175-179.

Norman, G.W.H. 1941. Hillsborough map sheet, Albert and Westmorland counties, New Brunswick. Geological Survey of Canada, Map 647A (with marginal notes).

Norman, G.W.H. 1935. Lake Ainslie map-area, Nova Scotia. Geological Survey of Canada, Memoir 177, 103p.

Oleksyshyn, J. 1976. Fossil plants of Pennsylvanian age from northwestern Narragansett basin. *In* Studies in New England Geology. *Edited by* P.C. Lyons and A.H. Brownlow. Geological Society of America Memoir 146, pp. 143-180.

Olsen, T., Steel, R., Hogseth, K., Skar, T., and Roe, S. 1995. Sequence architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah. Journal of Sedimentary Research, B65: 265-280.

Pe-Piper, G., and Jansa, L.F. 1986. Triassic olivine-normative diabase from Northumberland Strait, eastern Canada: Implications for continental rifting. Canadian Journal of Earth Sciences, 23: 1013-1021.

Perrodon, A. 1992. Petroleum systems: Models and applications. Journal of Petroleum Geology, 15: 319-326.

Peters, K.E. 1986. Guidelines for evaluating petroleum source rock using programmed pyrolysis. American Association of Petroleum Geologists Bulletin, 70: 318-329.

Petro-Canada et al. 1984. Well History, Petro-Canada et al. St. Paul P-91.

Phillips, T.L., Peppers, R.A., and DiMichele, W.A. 1985. Stratigraphic and interregional changes in Pennsylvanian coal-swamp vegetation. Environmental inferences. International Journal of Coal Geology, 5: 43-109.

Piper, D.J.W. 1995. Horton Group-equivalent sedimentation in the Cobequid Highlands. Abstract. *In* Mines and Minerals Branch Report of Activities 1995. Nova Scotia Department of Mines and Energy, Report 95-2, p.39.

Pique, A. and Skehan, J.W. 1992. Late Paleozoic orogenies in Western Africa and eastern North America: The diachronous closure of the Theic Ocean. Tectonics, 2: 392-404.

Plint, A.G., and Browne, G.H. 1994. Tectonic event stratigraphy in a fluvio-lacustrine, strike-slip setting: The Boss Point Formation (Westphalian A), Cumberland Basin, Maritime Canada. Journal of Sedimentary Research, B64: 341-364.

Plint, A.G., and van de Poll, H.W. 1984. Structural and sedimentary history of the Quaco Head area, southern New Brunswick. Canadian Journal of Earth Sciences, 21: 753-761.

Poole, H.S. 1903. Is there coal under Prince Edward Island?. Proceedings and Transactions, Nova Scotia Institue of Science, 11: 1-7.

Poole, W.H., Sanford, B.V., Williams, H., and Kelly, D.G. 1970. Geology of southeastern Canada. *In* Economic geology. *Edited by* R.J.W. Douglas. Geological Survey of Canada, Report No.1, pp. 229-299.

Poole, W.H. 1967. Tectonic evolution of Appalachian region of Canada. *In* Geology of the Atlantic region. *Edited by* E.R.W. Neale and H. Williams. Geological Association of Canada, Special Paper 4, pp. 9-51.

Posamentier, H.W., and Weimer, P. 1993. Siliciclastic sequence stratigraphy and petroleum geology - Where to from here? American Association of Petroleum Geologists Bulletin, 77: 731-742.

Posamentier, H.W., Allen, G.P., and James, D.P. 1992. High resolution sequence stratigraphy - the East Coulee Delta, Alberta. Journal of Sedimentary Petrology, 62: 310-317.

Posamentier, H.W., and Vail, P.R. 1988. Eustatic controls on clastic deposition II - Sequence and systems tract models. *In* Sea-level research: An integrated approach. *Edited by* C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.C. Van Wagoner. Society of Economic Paleontologists and Mineralogists, Special Publication 42, pp. 125-154.

Posamentier, H.W., Jervey, M.T., and Vail, P.R. 1988. Eustatic controls on clastic deposition I - Conceptual framework. *In* Sea-level research: An integrated approach. *Edited by* C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.C. Van Wagoner. Society of Economic Paleontologists and Mineralogists, Special Publication 42, pp. 109-124.

Pryor, W.A., and Sable, E.G. 1974. Carboniferous of the Eastern Interior Basin. *In* Carboniferous of the Southeastern United States. *Edited by* G. Brigs. Geological Society of America, Special Paper 148, pp. 281-313.

Puigdefabregas, C., Munzo, J.A., and Marzo, M. 1986. Thrust belt development in the eastern Pyrenees and related depositional sequences in the southern foreland basin. *In* Foreland Basins. *Edited by* P.A. Allen, and P. Homewood. International Association of Sedimentologists, Special Paper Number 8, pp. 229-246.

Putnam, P.E. 1993. A multidisciplinary analysis of Belly River-Brazeau (Campanian) fluvial channel reservoirs in west-central Alberta, Canada. Bulletin of Canadian Petroleum Geology, 41: 186-217.

Quinlan, G.M., and Lithoprobe East Transect Members. 1988. Structure and evolution of the Magdalen Basin: Constraints from lithoprobe seismic data. Geological Association of Canada Annual Meeting, St. John's. Newfoundland, May 1988, Program with Abstracts, v. 13, p.A101.

Quinlan, G.M., and Beaumont, C. 1984. Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the Eastern Interior of North America. Canadian Journal of Earth Sciences, 21: 973-996.

Rast, N. 1984. The Alleghenian orogeny in eastern North America. *In* Varsican tectonics in the North Atlantic. *Edited by* L.Hutton and D. Sanderson. Geological Society of London, Special Publication No. 14, pp. 197-217.

Rast, N. and Grant, R.J. 1973. The Variscan front in southern New Brunswick. American Journal of Science, 273: 572-579.

Ravenhurst, C. and Zentilli, M. 1987. A model for the evolution of hot (>2000C) overpressured brines under an evaporite seal: the Fundy/Magdalen Carboniferous Basin of Atlantic Canada and its associated Pb-Zn-Ba deposits. *In* Sedimentary Basins and Basin Forming Mechanisms. *Edited by* C. Beaumont, and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 335-349.

Reed, B.C., Nance, R.D., Calder, J.H., and Murphy, J.B. 1993. The Athol Syncline: tectonic evolution of a Westphalian A-B depocentre in the Maritimes Basin, Nova Scotia. Atlantic Geology, 29: 179-186.

Rehill, T.A., Gibling, M.R., and Williamson, M.A. 1995. Stratigraphy of the Central Maritimes Basin, eastern Canada: Non-marine sequence stratigraphy. *In* Current Research 1995-E, Geological Survey of Canada, pp. 221-231.

Rehill, T.A. 1993. Basin modelling in the Central Maritimes Basin. Industry Research Associates Scheme, Hydrocarbon Charge Modelling Project Newsletter, 5: 36-38.

Reiter, M., and Jessop, A.M. 1985. Estimates of terrestrial heat flow in offshore eastern Canada. Canadian Journal of Earth Sciences, 22: 1503-1517.

Reynolds, P.H., Elias, P., Muecke, G.K., and Grist, A.M. 1987. Thermal history of the southwestern Meguma Zone, Nova Scotia, from an $^{40}Ar/^{39}Ar$ and fisson track dating study of intrusive rocks. Canadian Journal of Earth Studies, 24: 1952-1965.

Riegel, W. 1991. Coal cyclothems and some models for their origin. *In* Cycles and events in stratigraphy. *Edited by* G. Einsele, W. Ricken, and A. Seilacher. Springer-Verlag, Berlin Heidelberg, pp. 733-750.

Robertson Research (North America) Ltd. 1974. The micropalaeontology, palynology and stratigraphy of the Murphy et al. North Sydney P-05 well. *Edited by* P.J. Rauwerda. Robertson Research (North America) Ltd, Exploration Report No. 90, 9p.

Robertson Research (North America) Ltd. 1976. The micropalaeontology, palynology and stratigraphy of the Shell Murphy et al. North Sydney F-24 well. *Edited by* G. Dolby and K.T. LaBorde. Robertson Research (North America) Ltd, Exploration Report No. 153, 15p..

Roliff, R.A. 1962. The Maritimes Basin of eastern Canada. Geological Association of Canada, Proceedings, 14: 21-41.

Rose, P.R., Everett, J.R., and Merin, I.S. 1986. Potential basin-centered gas accumulation in Cretaceous Trinidad Sandstone, Raton Basin, Colorado. *In* Geology of tight gas reservoirs. *Edited by* C.W. Spencer and R.F. Mast. American Association of Petroleum Geologists, Studies in Geology #24, pp. 111-128.

Ross, C.A. and Ross, J.R.P. 1987. Late Paleozoic sea-levels and depositional sequences. Cushman Foundation for Foraminifera Research Special Publication, 24: 137-149.

Rowely, D.B., Raymond, A., Totman Parrish, J., Lottes., A.L., Scotese, C.R., and Zeigler, A.M. 1985. Carboniferous paleogeographic, phytogeogeographic and paleoclimatic reconstructions. International Journal of Coal Geology, 5: 7-42.

Rust, B.R. and Gibling, M.R. 1990. Braidplain evolution in the Pennsylvanian South Bar Formation, Sydney Basin, Nova Scotia, Canada. Journal of Sedimentary Petrology, 60: 59-72.

Rust, B.R., Gibling, M.R., Best, M.A., Dilles, S.J., and Masson, A.G. 1987. A sedimentological overview of the coal-bearing Morien Group (Pennsylvanian), Sydney Basin, Nova Scotia, Canada. Canadian Journal of Earth Sciences, 24: 1869-1885.

Rust, B.R., Gibling, M.R., and Legun, A.S. 1984. Coal deposition in an anastomosing-fluvial system: the Pennsylvanian Cumberland Group south of Joggins, Nova Scotia, Canada. International Association of Sedimentologists, Special Publication 7, pp. 105-120

Ryan, R.J. 1993. Metallogenic and thermal evolution of the Maritimes Basin: Evidence from the Cumberland Basin of Nova Scotia. Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia. 333p.

Ryan, R.J., and Boehner, R.C. 1994. Geology of the Cumberland Basin, Cumberland, Colchester and Pictou counties, Nova Scotia. Nova Scotia Department of Mines and Energy, Memoir 10, p.222.

Ryan, R.J., and Zentilli, M. 1993. Allocyclic and thermochronological constraints on the evolution of the Maritimes Basin of Eastern Canada. Atlantic Geology, 29: 187-197.

Ryan, R.J., Boehner, R.C., and Calder, J.H. 1991. Lithostratigraphic revisions of the upper Carboniferous to lower Permian strata in the Cumberland Basin, Nova Scotia and the regional implications for the Maritimes Basin in Atlantic Canada. Bulletin of Canadian Petroleum Geology, v. 39, no. 4, pp. 289-314.

Ryan, R.J., Grist, A.M., and Zentilli, M. 1990. The thermal evolution of the Maritimes Basin: Evidence from apatite fission track analysis. Nova Scotia Department of Mines and Energy, Report 91-1, pp. 27-32.

Sanford, B.V., and Grant, A.C. 1990. Bedrock geological mapping and basin studies in the Gulf of St. Lawrence. Geological Survey of Canada, Paper 90-01b, pp. 33-42.

Sarep Ltd., 1971. Well history, Sarep H.Q. Brion Island No.1.

Saunders, K.I. 1995. Sedimentology and depostional environments of the Pennsylvanian Hub Cyclothem, Sydney Mines Formation, Cape Breton, Canada. M.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Schlager, W. 1993. Accomodation and supply - a dual control on stratigraphic sequences. Sedimentary Geology, 86: 111-136.

Schumm, S.A. 1993. River response to base level change: Implications for sequence stratigraphy. The Journal of Geology, 101: 279-294.

Schwab, F.L. 1986. Sedimentary 'signature' of foreland basin assemblages: Real or counterfeit?. *In* Foreland basins. *Edited by* P.A. Allen and P. Homewood. International Association of Sedimentologists, Special Paper Number 8, pp. 395-410.

Sclater, J.G., and Christie, P.A.F. 1980. Continental stretching: An explanation of the Post - Mid - Cretaceous subsidence of the Central North Sea Basin. Journal of Geophysical Research, 85: 3711-3739.

Scotese, C.R., and McKerrow, W.S. 1990. Revised world maps and introduction. *In* Palaeogeography and biogeography. *Edited by* W.S. McKerrow and C.R. Scotese. Geological Society of London, Memoir 12: 1-21.

Secor, D.T., Snoke, A.W., and Dallmeyer, R.D. 1986. Character of the Alleghanian orogeny in the southern Appalachians: Part III. Regional tectonic relations. Geological Society of America Bulletin, 97: 1345-1353.

Shanley K.W., and McCabe, P.J. 1994. Perspective on sequence stratigraphy of continental strata. American Association of Petroleum Geologists Bulletin, 78: 544-566.

Shanley, K.W. and McCabe, P.J. 1993. Alluvial architecture in a sequence stratigraphic framework: case history from the Upper Cretaceous of sourthern Utah, U.S.A. *In* Quantitative modelling of clastic hydrocarbon reservoirs and analogues. *Edited by* S. Flint and I Bryant. International Association of Sedimentologists, Special Publication No. 15, pp. 21-55.

Shanley, K.W., McCabe, P.J., and Hettinger, R.D. 1992. Tidal influence in Cretaceous fluvial strata from Utah, USA: A key to sequence stratigraphic interpretation. Sedimentology, 39: 905-930.

Shanmugam, S. 1988. Origin, recognition, and importance of erosional unconformities in sedimentary basins. *In* New perspectives in basin analysis. *Edited by* K.L. Kleinspehn and C. Paola. New York, Springer-Verlag, pp. 83-108.

Shell Canada Resources Limited, 1976. Well history, Shell et al. North Sydney F-24.

Shell Canada Resources Limited, 1973. Well history, Shell et al. Bradelle L-49.

Shideler, G.L. 1969. Dispersal patterns of Pennsylvanian sandstones in the Michigan Basin. Journal of Sedimentary Petrology, 39: 1229-1237.

Sinclair, I.K. 1992. A review of the geology and hydrocarbon potential of the Carboniferous Bay St. George Sub-basin. Canada-Newfoundland Offshore Petroleum Board, Report GL-CNOPB-92-01, 31p.

Skehan, J.W., Rast, N., and Mosher, S. 1986. Palcoenvironmental and tectonic controls of sedimentation in coal-forming basins of southeastern New England. *In* Paleoenvironmental and tectonic controls in coal-forming basins of the United States. *Edited by* P.C. Lyons and C.L. Rice. Geological Society of America, Special Paper 210: 9-30.

Slatt, R.M. 1992. Geological methods. *In* Development geology reference manual. *Edited by* D.M. Thompson and A.M Woods. American Association of Petroleum Geologists, Methods in Exploration Series, No.10, pp. 261-350.

Slingerland R., and Furlong, K.P. 1989. Geodynamic and geomorphic evolution of the Permo-Triassic Appalachian Mountains. Geomorphology, 2: 23-37.

Sloss, L.L. 1963. Sequences in the cratonic interior of North America. Geological Society of America Bulletin, 74: 93-114.

Solomon, S.M. 1986. Sedimentology and fossil fuel potential of the upper Carboniferous Barachois Group, western Newfoundland. M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland.

Soquip et al. 1975a. Well history, Soquip et al. Naufrage No.1.

Soquip et al. 1975b. Well history, Soquip et al. Tyrone No.1.

SOQUIP, 1987. Estuary and Gulf of St. Lawrence; Geological - geophysical geochemical data integration. Geological Survey of Canada, Open File 1721.

Souaya, F.J. 1975. Stratigraphy and biostratigraphy of Gulf Anschutz Scurry Rainbow Hastings No. 1 well, Nova Scotia. Gulf Oil Canada, Unpublished report, 17p.

St. Peter, C. 1996. Geology of the Carboniferous Hopwell and Cumberland groups, southeastern New Brunswick. Atlantic Geoscience Society, Annual General Meeting and Collquium, Program and Abtracts, p. 29.

St. Peter, C. 1993. Maritimes Basin evolution: Key geologic and seismic evidence from the Moncton subbasin of New Brunswick. Atlantic Geology, 29: 233-270.

Steel, R.J. 1976. Devonian basins of western Norway - sedimentary response to tectonism and to varying tectonic context. Tectonophysics, 36: 207-224.

Steltenpohl, M.G. and Kunk, M.J. 1993. $^{40}Ar/^{39}Ar$ thermochronology and Alleghanian development of the southernmost Appalachian Piedmont, Alabama and southwest Georgia. Geological Society of America Bulletin, 105: 819-833.

Stemmerik, L. 1996. Upper Carboniferous cyclic shelf sedimentation, North Greenland and the Barens Sea. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.A134.

Stemmerik, L., and Worsley, D. 1988. Late Palaeozoic sequence correlations, North Greenland, Svalbard and the Barents Shelf. *In* Correlation in hydrocarbon exploration. *Edited by* J.D. Collinson. Norwegian Petroleum Society, Graham and Trotman, London, pp. 99-111.

Stockmal, G.S., Cant, D.J., and Bell, J.S. 1992. Relationship of the stratigraphy of the Western Canada foreland basin to Cordilleran tectonics: insights from geodynamic models. *In* Foreland basins and foldbelts. *Edited by* R.W. Macqueen and D.A. Leckie. American Association of Petroleum Geologists, Memoir 55, pp. 107-124.

Stockmal, G.S., Colman-Sadd, S.P., Keen, C.E., Marillier, F., O'Brian, S.J., and Quinlan, G.M. 1990. Deep seismic structure and plate tectonic evolution of the Canadian Appalachians. Tectonics, vol. 9: 45-62.

Stow, D.A.V., Howell, D.G., and Nelson, C.H. 1985. Sedimentary, tectonic, and sea-level controls. *In* Submarine fans and related turbidite systems. *Edited by* A.H. Bouma, W.R. Normark, and N.E. Barnes, Springer-Verlag, pp. 15-22.

Tandon, S.K., and Gibling, M.R. 1994. Calcrete and coal in late Carboniferous cyclothems of Nova Scotia, Canada: Climate and sea-level changes linked. Geology, 22: 755-758.

Tankard, A.J. 1986. Depositional response to forland deformation in the Carboniferous of eastern Kentucky. American Association of Petroleum Geologists Bulletin, 70: 853-868.

Tapponnier, P., Peltzer, A.Y., Le Dain, Armijo, R., and Cobboid, P. 1982. Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine. Geology, 10: 511-616.

Teichmuller, R., and Teichmuller, M. 1986. Relations between coalification and palaeogeothermics in Varsican and Alpidic foredeeps of Western Europe. *In* Lecture notes in earth sciences, Volume 5: Paleogeothermics - Evaluation of geothermal conditions in the geologic past. *Edited by* G. Buntebarth and L. Stegena. Springer-Verlag, Heidelberg, pp. 53-78.

Thibaudeau, S.A., and Medioli, F.S. 1986. Carboniferous thecoamoebian and marsh foraminifera: new stratigraphic tools for ancient paralic deposits. Geological Society of America Abstracts with Programs, 17: p.A117.

Thrasher, J. 1992. Thermal effects of the Tertiary Cuillins Intrusive Complex in the Jurassic of the Hebrides: an organic geochemical study. *In* Basins on the Atlantic seaboard: Petroleum geology, sedimentology and basin evolution. *Edited by* J. Parnell. Geological Society, Special Publication No. 62, pp. 35-49.

Tissot, B.P., and Welte, D.H. 1984. Petroleum formation and occurrence (second edition). Springer-Verlag, Berlin, 539p.

Tissot, B.P., Pelet, R., and Ungerer, P.H. 1987. Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation. American Association of Petroleum Geologists Bulletin, 71: 1445-1466.

Tissot, B., and Espitalie, J. 1975. L'evolution thermique de la matiere organique des sediments: Applications d'une simulation mathematicque. Revue de l'Institut Francais du Petrole, 30: 743-777.

Towe, K.M. 1959. Petrology and source of sediments in the Narragansett Basin of Rhode Island and Massachusetts. Journal of Sedimentary Petrology, 29: 503-512.

Trask, C.B., and Palmer, J.E. 1986. Structural and depositional history of the Pennsylvanian System in Illinois. *In* Paleoenvironmental and tectonic controls in coal-forming basins of the United States. *Edited by* P.C. Lyons and C.L. Rice. Geological Society of America, Special Paper 210: 63-77.

Ungerer, P., Burrus, J., Doligez, Chenet, P.Y., and Bessis, F. 1990 Basin evaluation by integrated two-dimensional modelling of heat transfer, fluid flow, hydrocarbon generation and migration. American Association of Petroleum Geologists Bulletin, 74: 309-335.

Ungerer, P., Bessis, F., Chenet, P.Y., Durand, B., Nogaret, E., Chiarelli, A., Oudin, J.L., and Perrin, 1984. Geological and geochemical models in oil exploration: principles and practical examples. *In* Petroleum geochemistry and basin evaluation. *Edited by* G. Demaison. American Association of Petroleum Geologists, Memoir 35, pp. 53-77.

Utting, J. 1984. Palnological investigation of St. Paul P-91. *In* Well history, Petro-Canada et al., St. Paul P-91. Petro-Canada Resources, pp. 9-10.

Utting, J. 1978. Palynological investigation of the Windsor Group (Mississippian) of Port Hood Island and other localities on Cape Breton Island, Nova Scotia. Geological Survey of Canada, Paper 78-1A, pp. 205-207.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., and Perez-Cruz, C. 1991. The stratigraphic signatures of tectonics, eustacy and sedimentology - an overview. *In* Cycles and events in stratigraphy. *Edited by* G. Einsels, W. Ricken, and A. Seilacher. Springer-Verlag, New York, New York, pp. 611-659.

Vail, P.R., Mitchum, R.M.Jr., Todd, R.G., Widmier, J.M., Thompson, S.III., Sangree, J.B., Bubb, J.N., and Hatlelid, W.G. 1977. Seismic stratigraphy and global changes of sea level. *In* Seismic stratigraphy - applications to hydrocarbon exploration. *Edited by* C.E. Payton. American Association of Petroleum Geologists, Memoir 26, pp. 49-212.

van de Poll, H.W. 1995. Upper Paleozoic rocks: New Brunswick. Prince Edward Island and Iles de la Madeleine. *In* Chapter 5 of Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, no. 6, pp. 493-523.

van de Poll, H.W. 1989. Lithostratigraphy of the Prince Edward Island Redbeds. Atlantic Geology, 25: 23-35.

van de Poll, H.W. 1973. Stratigraphy, sediment dispersal and facies analysis of the Pennsylvanian Pictou Group in New Brunswick. Maritimes Sediments, 9: 72-77.

van de Poll, H.W. 1966. Sedimentation and paleocurrents during Pennsylvanian time in the Moncton Basin, New Brunswick. New Brunswick Department of Natural Resources, Mineral Division, Report of Investigation No. 1, 33p.

van de Poll, H.W., Gibling, M.R., and Hyde, R.S. 1995. Upper Paleozoic rocks. *In* Chapter 5 of Geology of the Appalachian-Caledonian orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, no. 6, pp. 449-455.

Van Wagoner, J.C., Mitchum, R.M, Campion, K.M., and Rahmanian, V.D. 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. American Association of Petroleum Geologists, Methods in Exploration Series 7, p. 55.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vial, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J. 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. *In* Sea-level changes: An integrated approach. *Edited by* C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner. Society of Economic Paleontologists and Mineralogists, Special Publication 42, pp. 39-45.

Veevers, J.J., and Powell, C.McA. 1987. Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica. Geological Society of America Bulletin, 98: 475-487.

Visher, G.S, 1984. Exploration stratigraphy. Pennwell Publishing Company, Tulsa, Oklahoma, 334p.

von der Borch, C.C., Christie-Blick, N., and Grady, A.E. 1988. Depositional sequence analysis applied to Late Proterozoic Wilpena Group, Adelaide Geosyncline, South Australia. Australian Journal of Earth Sciences, 35: 59-71.

Waldron, J.W.F., Piper, D.J.W., and Pe-Piper, G. 1989. Deformation of the Cape Chignecto Pluton, Cobequid Highlands, Nova Scotia: Thrusting at the Meguma-Avalon boundary. Atlantic Geology, 25: 51-62.

Walker, R.G. 1990. Facies modelling and sequence stratigraphy. Journal of Sedimentary Petrology, 60: 777-786.

Wang, W.H. 1992. Origin of reddening and secondary porosity in Carboniferous sandstones, Northern Ireland. *In* Basins of the Atlantic seaboard: Petroleum geology, sedimentology and basin evolution. *Edited by* J. Parnel. Geological Society Special Publication 62, pp. 243-254.

Waples, D.W. 1980. Time and temperature in petroleum formation: Application of Lopatin's Method to petroleum exploration. American Association of Petroleum Geologists Bulletin, 64: 916-926.

Waples, D.W., Kamata, H. and Suizu, M. 1992. The art of maturity modelling. Part 1: Finding a satisfactory geologic model. American Association of Petroleum Geologists Bulletin, 76: 31-46.

Waterfield, J.J. 1986. Sedimentology and stratigraphy of the Canso and Riversdale fluvial strata at Broad Cove, Cape Breton Island, Nova Scotia. B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia.

Weaver, C.E. 1989. Clays, muds, and shales. Developments in Sedimentology 44, Elesevier, Amsterdam, 819p.

Weaver, C.E. 1960. Possible uses of clay minerals in search for oil. American Association of Petroleum Geologists Bulletin, 44: 1505-1518.

Webb, G.W. 1969. Paleozoic wrench faults in Canadian Appalachians. *In* North Atlantic - Geology and Continental Drift. *Edited by* M. Kay. American Association of Petroleum Geologists, Memoir 12, pp. 754-786.

Webb, G.W. 1963. Occurrence and exploration significance of strike slip faults in southern New Brunswick, Canada. American Association of Petroleum Geologists Bulletin, 47: 1904-1927.

Weber, L.J., Sarg, J.F., and Armentrout, J.M. 1996. The stratigraphic hierarchy: Framework for integrated basin analysis at the exploration and production scales - Paradox Basin case study. American Association of Petroleum Geologists, Annual Convention, Program with Abstracts, p.A148.

Weimer, R.J. 1992. Developments in sequence stratrigraphy: Forland and cratonic basins. American Association of Petroleum Geologists Bulletin, 76: 965-982.

Welte, D.H., and Yalcin, M.N. 1988. Basin modelling - a new comprehensive method in petroleum geology. Organic Geochemistry, 13: 141-151.

Welte, D.H., Schaefer, F.G., and Yalcin, M.N. 1988. Gas generation from source rocks: aspects of a quantitative treatment. Chemical Geology, 71: 105-116.

Welte, D.H., and Yukler, M.A. 1981. Petroleum origin and accumulation evolution - a quantitative model. American Association of Petroleum Geologists Bulletin, 65: 1387-1396.

West, D.W. 1946. Geological supplement and conclusions for Hillsborough No.1, Prince Edward Island, Canada. Geological Survey of Canada, Hillsborough No.1 Supplementary Report GR-NY-51, 14p.

Westoll, T.S. 1968. Sedimentary rhythms in coal-bearing strata. *In* Coal and coal-bearing strata. *Edited by* D. Murchison and T.S. Westoll. American Elsevier Publishing Company Inc., New York, pp. 71-103.

Whiting, B.M., and Thomas, W.A. 1994. Three-dimensional controls on subsidence of a foreland basin associated with a thrust-belt recess. Black Warrior basin, Alabama and Mississippi. Geology, 22: 727-730.

Wightman, W.G. 1994. Cable Head E-95 and Brion Island No.1 wells: Agglutinated foraminifera and thecamoebian assemblages. Paleotec Geological Consulting, unpublished report, 3p.

Wightman, W.G., Grant, A.C., and Rehill, T.A. 1994a. Paleontological evidence for marine influence during deposition of the Westphalian coal measures in the Gulf of St. Lawrence-Sydney Basin region, Atlantic Canada. *In* Current Research 1994-D: Geological Survey of Canada, pp. 41-50.

Wightman, W.G., Scott, D.B., Medioli, F.S., and Gibling, M.R. 1994b. Agglutinated foraminifera and thecamoebians from the Late Carboniferous Sydney Coalfield, Nova Scotia: Paleoecology, paleoenvironments and paleogeographical implications. Palaeogeography, Palaeoclimatology, and Palaeoecology, 106: 187-202.

Wightman, W.G., Scott, D.B., Mediolli, F.S., and Gibling, M.R. 1993. Carboniferous marsh foraminifera from coal-bearing strata at the Sydney basin. Nova Scotia: A new tool for identifying paralic coal-forming enironments. Geology, 21: 631-634.

Wilgus, C.K . Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, J.C., and Kendall, C.G. St. C., *Editors*, 1988. Sea-level changes: An integrated approach. Society of Economic Paleontologists and Mineralogists, Special Publication No. 42, 407p.

Willard, D.A., and Klein, G.deV. 1990. Tectonic subsidence history of the Central Appalachian Basin and its influence on Pennsylvanian coal deposition. Southeastern Geology, 30: 217-239.

Williams, G.D. 1993. Tectonics and seismic sequence stratigraphy: An introduction. *In* Tectonics and seismic sequence stratigraphy. *Edited by* G.D. Williams, and A. Dobb. Geologi al Society, Special Publication No. 71, pp. 1-13.

Williams, E.P. 1974. Geology and petroleum possibilities in and around Gulf of St. Lawrence. American Association of Petroleum Geologists Bulletin, 58: 1137-1155.

Williams, E.P. 1973. St. Lawrence Lowlands, Gaspe, and Gulf of St Lawrence areas. *In* The future petroleum provinces of Canada - their geology and potential. *Edited by* R.G. McCrossan. Canadian Society of Petroleum Geologists, Memoir 1, pp. 561-587.

Williamson, M.A. 1992. The subsidence, compaction, thermal and maturation history of the Egret Member source rock, Jeanne D'Arc Basin, offshore Newfoundland. Bulletin of Canadian Petroleum Geology, 40: 136-150.

Williamson, M.A., DesRoches, K., and King S. 1994. Overpressures and hydrocarbon migration in the Hibernia-Nautilus area of the Jeanne D'Arc Basin, offshore Newfoundland: Reply. Bulletin of Canadian Petroleum Geology, 42: 272-277.

Wiltschko, D.V., and Dorr, J.A. 1983. Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah. American Association of Petroleum Geologists Bulletin, 67: 1304-1322.

Winston, R.B. 1990. Implications of paleobotany of Pennsylvanian-age coals of the central Appalachian basin for climate and coal-bed development. Geological Society of America Bulletin, 102: 1720-1726.

Winston, R.B., and Stanton, R.W. 1989. Plants, coal and climate in the Pennsylvanian of the Central Appalachians. *In* Carboniferous geology of the eastern United States, International Geological Congress Feild Trip Guidbook T143. *Edited by* C.B. Cecil and C. Eble. American Geophysical Union, Washington, D.C., pp. 118-126

Wintsch, R.P., and Sutter, J.F. 1986. A tectonic model for the Late Paleozoic of southeastern New England. Journal of Geology, 94: 459-472.

Wood, G.H.Jr., Kehn, T.M., and Eggleston, J.R. 1986. Depositional and structural history of the Pennsylvania Anthracite region. *In* Paleoenvironmental and tectonic controls in coal-forming basins of the United States. *Edited by* P.C. Lyons and C.L. Rice. Geological Society of America, Special Paper 210: 31-47.

Wood, G.H.Jr., Trexler, J.P., Arndt, H.H., Yelenosky, A., and Soren, J. 1956. Subdivision of the Pottsville formation in Southern Anthracite Field, Pennsylvanian. American Association of Petroleum Geologists Bulletin, 40: 2669-2688.

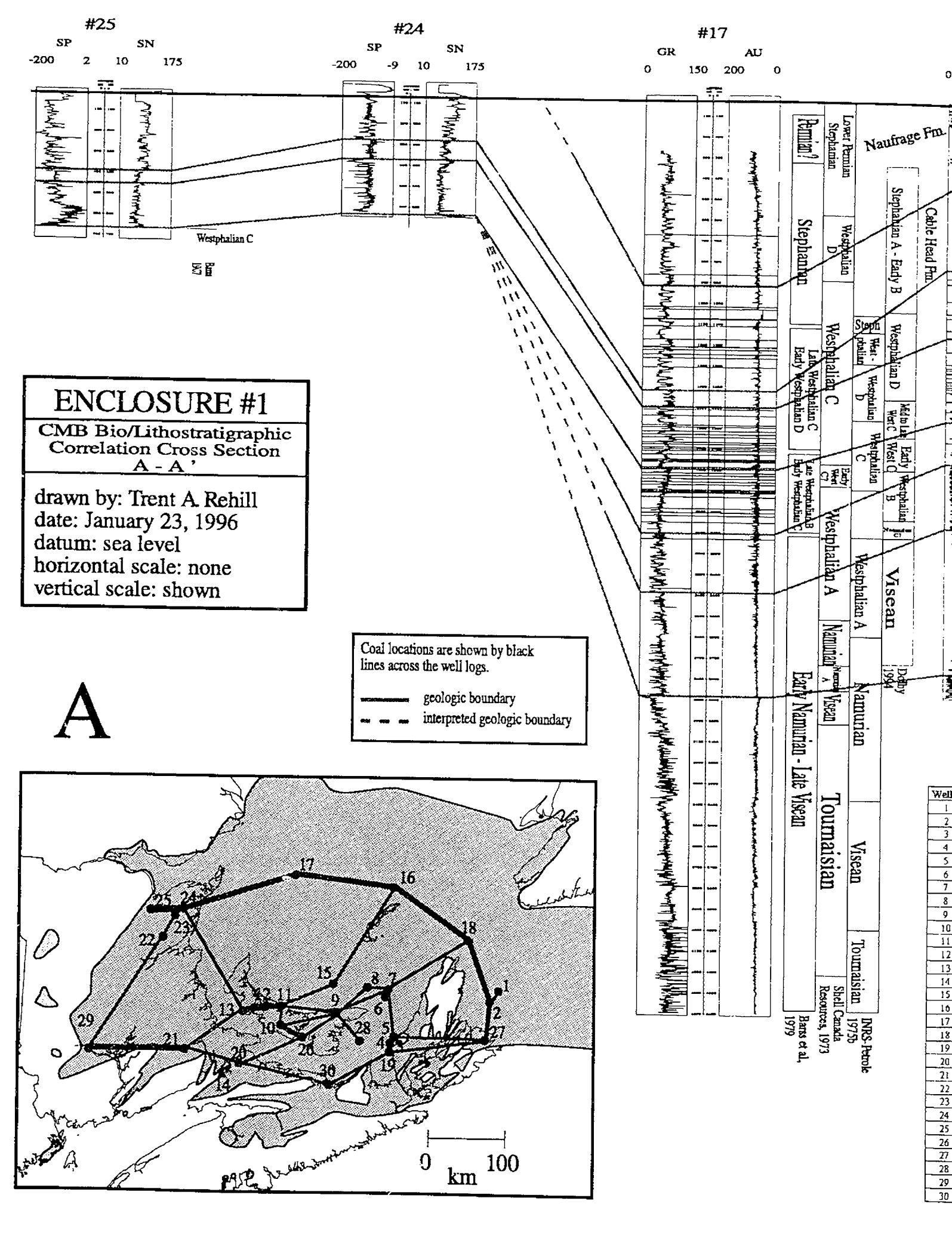
Wright, V.P., and Marriott, S.B. 1993. The sequence stratigraphy of fluvial depositional systems: The role of floodplain sediment storage. Sedimentary Geology 86: 203-210.

Wygrala, B.P. 1988. Integrated computer-aided basin modelling applied to analysis of hydrocarbon generation history in a Northern Italian oil field. Organic Geochemistry, 13: 187-197.

Xue, L., and Galloway, W.E. 1993. Genetic sequence stratigraphic framework, depostional style and hydrocarbon occurrence of the Upper Cretaceous QYN Formations in the Songliao Lacustrine Basin, Northeastern China. American Association of Petroleum Geologists Bulletin, 77: 1792-1808.

Yeo, G.M., and Ruixiang, G. 1987. Stellarton Graben: an Upper Carboniferous pull - apart basin in northern Nova Scotia. *In* Sedimentary basins and basin forming mechanisms. *Edited by* C. Beaumont and A.J. Tankard. Canadian Society of Petroleum Geologists, Memoir 12, pp. 299-309.

Ziegler, P.A. 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. American Association of Petroleum Geologists, Memoir 43, 198p.




# ENCLOSURE #1

**CMB Bio/Lithostratigraphic Correlation Cross Section A - A'**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown

Coal locations are shown by black lines across the well logs.

——— geologic boundary
– – – interpreted geologic boundary

A




| Well |
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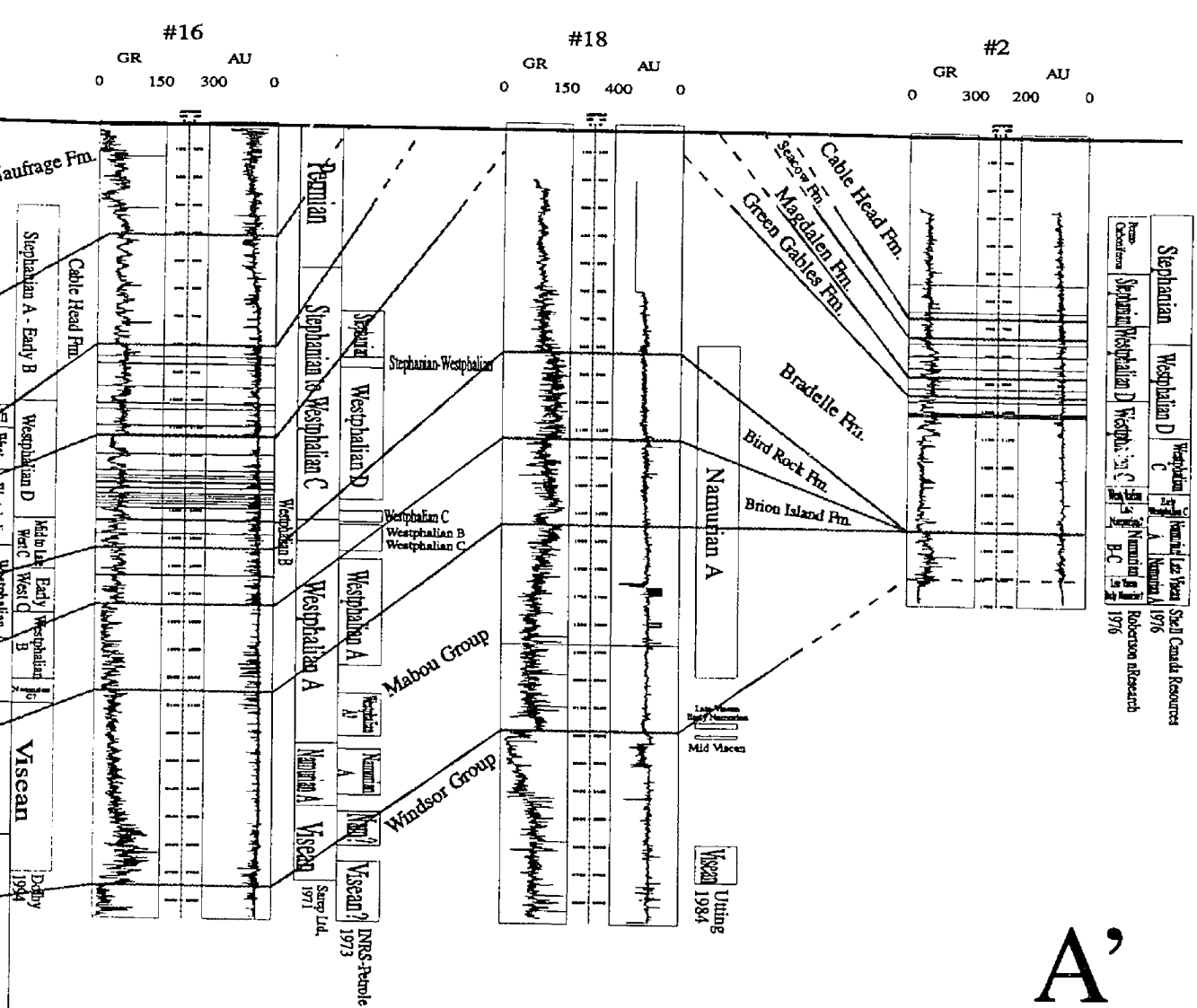
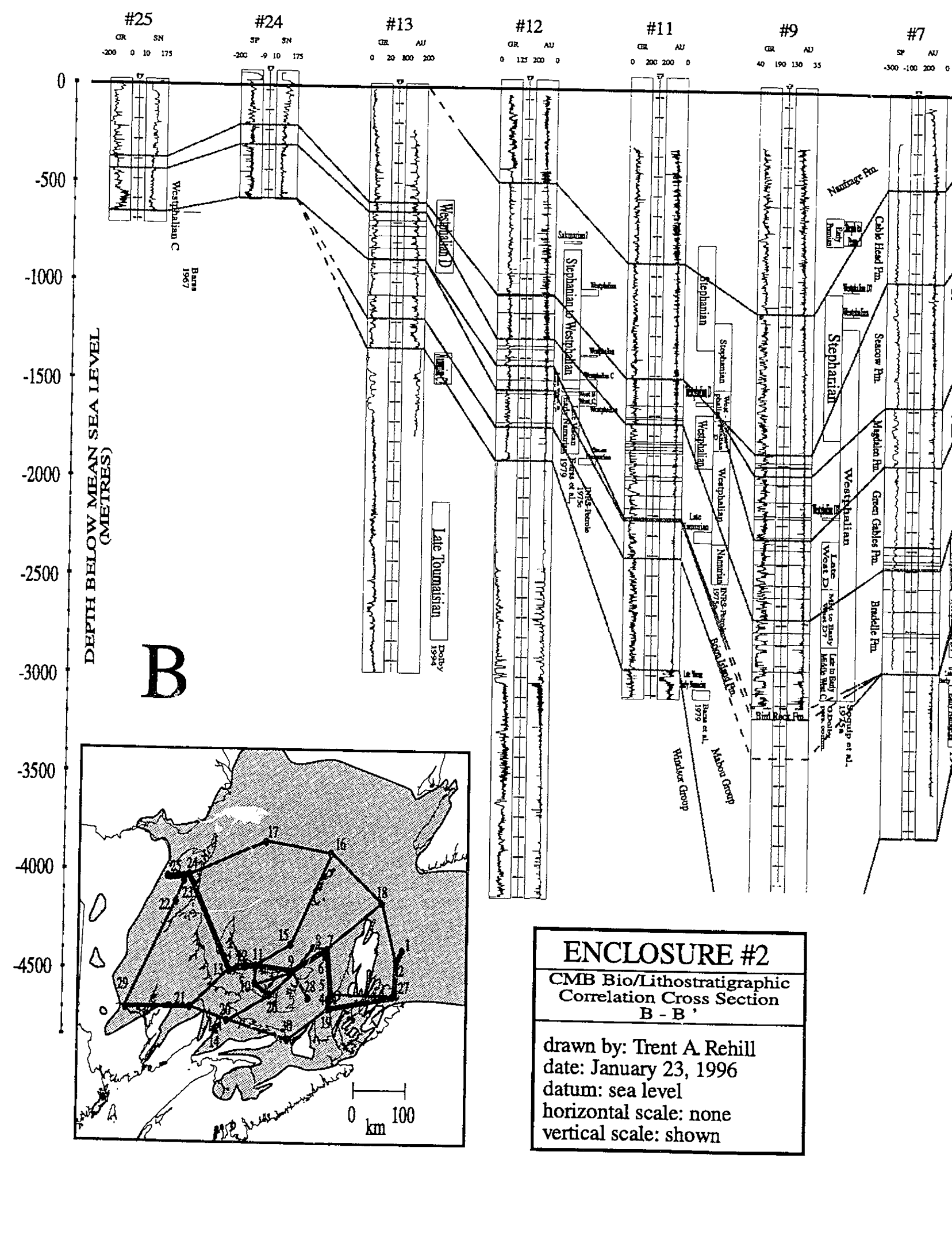


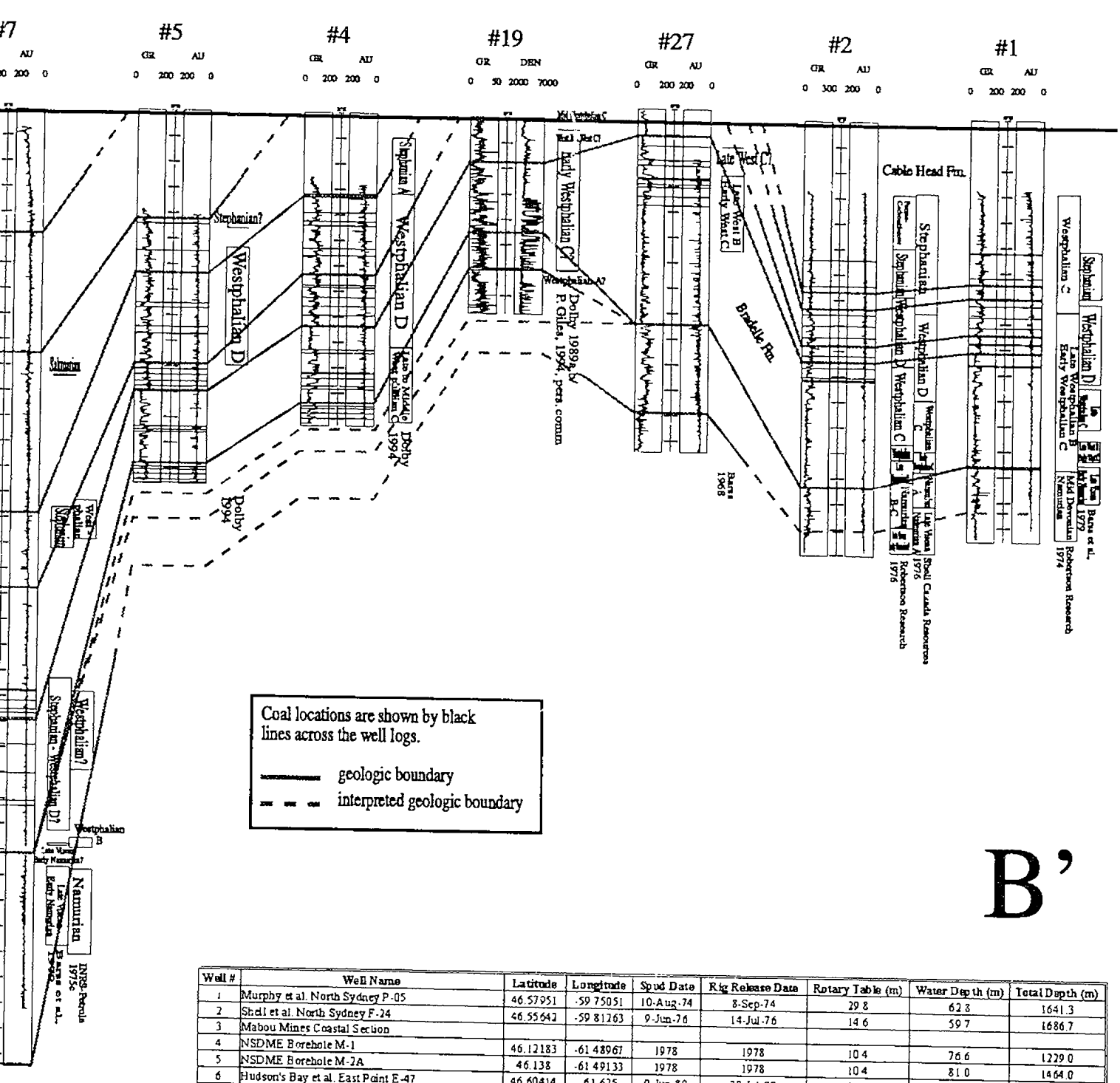

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Inshtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.97473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |




# ENCLOSURE #2

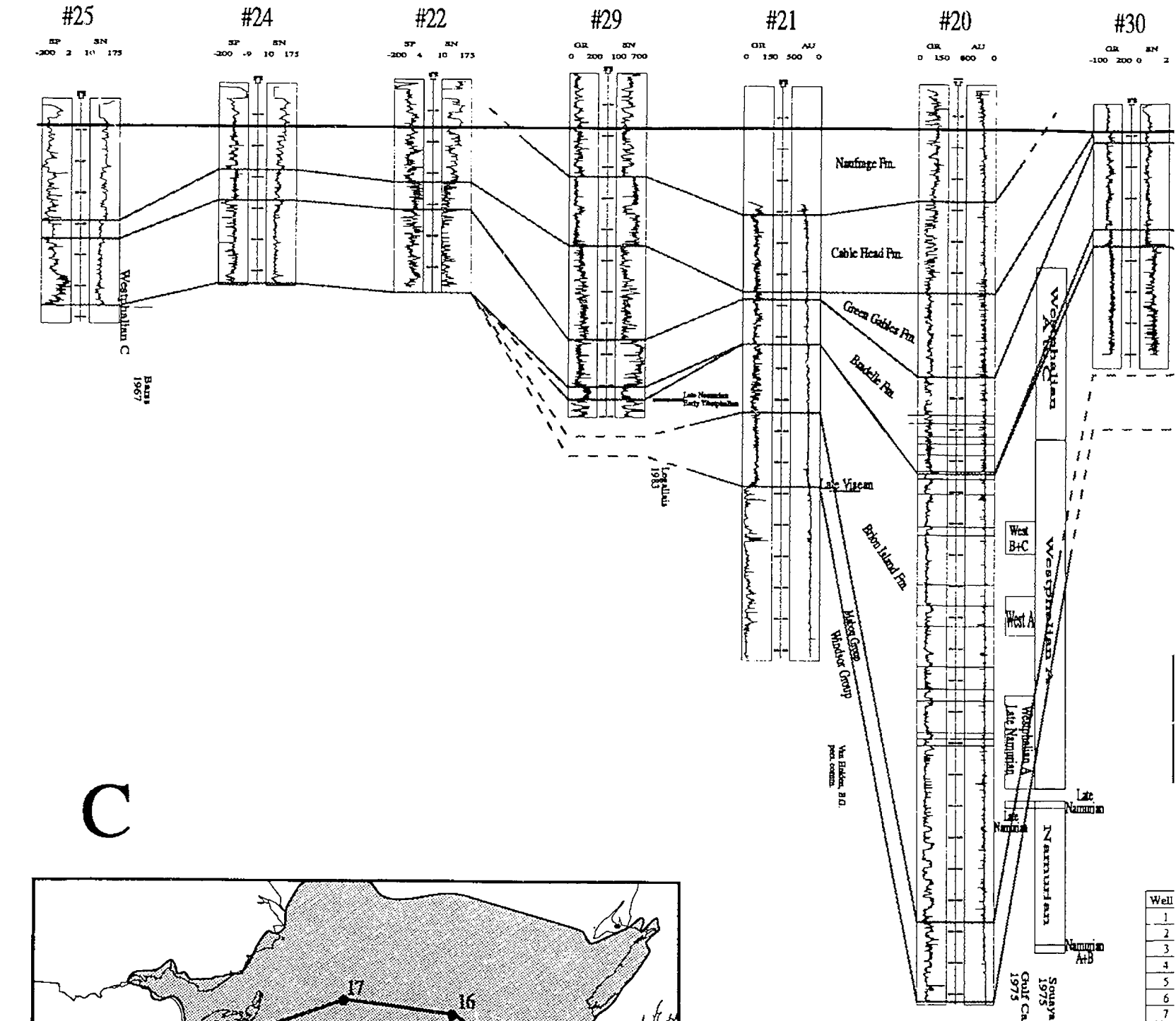
**CMB Bio/Lithostratigraphic Correlation Cross Section B - B'**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown

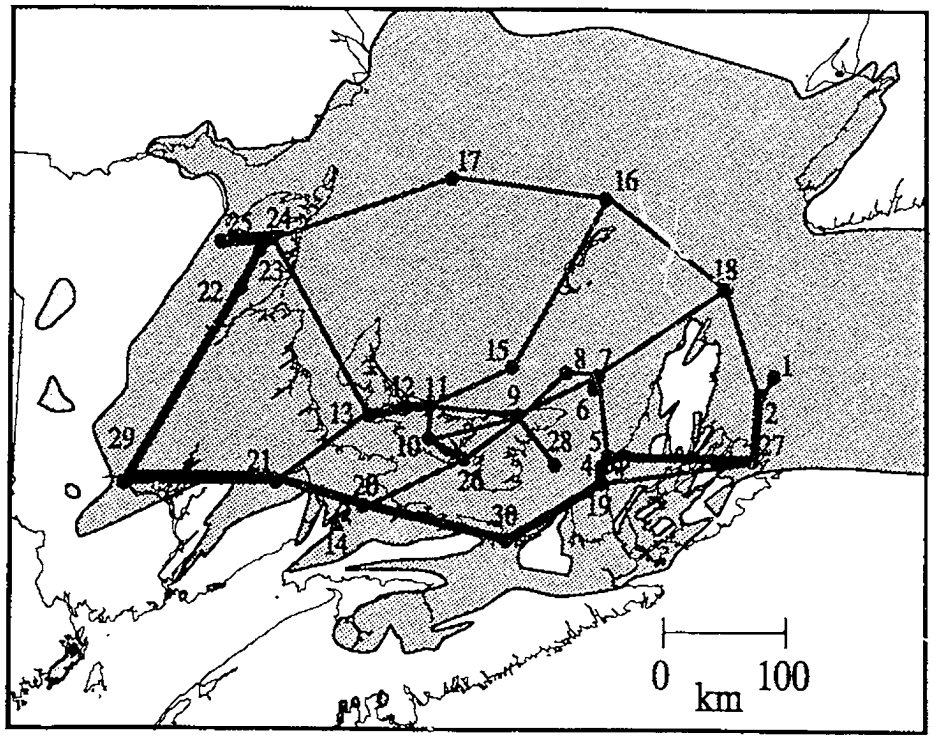



B'

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No 1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No. 1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No 1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No 1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |




C




| Well |
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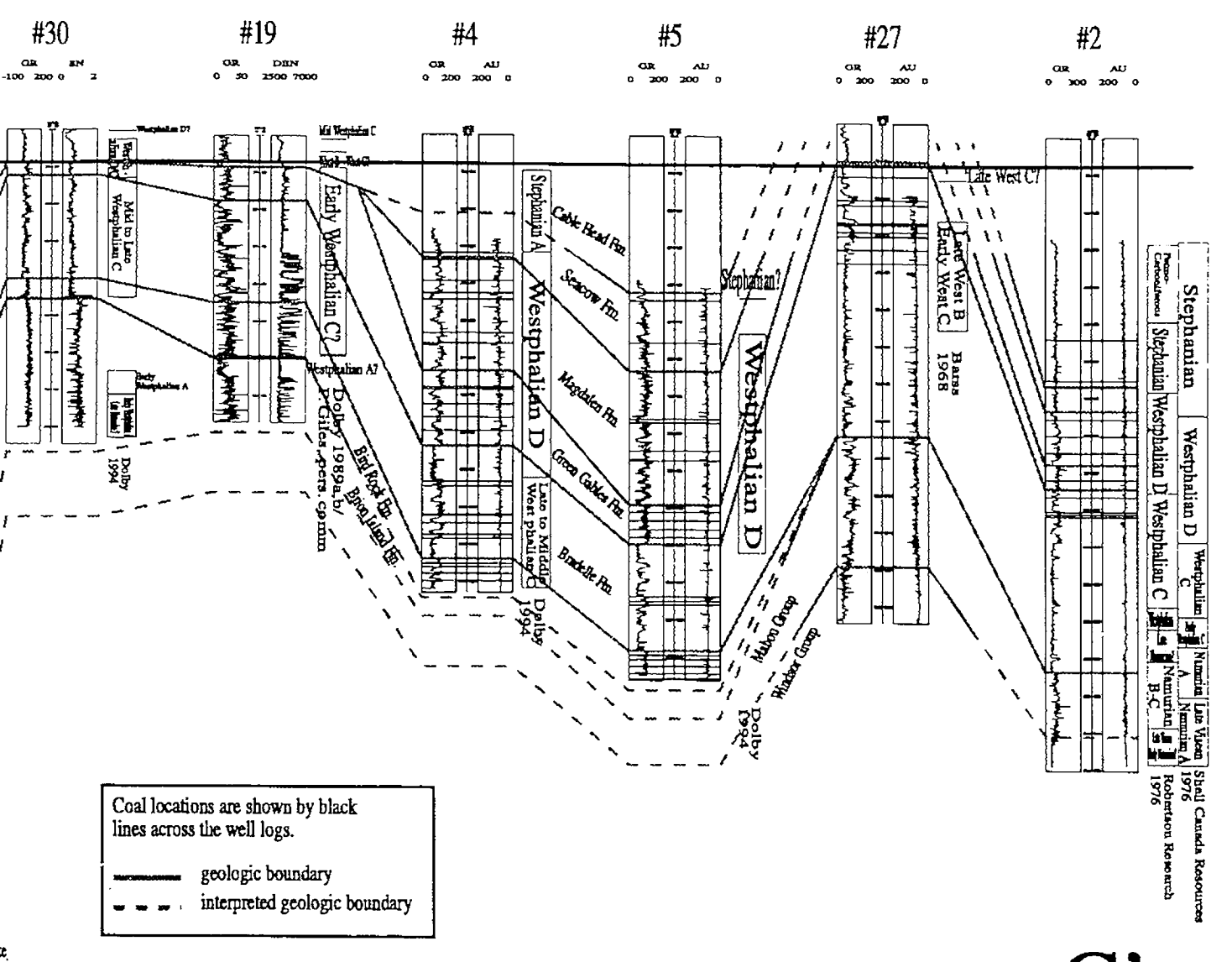
# ENCLOSURE #3

**CMB Bio/Lithostratigraphic Correlation Cross Section C - C'**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown



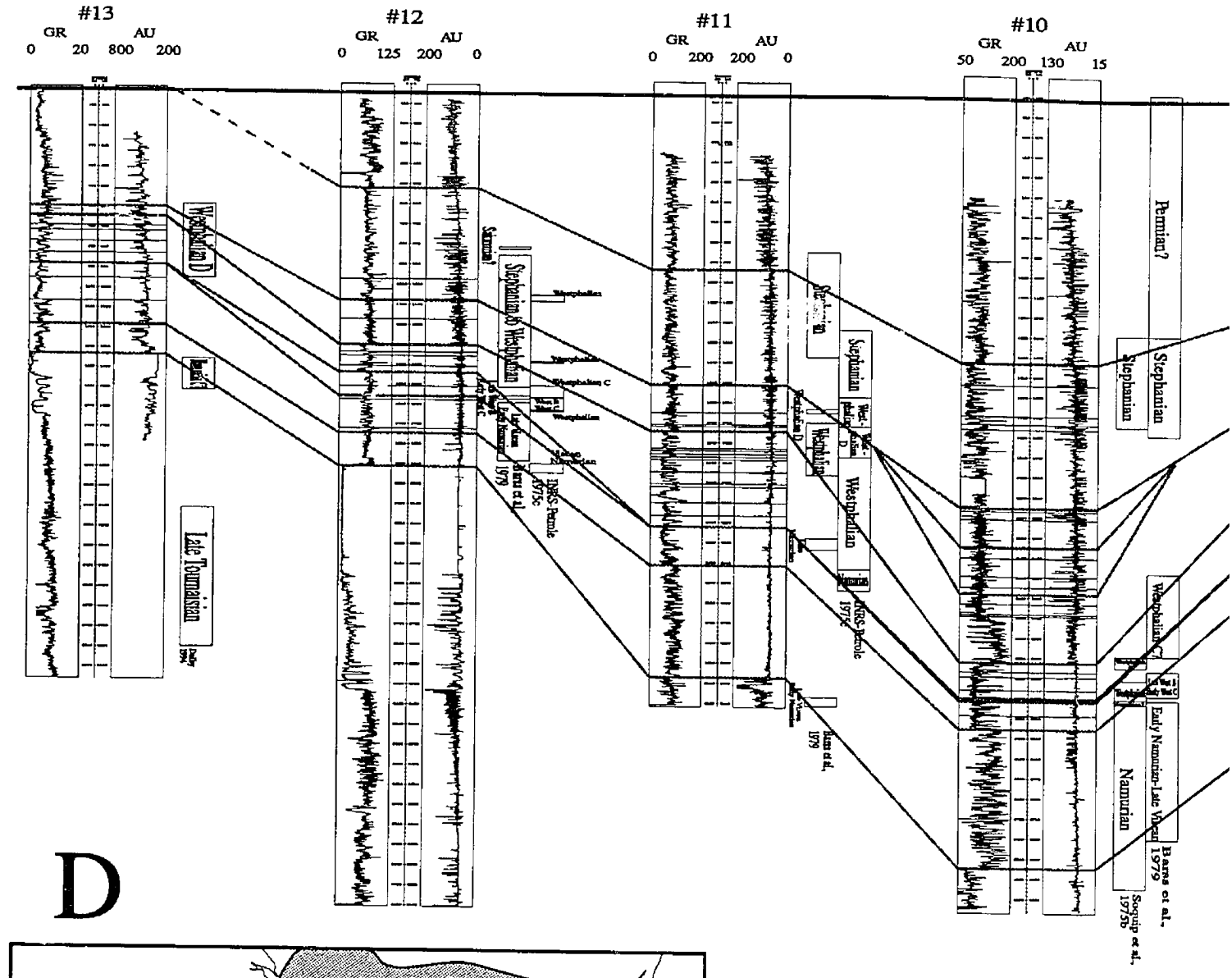

Coal locations are shown by black lines across the well logs.

geologic boundary

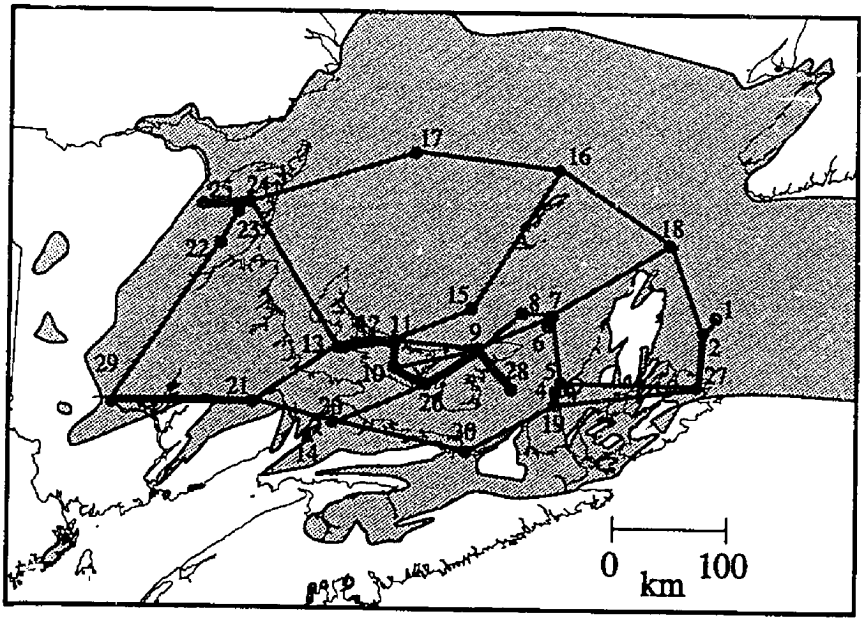
interpreted geologic boundary

C'

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al North Sydney P-05 | 46 57951 | -59 75051 | 10-Aug-74 | 8-Sep-74 | 29 8 | 62 8 | 1641 3 |
| 2 | Shell et al North Sydney F-24 | 46 55642 | -59 31263 | 9-Jun-76 | 14-Jul-76 | 14 6 | 59 7 | 1686 7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46 12183 | -61 48967 | 1978 | 1978 | 10 4 | 76 6 | 1229 0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61 49133 | 1978 | 1978 | 10 4 | 81 0 | 1464 0 |
| 6 | Hudson's Bay et al East Point E-47 | 46 60414 | -61 625 | 9-Jun-80 | 29-Jul-80 | 25 0 | 85 0 | 2662 0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46 63972 | -61 62389 | 26-Jun-70 | 16-Nov-70 | 9 7 | 61 8 | 3484 6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46 65553 | -61 91247 | 1-Aug-80 | 27-Aug-80 | 27 6 | 56.2 | 1734 0 |
| 9 | Soquip et al Naufrage No 1 | 46.46833 | -62 46417 | 29-Aug-75 | 23-Oct-75 | 4 1 | +22 2 | 3105 3 |
| 10 | Soquip et al. Tyrone No 1 | 46 26942 | -63 33886 | 26-Feb-75 | 19-Jul-77 | 4 2 | +110 3 | 4166 6 |
| 11 | Hudson's Bay-Fina Green Gables No 1 | 46 47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6 4 | +61 9 | 3389 2 |
| 12 | Hudson's Bay-Fina Inshtown No 1 | 46 50107 | -63 60428 | 24-Jan-72 | 5-Apr-72 | 6 4 | 39 9 | 4107 8 |
| 13 | Imperial Wellington Station No 1 | 46 43611 | -64.02361 | 3 Mar-58 | 3-Jul 58 | 5 1 | +12 8 | 2960 8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46 73803 | -62 495 | 26-Jun-83 | 7-Sep-83 | 28 0 | 54 7 | 3235 0 |
| 16 | Sarep H.Q. Brion Island No 1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4 8 | +6 6 | 3168 7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29 9 | 56 7 | 4368 4 |
| 18 | Petro-Canada et al St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24 9 | 173 6 | 2883 0 |
| 19 | NSDME PH-3 | 45 995 | -61 56 | 1975 | 1975 | 7 5 | +7 5 | 778 0 |
| 20 | Gulf et al. Hastings No 1 | 45 84306 | -64 08139 | 11-Jun-75 | 11-Aug-75 | 18 6 | +74 6 | 2939 5 |
| 21 | Irving Chevron et al Middlesex #1 | 45 97772 | -65 00256 | 24-Aug-82 | 16-Oct-82 | 7 0 | +63 7 | 1835 0 |
| 22 | Hudson's Bay Bartibog No 1 | 47 21278 | -65 40139 | 6-Aug-67 | 29-Aug-67 | 1 5 | +89 0 | 683 1 |
| 23 | Hudson's Bay St Isidore No 1 | 47.54472 | -65 05806 | 29-Jun-67 | 16-Jul-67 | 1 5 | +62 5 | 732 5 |
| 24 | Hudson's Bay St Isidore No 2 | 47 52667 | -65 16056 | 20-Aug 67 | 12 Sep-67 | 1 5 | +73 8 | 642 2 |
| 25 | Hudson's Bay Blanchard No 1 | 47.71333 | -65 89556 | 16-Jul-67 | 4-Aug-67 | 1 5 | +20 7 | 718 9 |
| 26 | Island Development Company Hillsborough No 1 | 46.12417 | -63 08667 | 11 Oct-43 | 5-Dec-44 | 6 4 | 7 3 | 4479 3 |
| 27 | Murphy et al. Birch Grove No 1 | 46 14511 | -59 93473 | 2-Feb-68 | 20-May-68 | 3 2 | +46 5 | 1343 6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46 07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9 4 | 29 9 | 2974 7 |
| 29 | Seru Nucleaire Canada Ltee Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1 5 | +112 5 | 1102 0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6 0 | +24 0 | 845 0 |




# D




Coal locations are shown by black lines across the well logs.

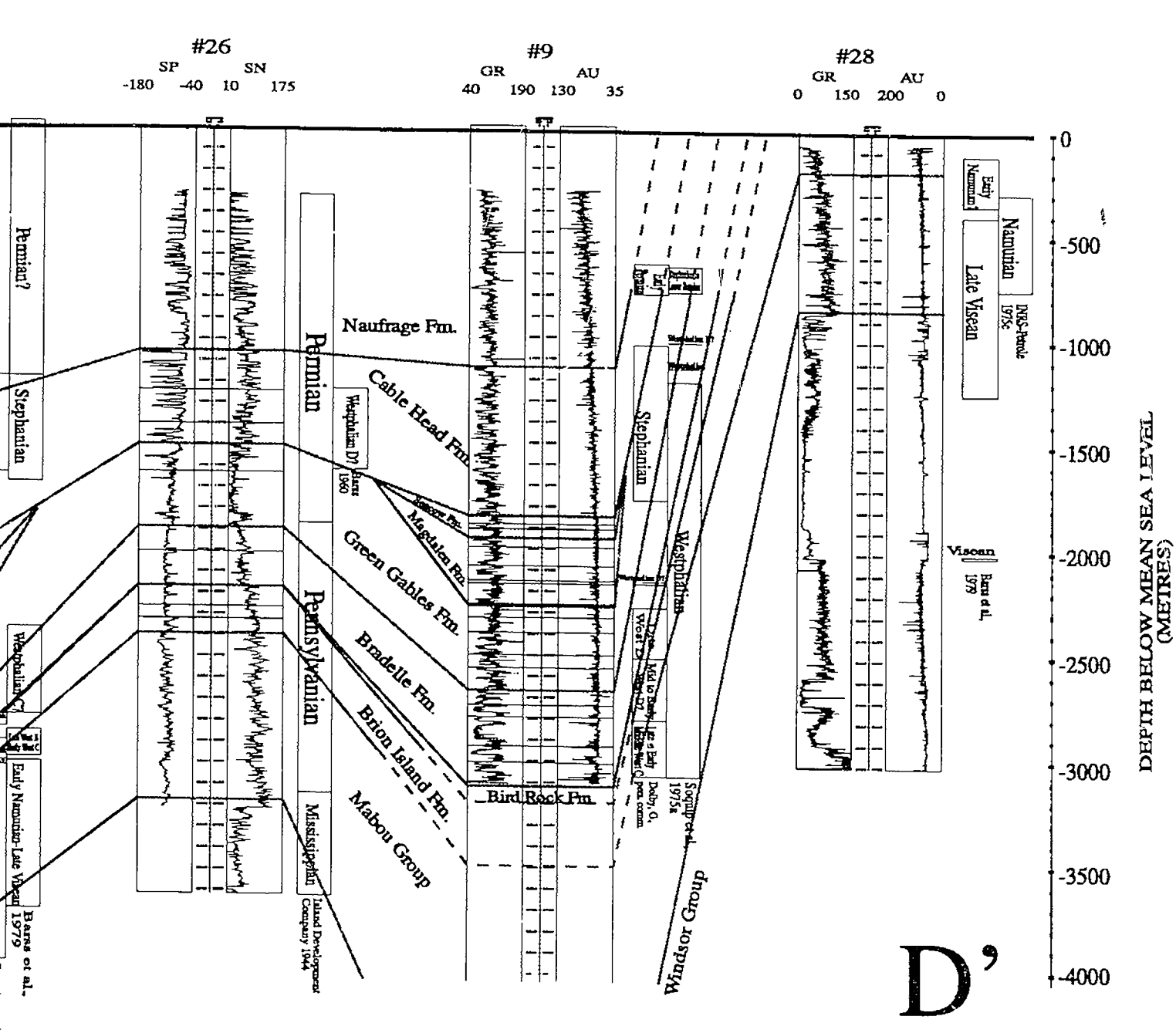
geologic boundary

interpreted geologic boundary

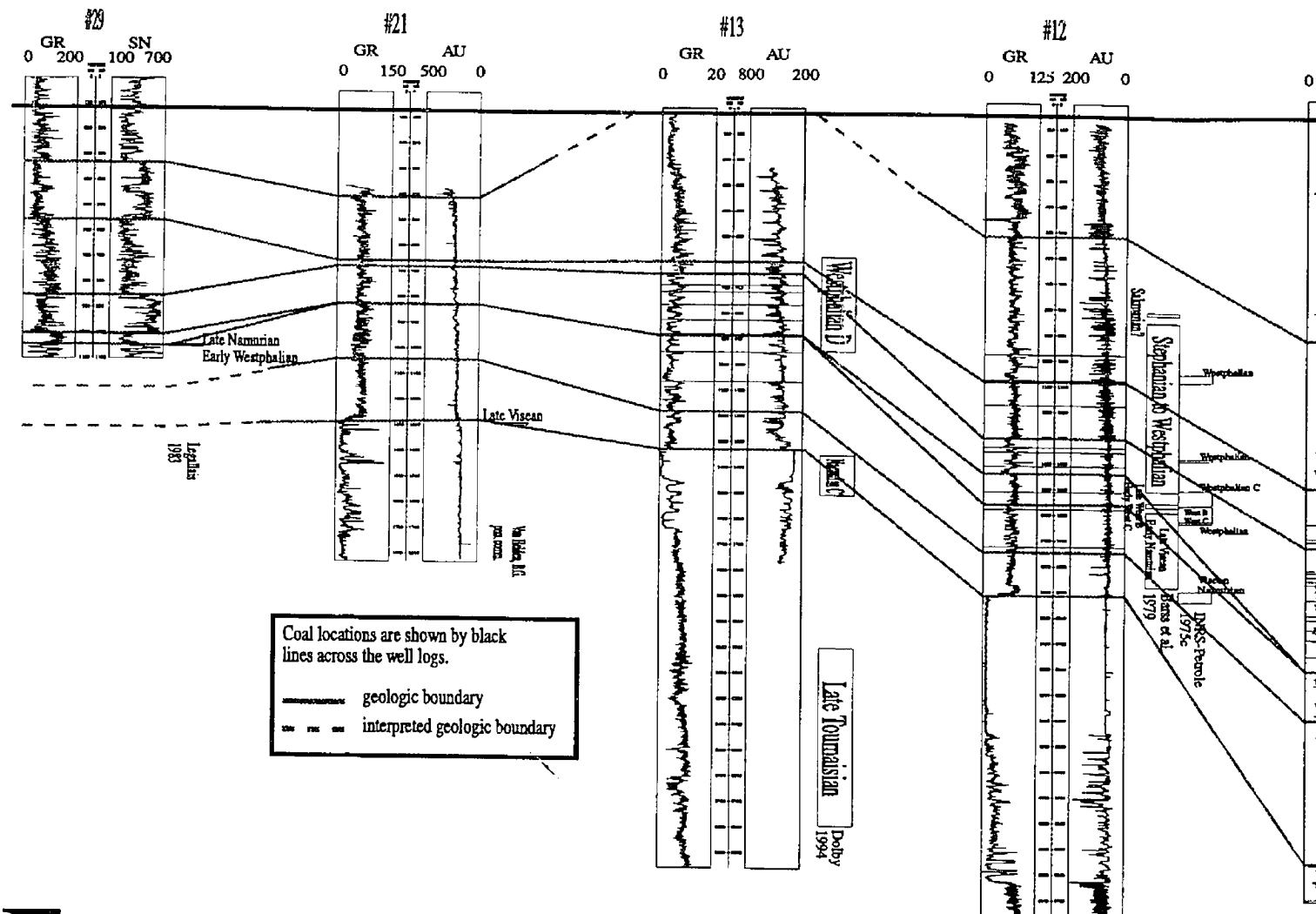
## ENCLOSURE #4

**CMB Bio/Lithostratigraphic Correlation Cross Section D - D '**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |



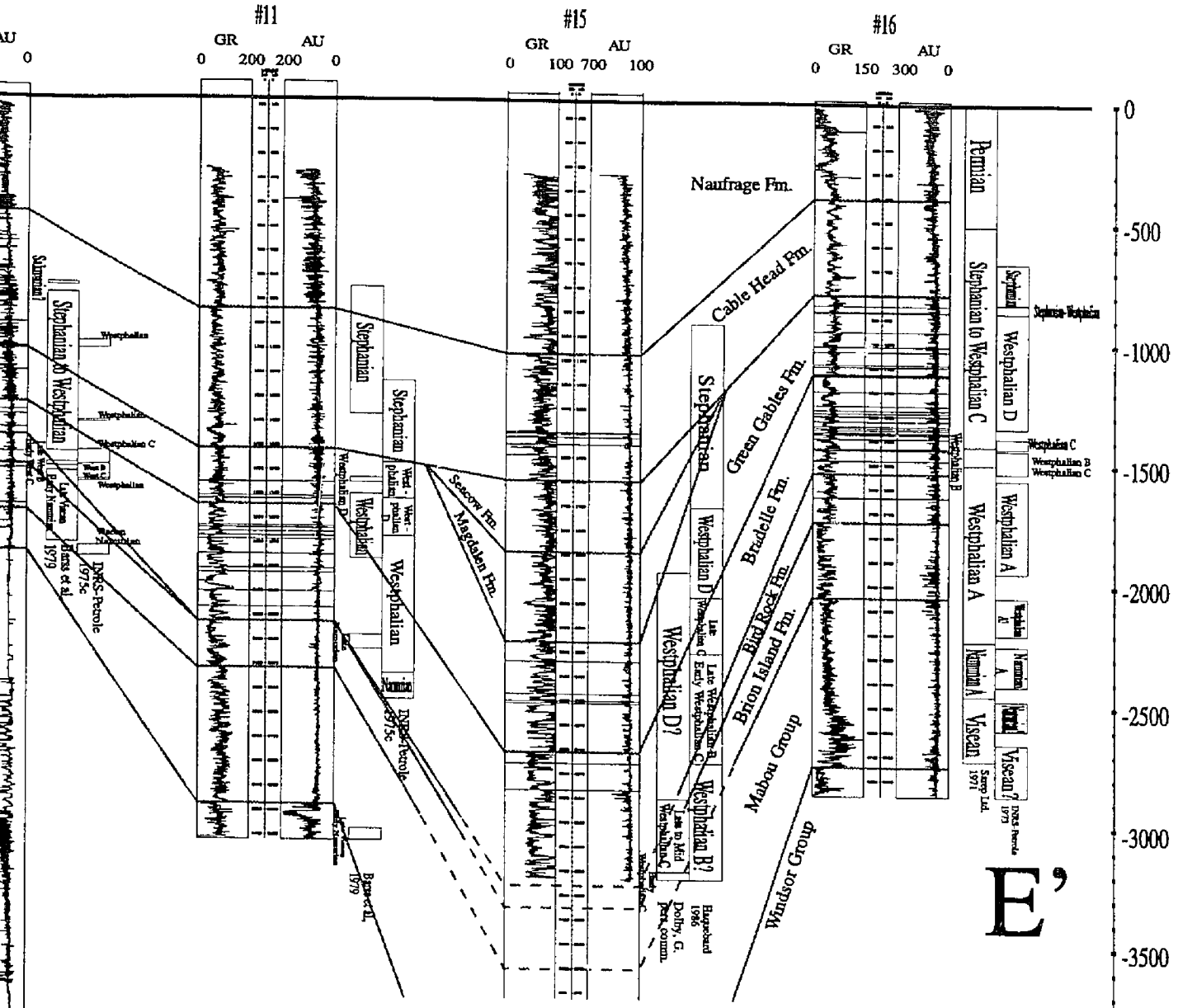

# E

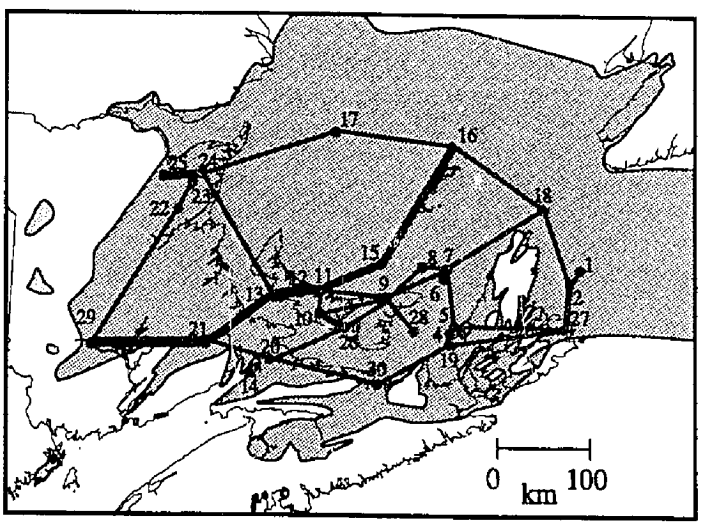
| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 5.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.066 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |

## ENCLOSURE #5

**CMB Bio/Lithostratigraphic Correlation Cross Section**
**E - E '**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown

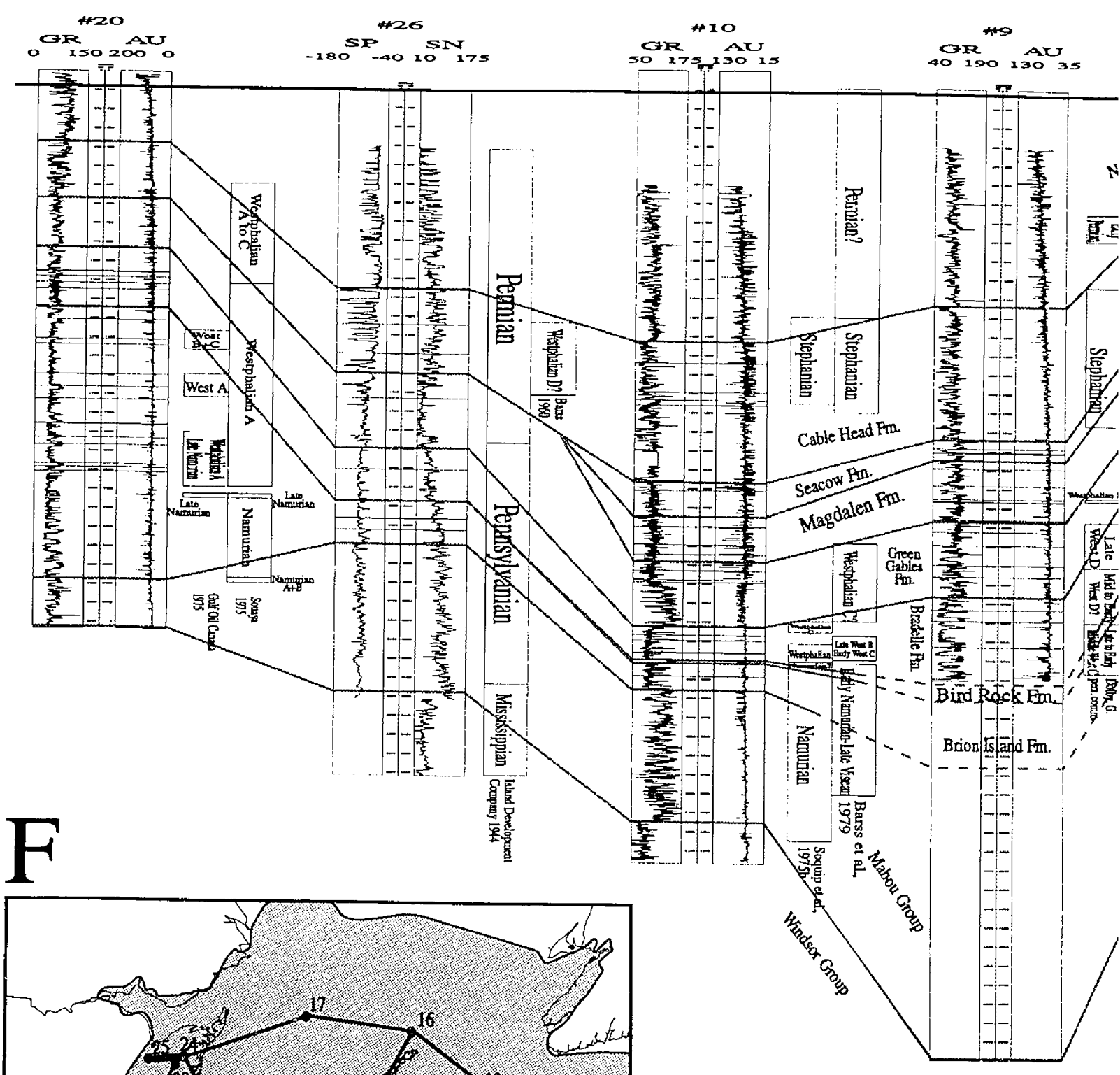


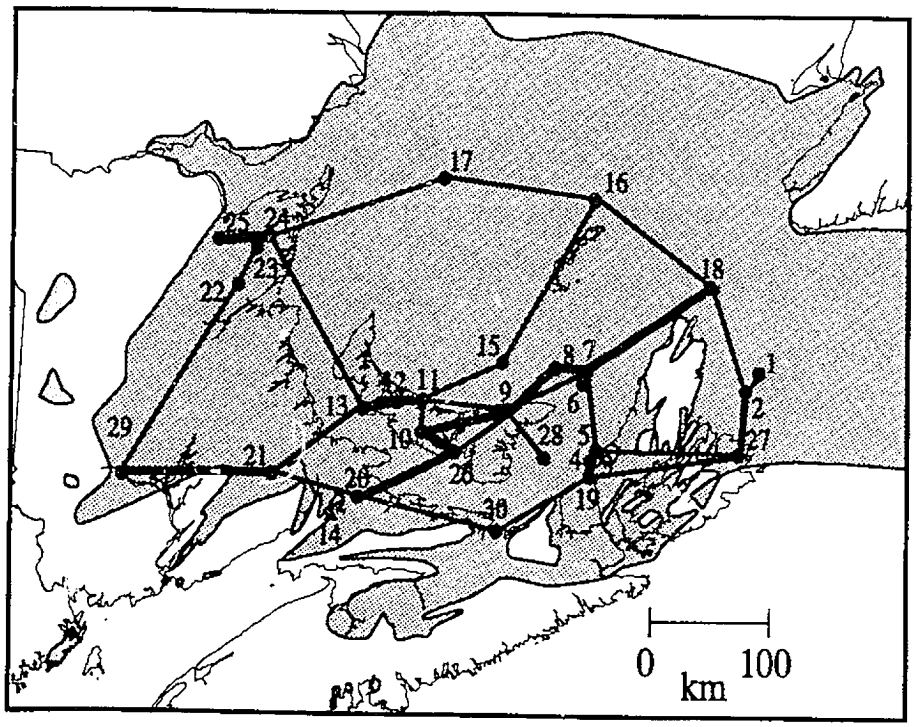

# LOSURE #5

p/Lithostratigraphic
ion Cross Section
E - E '

Trent A. Rehill
uary 23, 1996
a level
l scale: none
cale: shown



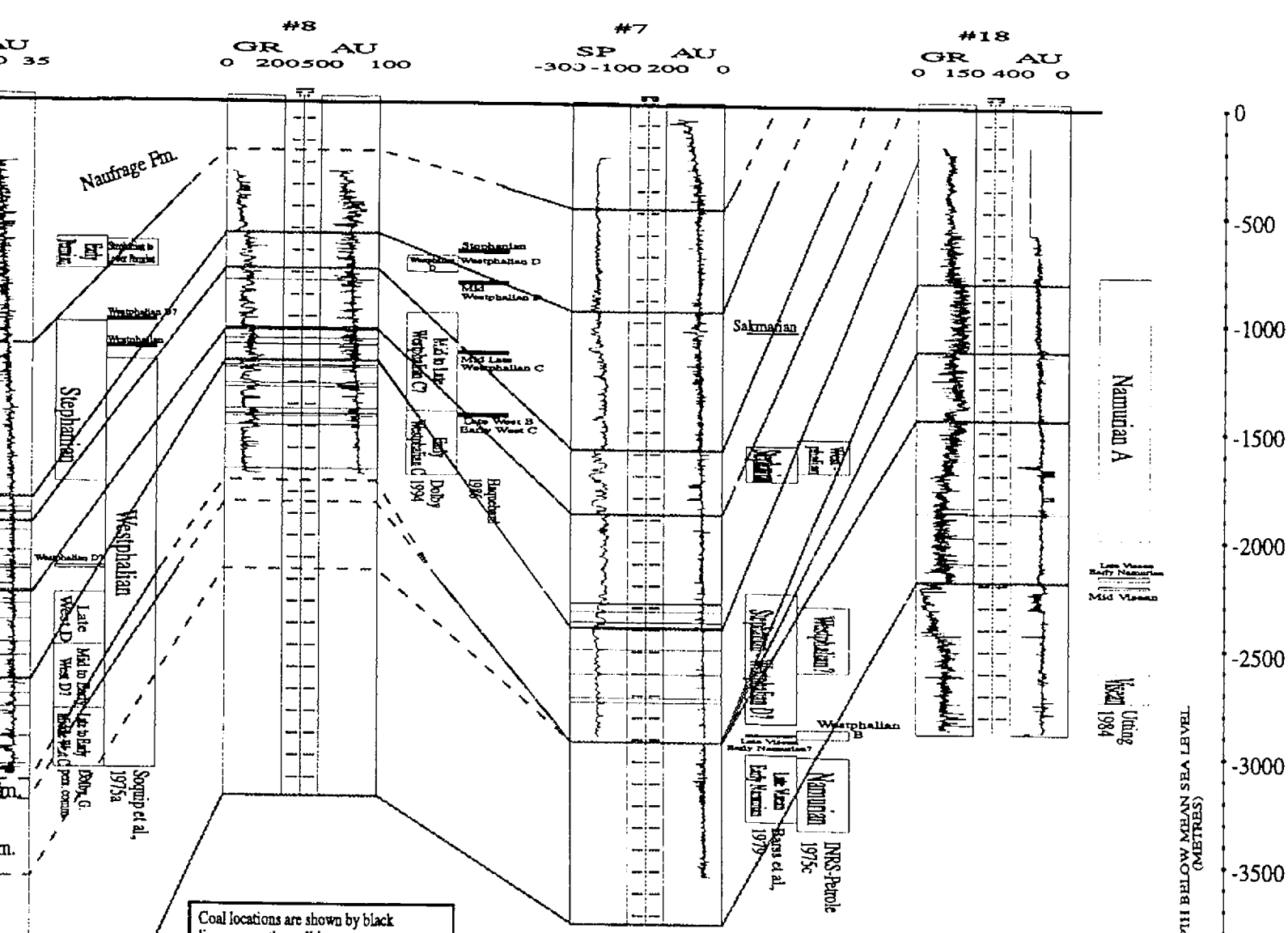

F




# ENCLOSURE #6

CMB Bio/Lithostratigraphic Correlation Cross Section
F - F'

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown



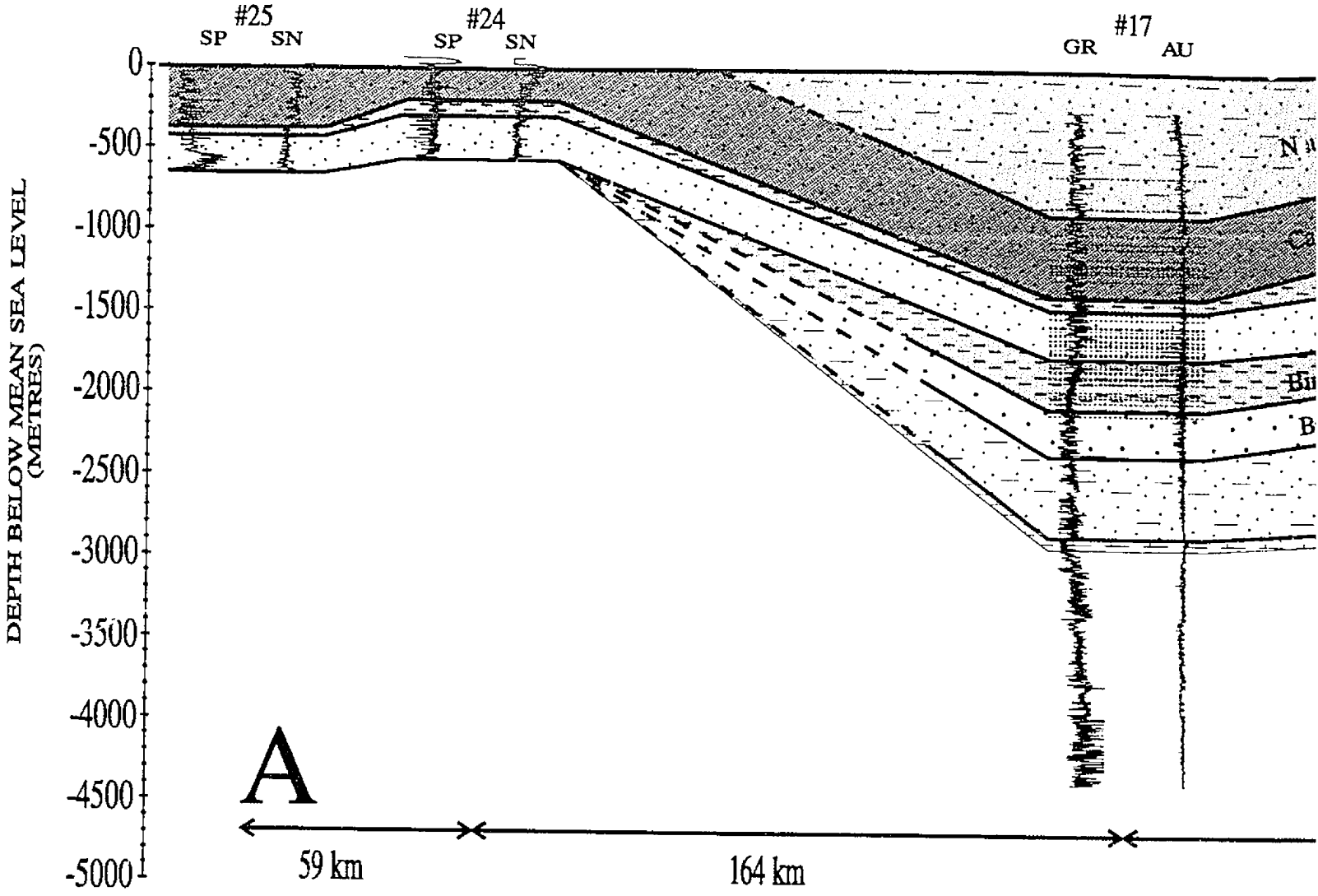

Coal locations are shown by black lines across the well logs.

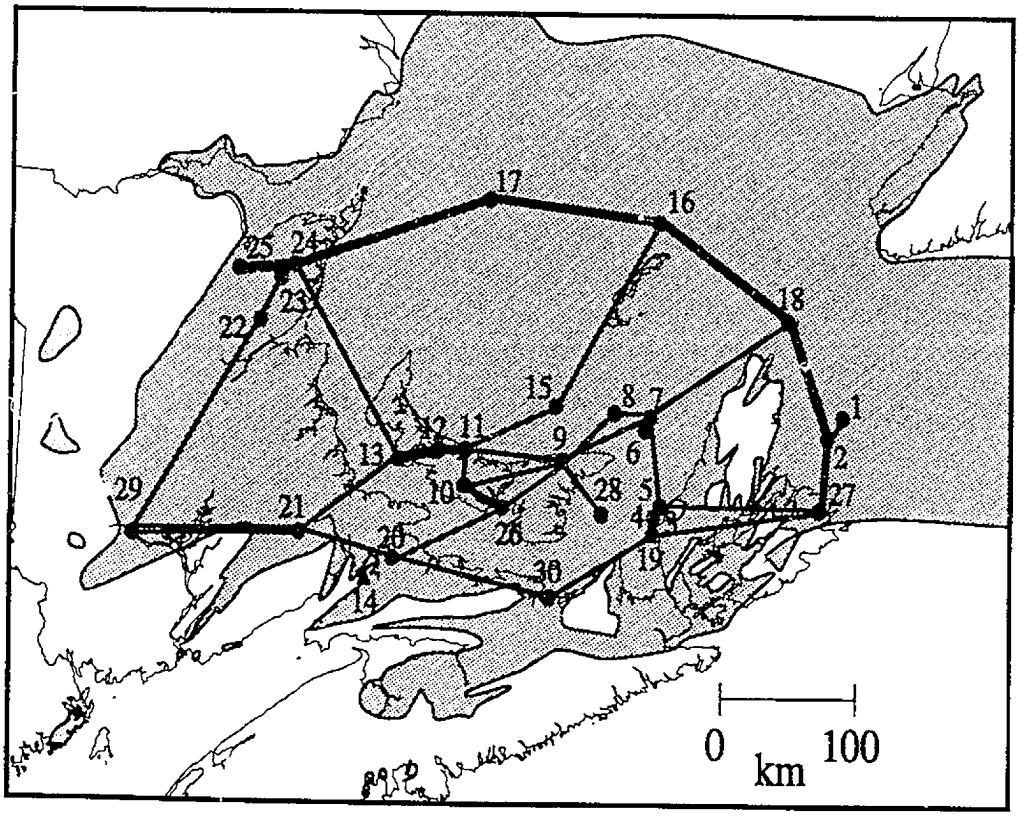
geologic boundary

interpreted geologic boundary

F'

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.3 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 35.0 | 2652.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 51.8 | 3434.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 9.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 9.2 | +110.3 | 4156.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4358.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +82.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-63 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |




Coal locations are shown by black lines across the well logs.

- marine unit
- shaly sand
- coarse sand
- medium sand red beds
- medium sand
- sandy shale red beds
- shale

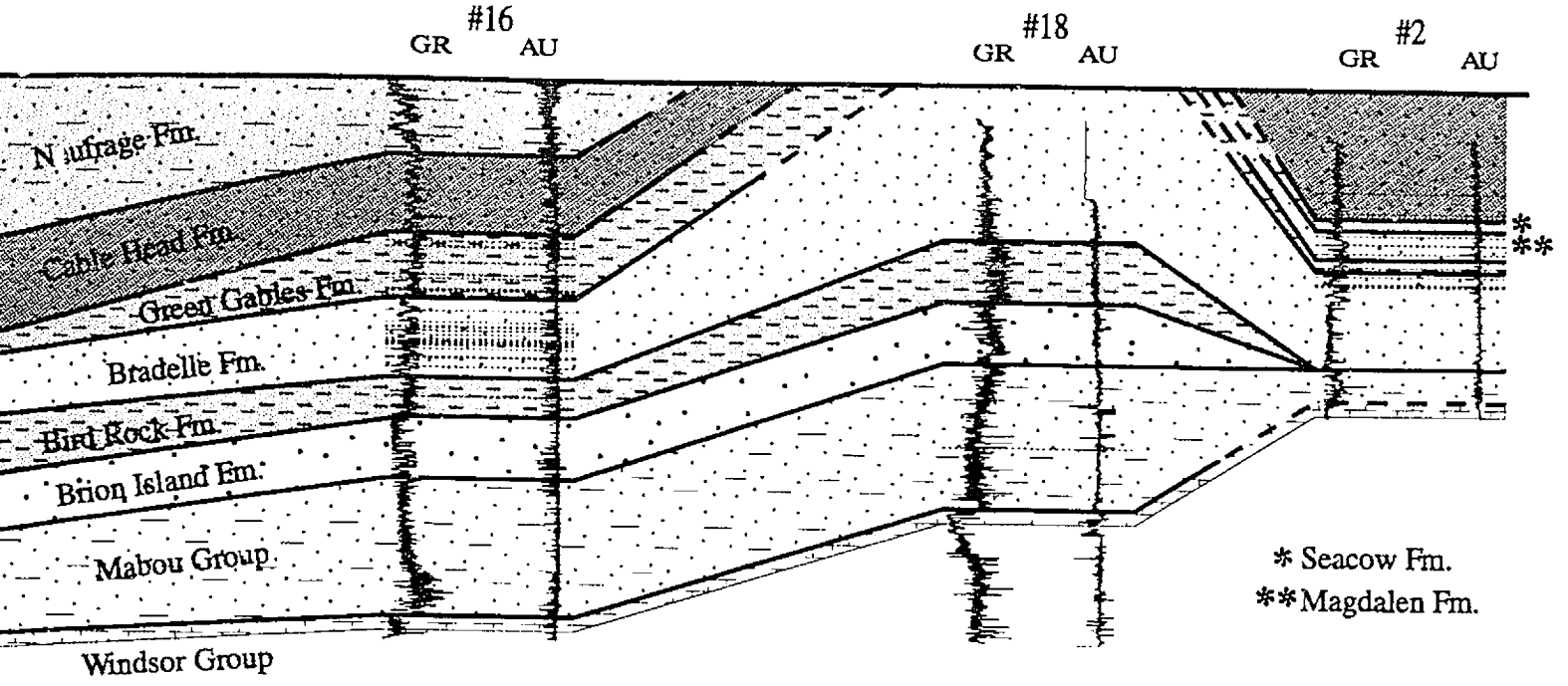
geologic boundary

interpreted geologic boundary

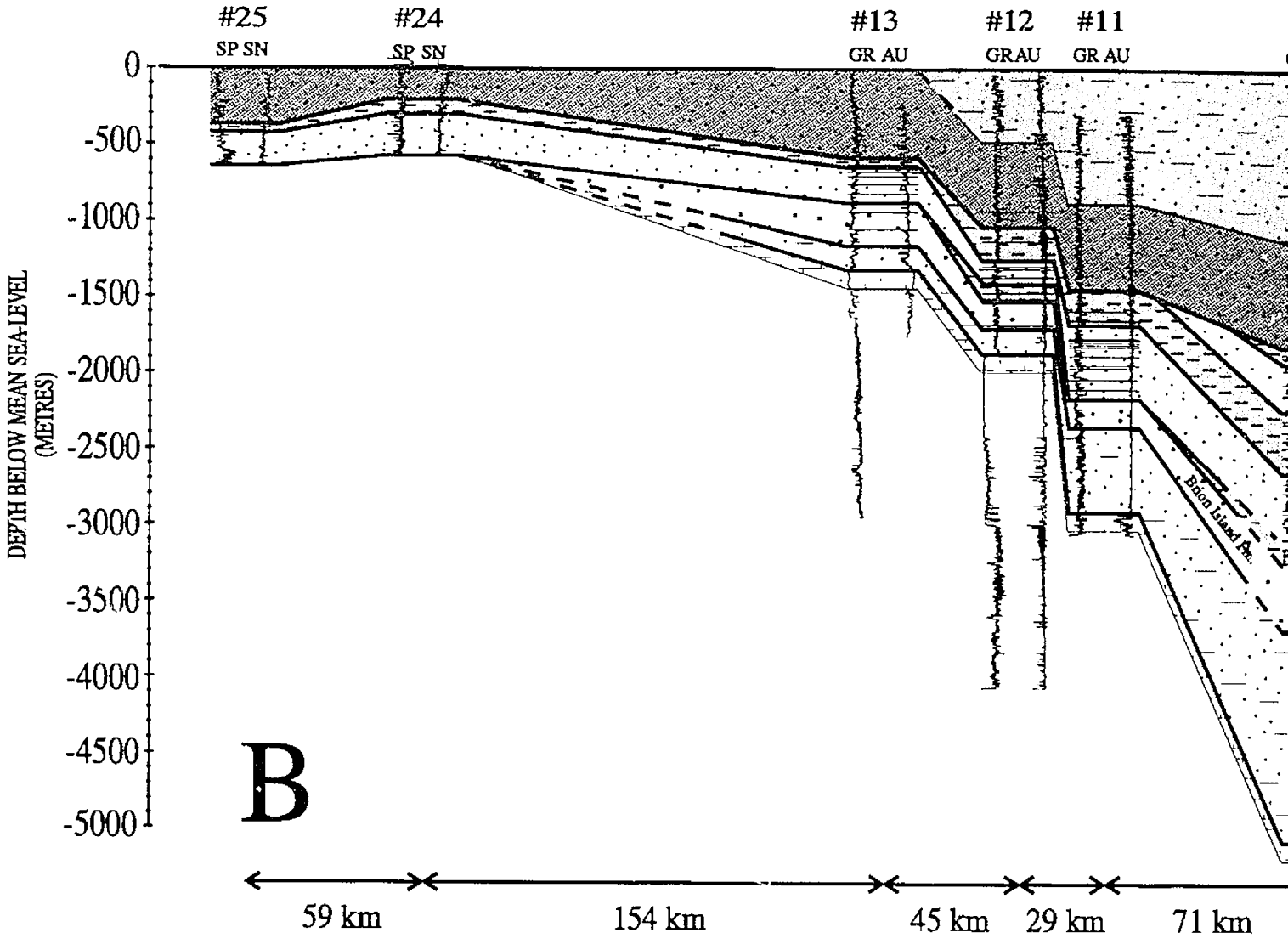
# ENCLOSURE #7

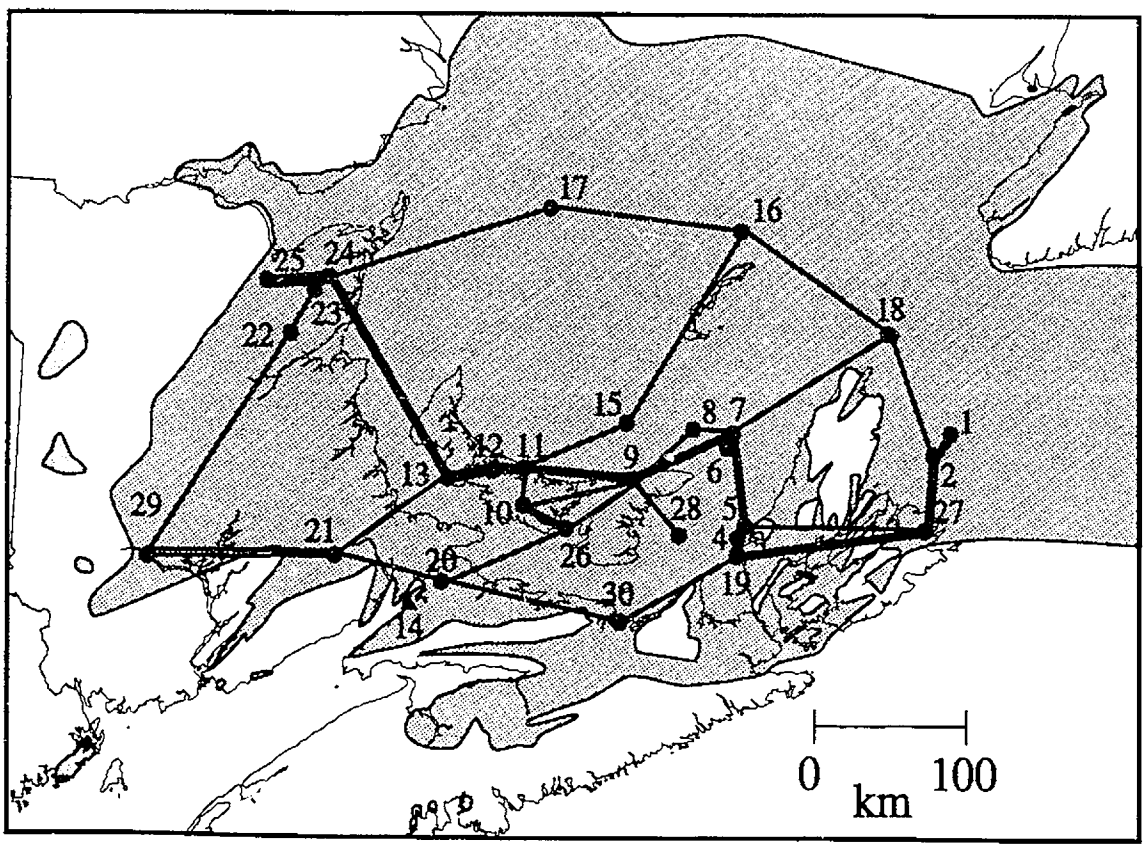
CMB Structural Cross Section
A - A '

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |




Coal locations are shown by black lines across the well logs.

- marine unit
- shaly sand
- coarse sand
- medium sand
- sandy shale red beds
- shale

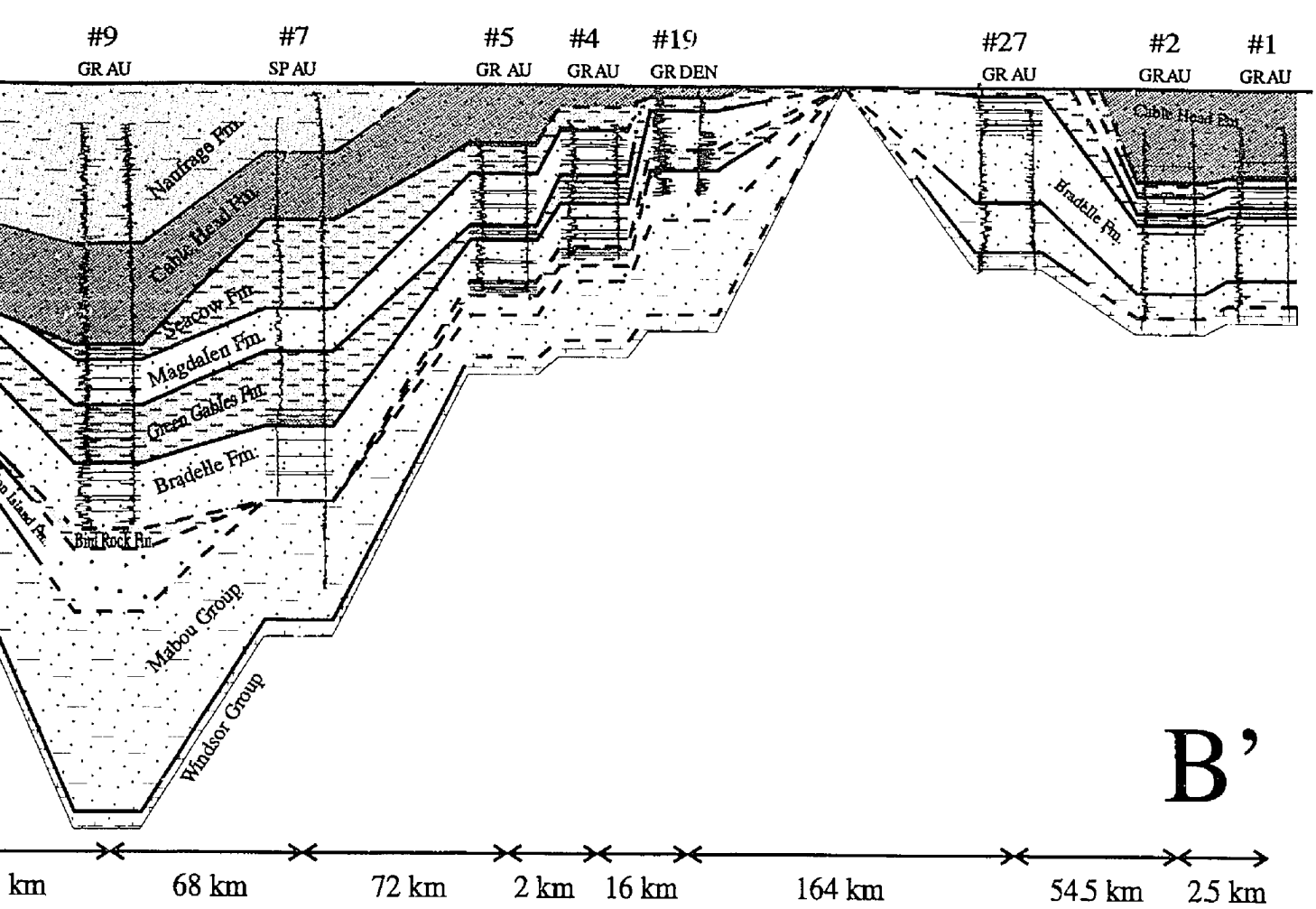
geologic boundary

interpreted geologic boundary

# ENCLOSURE #8

CMB Structural Cross Section B - B'

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




black

shaly sand

medium sand
red beds
sandy shale
red beds

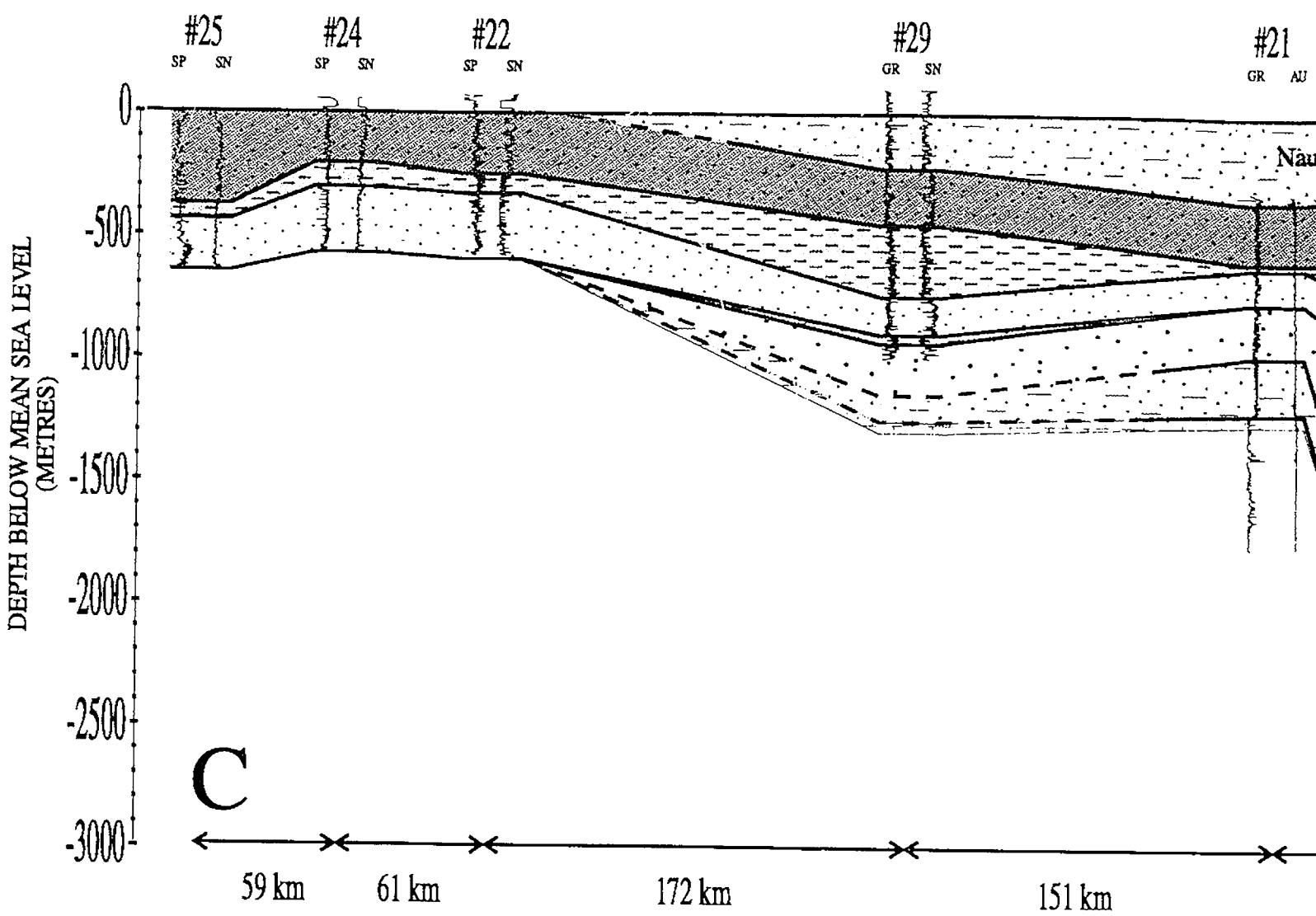
ary
ogic boundary

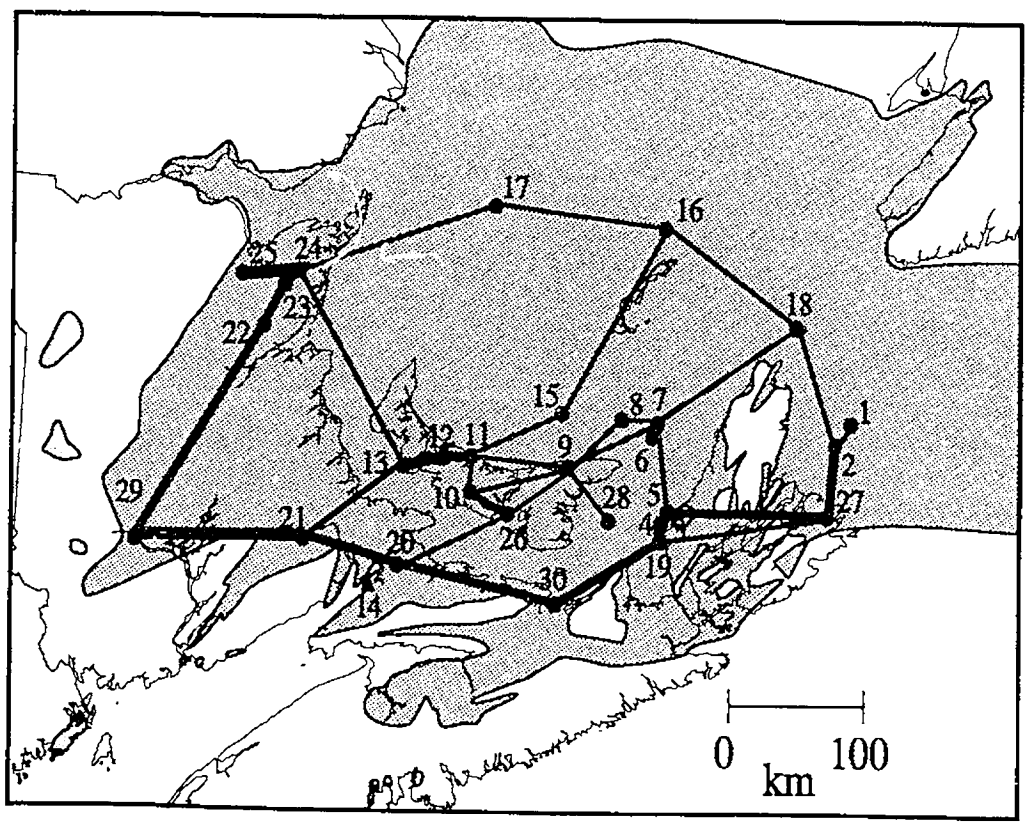
RE #8
oss Section

Rehill
996

own
vn

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6583 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |



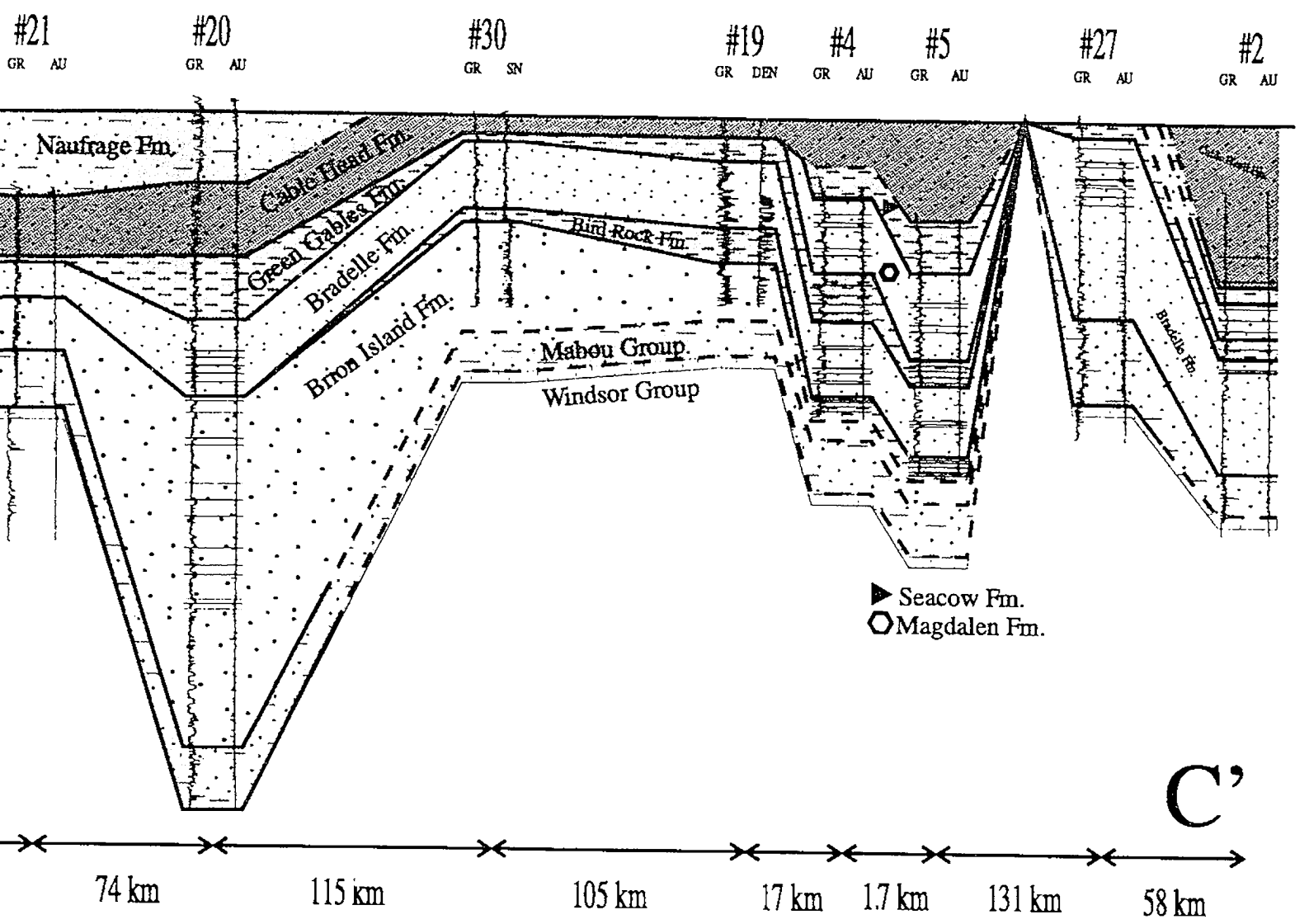

Coal locations are shown by black lines across the well logs.

- marine unit
- shaly sand
- coarse sand
- medium sand red beds
- medium sand
- sandy shale red beds
- shale
- geologic boundary
- interpreted geologic boundary

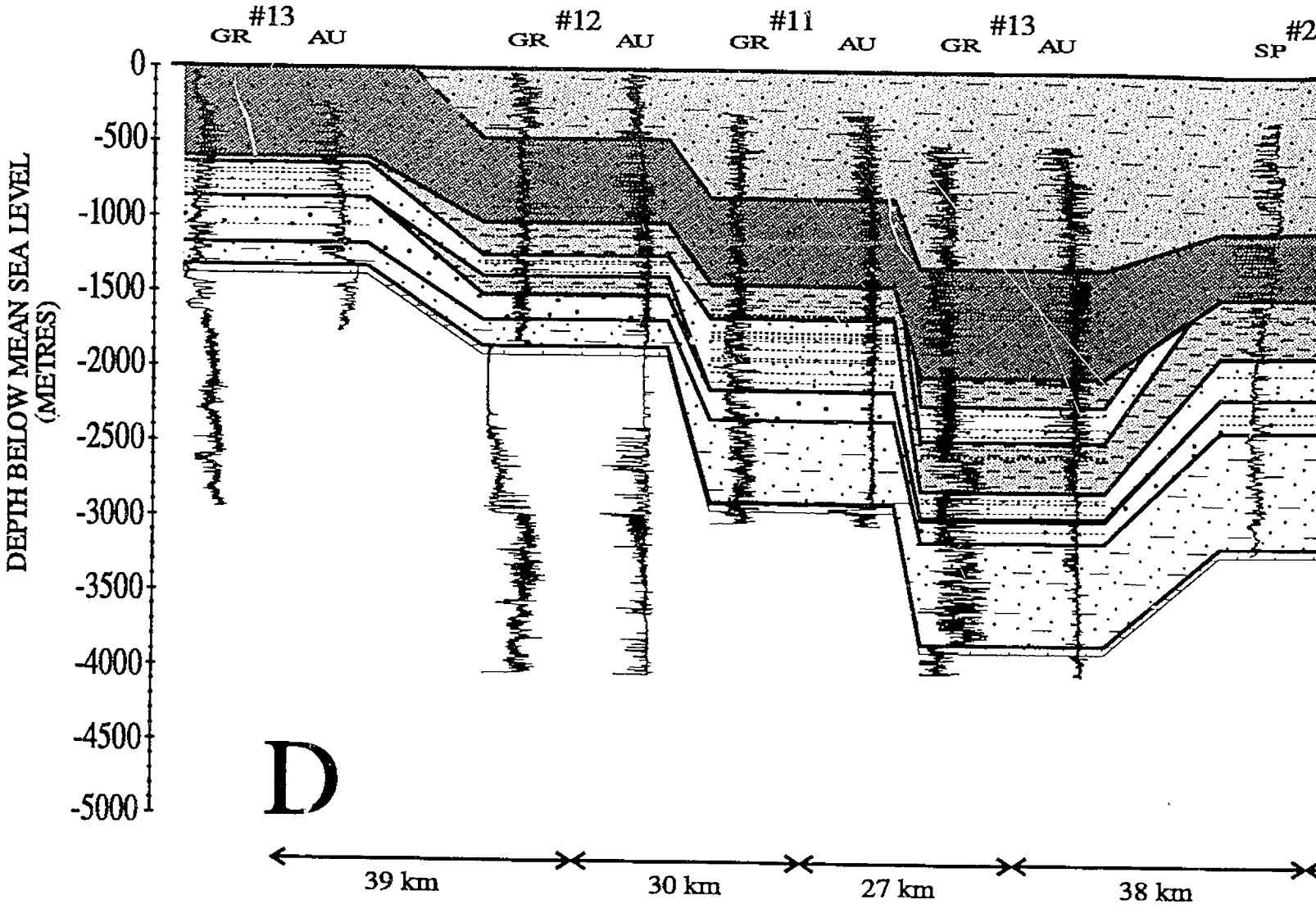
## ENCLOSURE #9

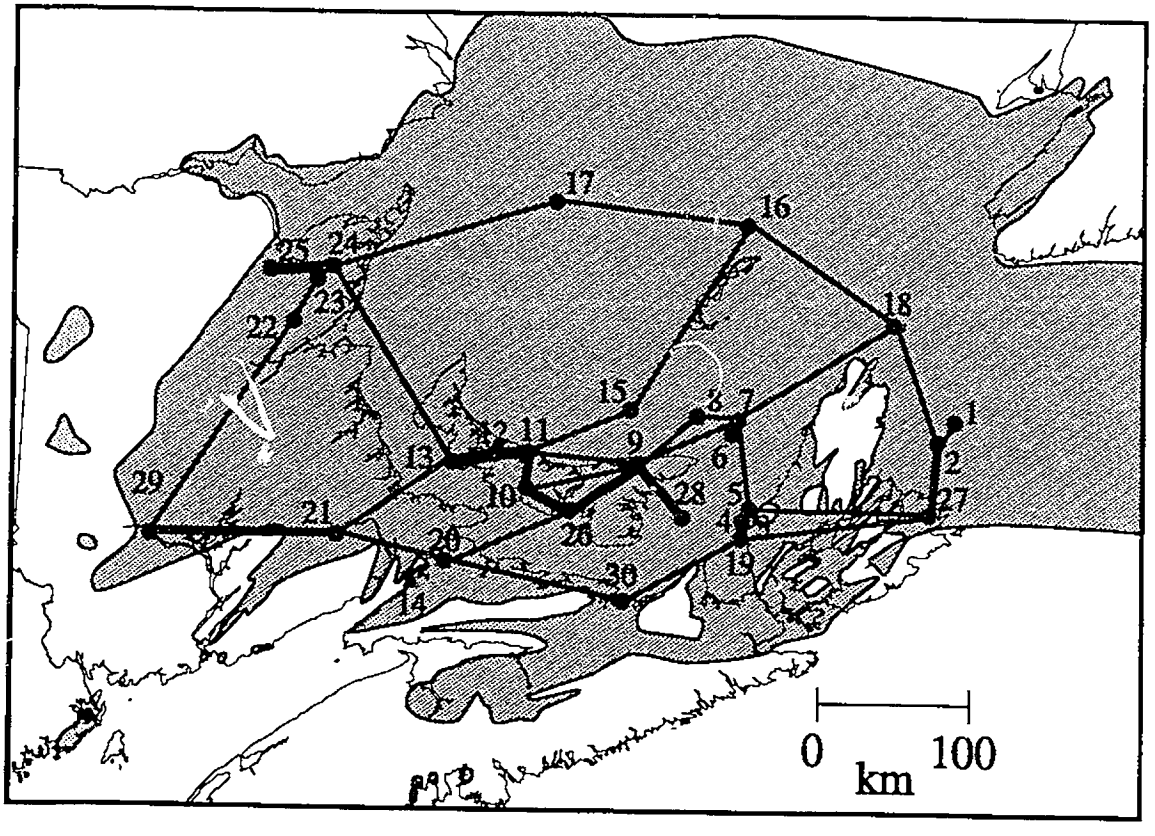
CMB Structural Cross Section
C - C'

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al North Sydney P-05 | 46 57951 | -59 75051 | 10-Aug-74 | 8-Sep-74 | 29 8 | 62 8 | 1641 3 |
| 2 | Shell et al. North Sydney F-24 | 46 55642 | -59 81263 | 9-Jun-76 | 14-Jul-76 | 14 6 | 59 7 | 1686 7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46 12183 | -61 48967 | 1978 | 1978 | 10 4 | 76 6 | 1229 0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464 0 |
| 6 | Hudson's Bay et al East Point E-47 | 46 60414 | -61 625 | 9-Jun-80 | 29-Jul-80 | 25 0 | 85 0 | 2662 0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9 7 | 61 8 | 3484.6 |
| 8 | Hudson's Bay et al Beaton Point F-70 | 46 65553 | -61 91247 | 1-Aug-80 | 27-Aug-80 | 27 6 | 56 2 | 1734 0 |
| 9 | Soquip et al Naufrage No 1 | 46 46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4 1 | +22 2 | 3105 3 |
| 10 | Soquip et al Tyrone No 1 | 46 26942 | -63 33886 | 26-Feb-75 | 19-Jul-77 | 4 2 | +110 3 | 4166 6 |
| 11 | Hudson's Bay-Fina Green Gables No 1 | 46 47744 | -63 36117 | 4-Jun-72 | 11-Sep-72 | 6 4 | +61 9 | 3389 ? |
| 12 | Hudson's Bay-Fina Inshtown No 1 | 46 50107 | -63 60428 | 24-Jan-72 | 5-Apr-72 | 6 4 | 39 9 | 4107 8 |
| 13 | Imperial Wellington Station No 1 | 46 43611 | -64 02361 | 3-Mar-58 | 3-Jul-58 | 5 1 | +12 8 | 2960 8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62 495 | 26-Jun-83 | 7-Sep-83 | 28 0 | 54 7 | 3235 0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4 8 | +6 6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47 97393 | -63 13841 | 7-Sep-73 | 1-Dec-73 | 29 9 | 56 7 | 4368 4 |
| 18 | Petro-Canada et al St Paul P-91 | 47 18278 | -60 22694 | 2-Sep-83 | 31-Dec-83 | 24 9 | 173 6 | 2883.0 |
| 19 | NSDME PH-3 | 45 995 | -61 56 | 1975 | 1975 | 7 5 | +7 5 | 778 0 |
| 20 | Gulf et al. Hastings No 1 | 45 84306 | -64 08139 | 11-Jun-75 | 11-Aug-75 | 18 6 | +74 6 | 2939 5 |
| 21 | Irving Chevron et al Middlesex #1 | 45 97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7 0 | +63 7 | 1835 0 |
| 22 | Hudson's Bay Barnbog No 1 | 47 21278 | -65 40139 | 6-Aug-67 | 29-Aug-67 | 1 5 | +89 0 | 683 1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47 54472 | -65 05806 | 29-Jun-67 | 16-Jul-67 | 1 5 | +62 5 | 732 5 |
| 24 | Hudson's Bay St Isidore No.2 | 47 52667 | -65 16056 | 29-Aug-67 | 12-Sep-67 | 1 5 | +73 8 | 642 2 |
| 25 | Hudson's Bay Blanchard No.1 | 47 71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1 5 | +20 7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46 12417 | -63 08667 | 11-Oct-43 | 5-Dec-44 | 6 4 | 7 3 | 4479 3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46 5 | 1343.6 |
| 28 | Hudson's Bay et al Northumberland Strait F-25 | 46 07365 | -62 06268 | 7-Apr-70 | 11-Jun-70 | 9 4 | 29 9 | 2974 7 |
| 29 | Seru Nucleaire Canada Ltee Fredericton 2 | 45 9322 | -66 6586 | 3-Mar-79 | 26-Apr-79 | 1 5 | +112 5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62 666 | 11-Jun-86 | July, 1986 | 6 0 | +24 0 | 845 0 |




Coal locations are shown by black lines across the well logs.

- marine unit
- shaly sand
- coarse sand
- medium sand red beds
- medium sand
- sandy shale red beds
- shale

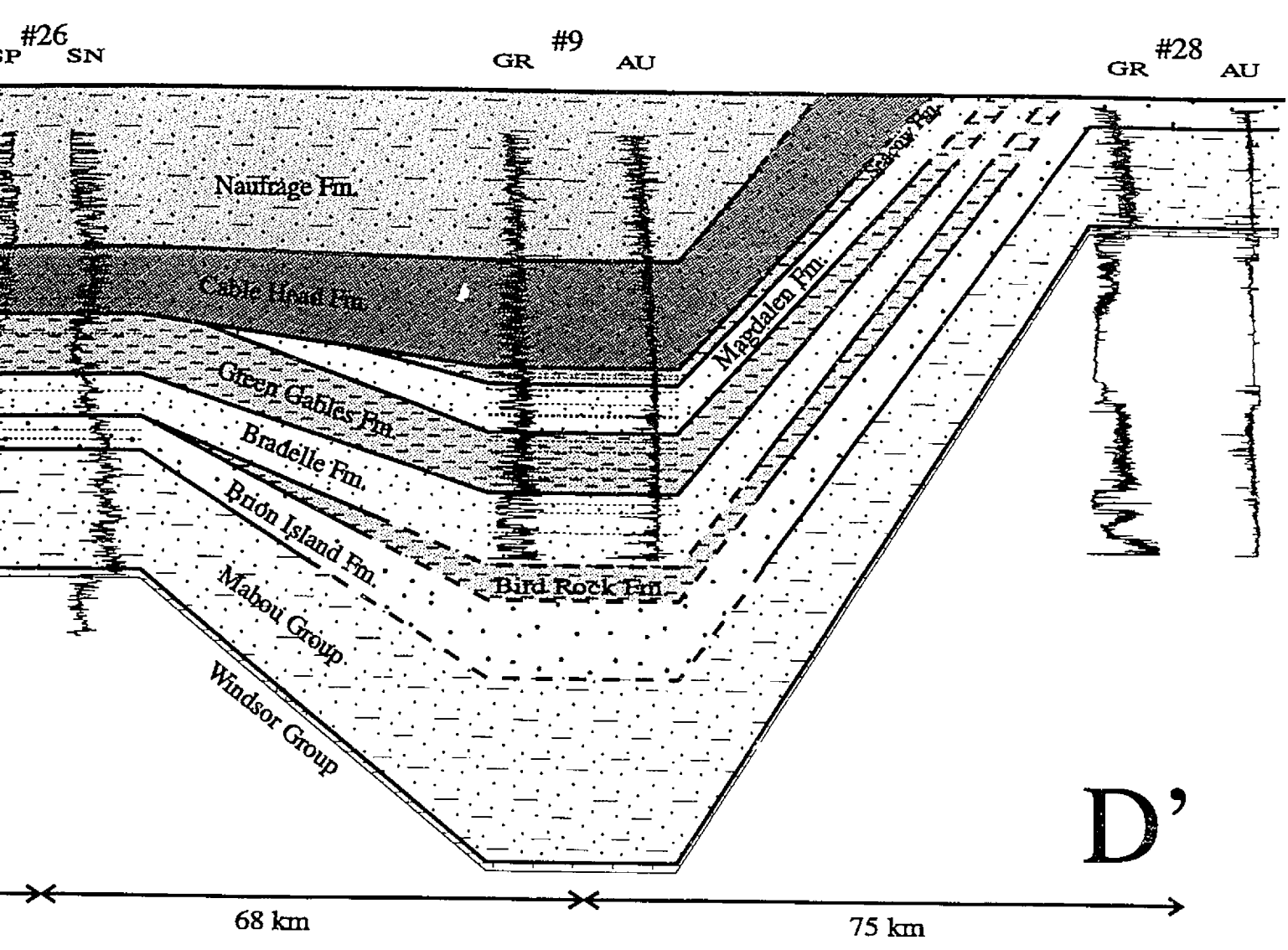
geologic boundary

interpreted geologic boundary

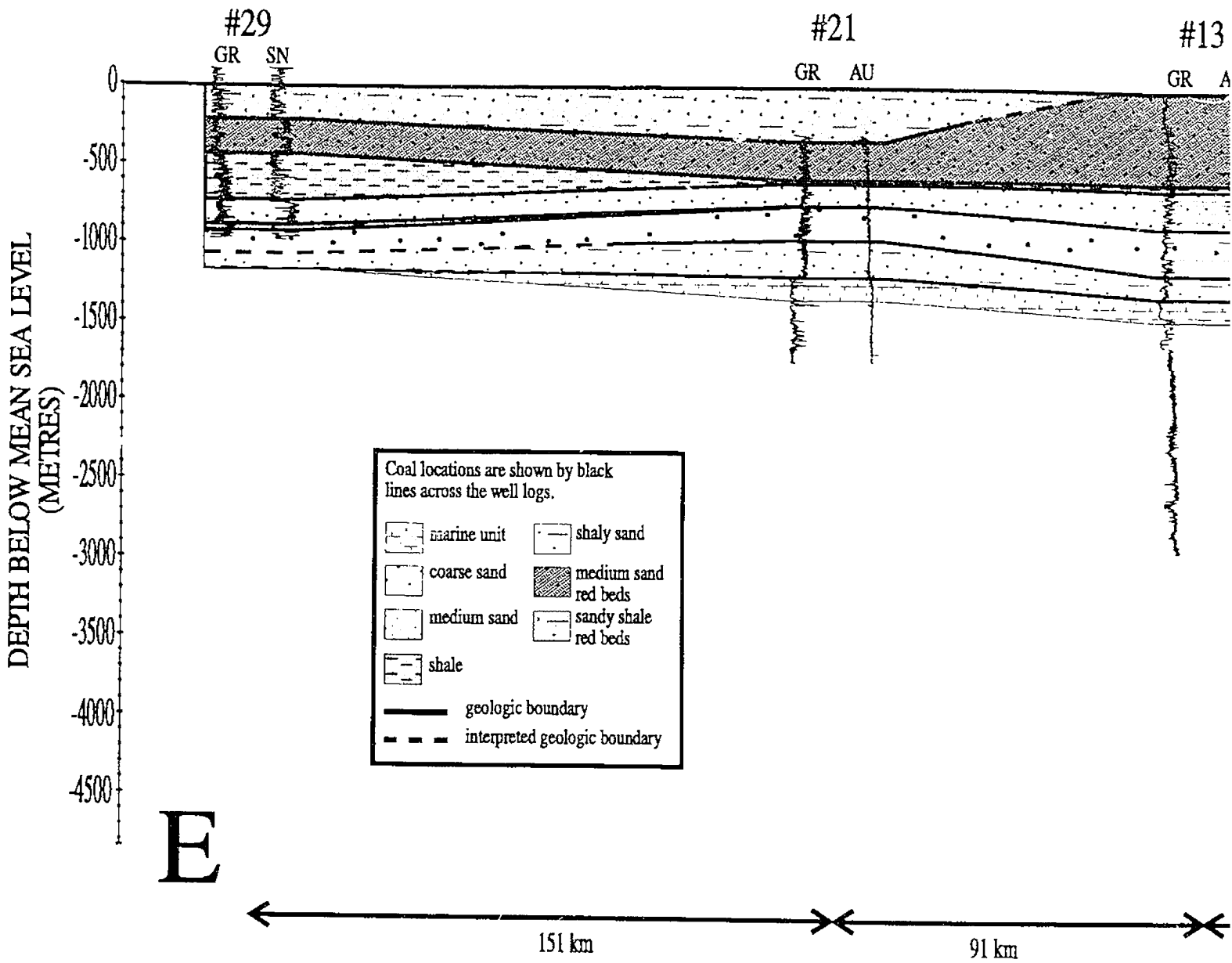
# ENCLOSURE #10

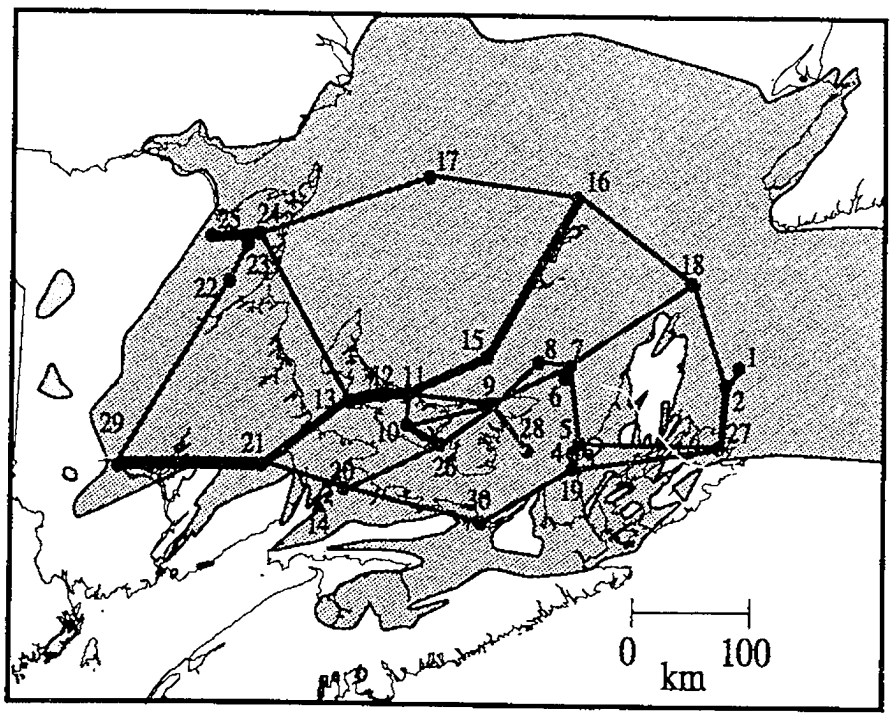
CMB Structural Cross Section
D - D'

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.6 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |

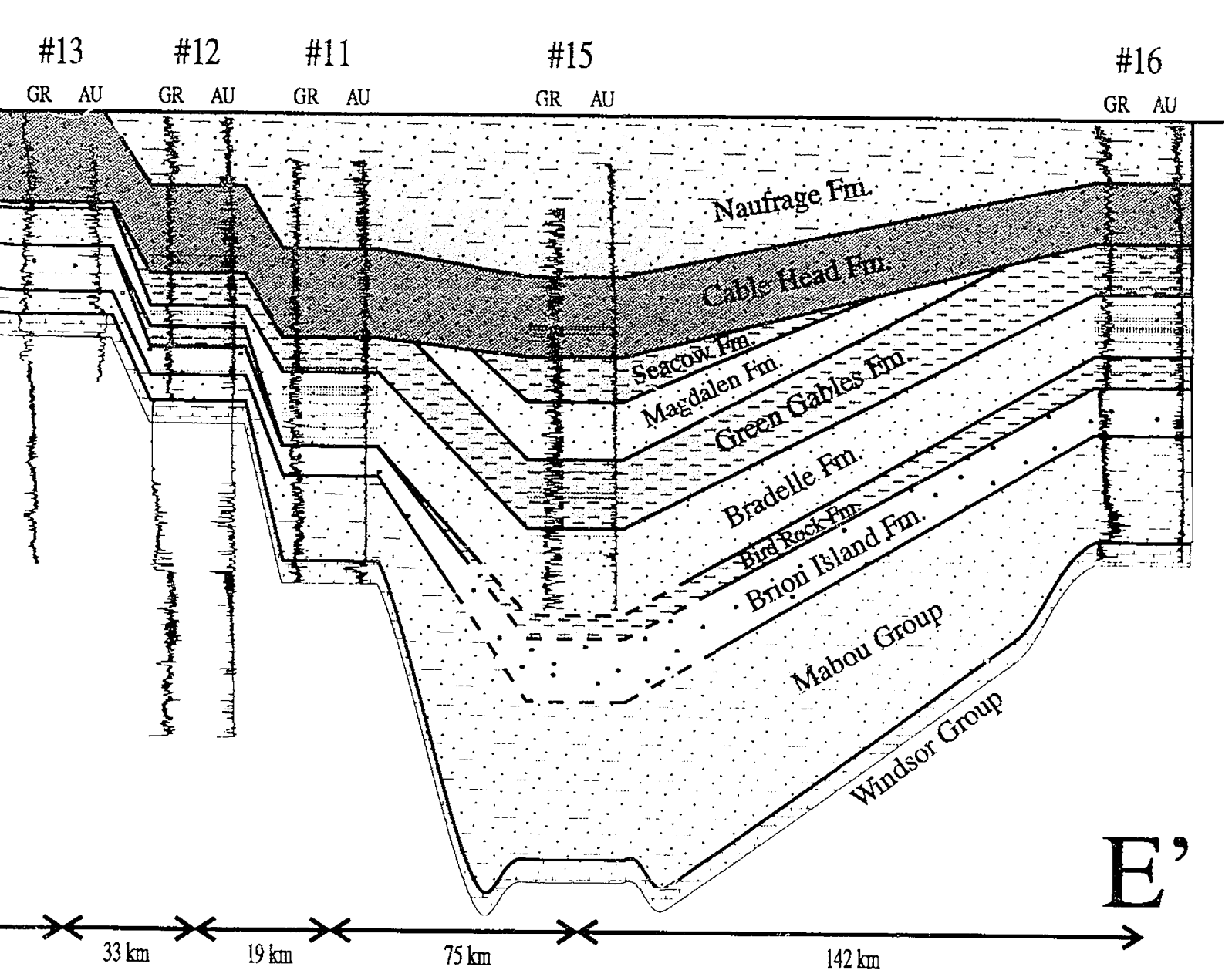


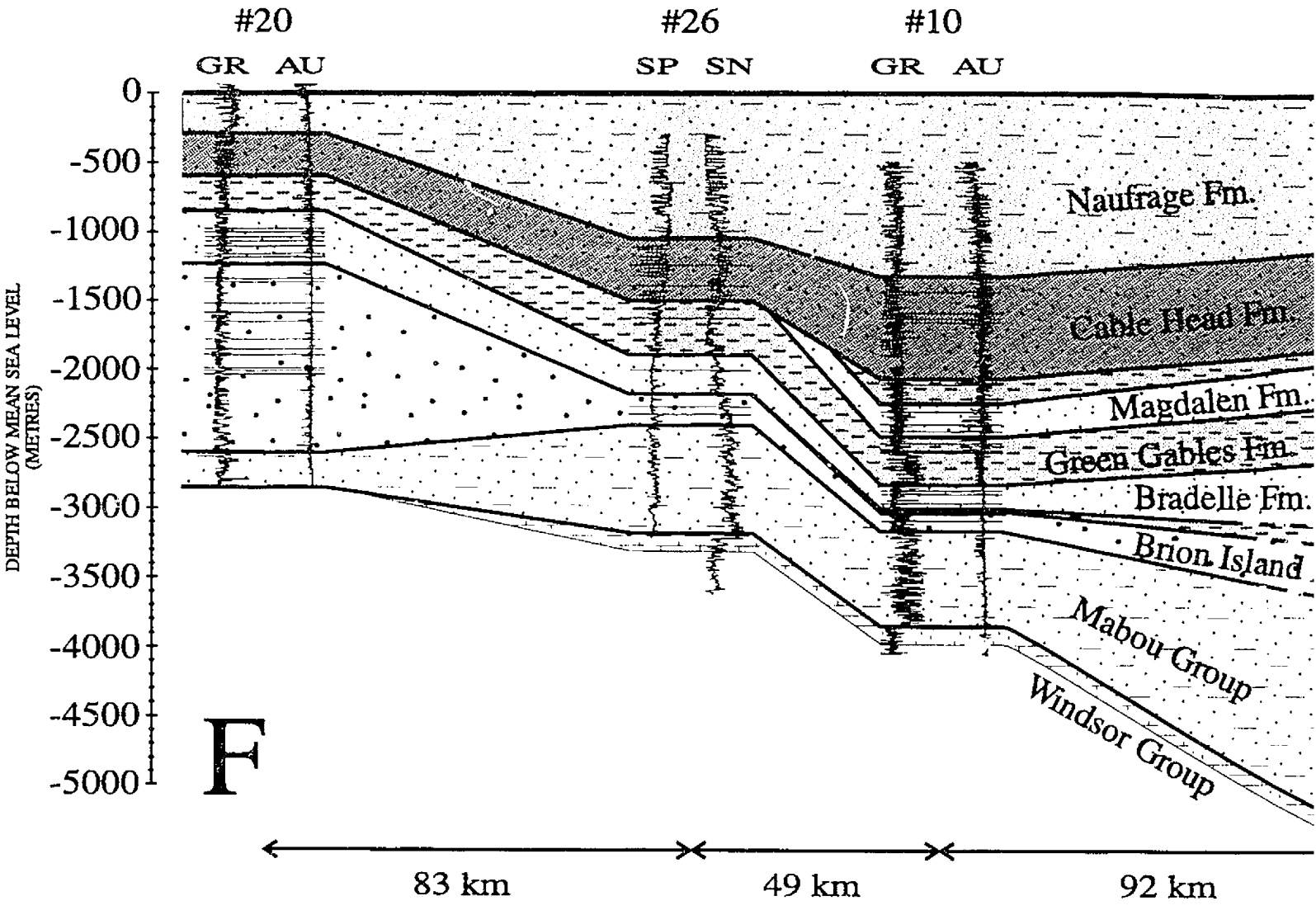

# ENCLOSURE #11

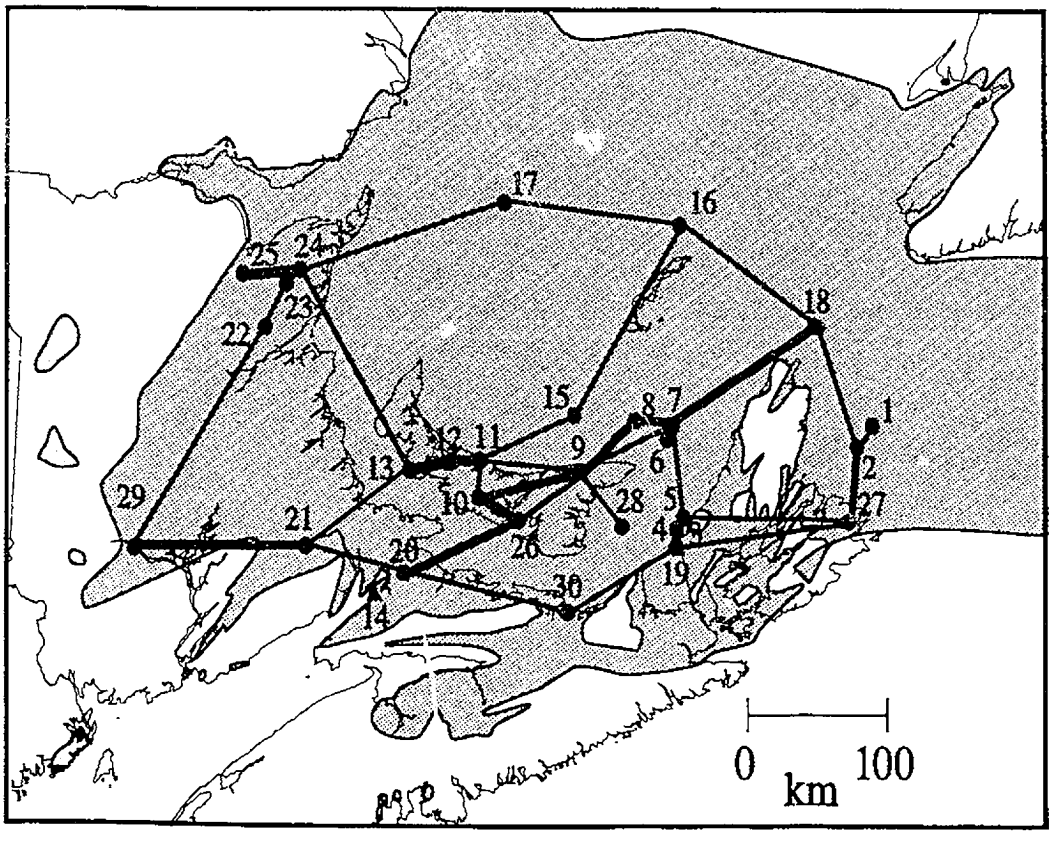
CMB Structural Cross Section
E - E '

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al North Sydney P-05 | 46 57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29 8 | 62 8 | 1641 3 |
| 2 | Shell et al North Sydney F-24 | 46 55642 | 59.81263 | 9 Jun 76 | 14 Jul 76 | 14 6 | 59 7 | 1686 7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46 12183 | -61.48967 | 1978 | 1978 | 10 4 | 76 6 | 1229 0 |
| 5 | NSDME Borehole M-2A | 46 138 | -61.49133 | 1978 | 1978 | 10 4 | 81 0 | 1464 0 |
| 6 | Hudson's Bay et al East Point E-47 | 46 60414 | -61 625 | 9-Jun-80 | 29-Jul-80 | 25 0 | 85 0 | 2662 0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46 63972 | -61 62389 | 26-Jun-70 | 16-Nov-70 | 9 7 | 61 8 | 3484 6 |
| 8 | Hudson's Bay et al Beaton Point F-70 | 46 65553 | -61 91247 | 1-Aug-80 | 27-Aug-80 | 27 6 | 56 2 | 1734 0 |
| 9 | Soquip et al Naufrage No 1 | 46 46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4 1 | +22 2 | 3105 3 |
| 10 | Soquip et al Tyrone No 1 | 46 26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4 2 | +110 3 | 4166 6 |
| 11 | Hudson's Bay-Fina Green Gables No 1 | 46 47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6 4 | +61 9 | 3389 2 |
| 12 | Hudson's Bay-Fina Inishtown No 1 | 46 50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6 4 | 39 9 | 4107 8 |
| 13 | Imperial Wellington Station No 1 | 46 43611 | -64 02361 | 3-Mar-58 | 3-Jul-58 | 5 1 | +12 8 | 2960 8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46 73803 | -62 495 | 26 Jun-83 | 7 Sep 83 | 28 0 | 54 7 | 3235 0 |
| 16 | Sarep H Q Brion Island No 1 | 47 78463 | -61 4661 | 18-Sep-70 | 11-Dec-70 | 4 8 | +6 6 | 3168 7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47 97393 | -63 13841 | 7-Sep-73 | 1 Dec-73 | 29 9 | 56 7 | 4368 4 |
| 18 | Petro-Canada et al St Paul P-91 | 47 18278 | -60 22694 | 2-Sep-83 | 31-Dec-83 | 24 9 | 173 6 | 2883 0 |
| 19 | NSDME PH-3 | 45.995 | -61 56 | 1975 | 1975 | 7 5 | +7 5 | 778.0 |
| 20 | Gulf et al Hastings No 1 | 45 84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18 6 | +74 6 | 2939 5 |
| 21 | Irving Chevron et al Middlesex #1 | 45 97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7 9 | +63 7 | 1835 0 |
| 22 | Hudson's Bay Barnbog No 1 | 47 21278 | -65 40139 | 6-Aug-67 | 29-Aug-67 | 1 5 | +89 0 | 683 1 |
| 23 | Hudson's Bay St Isidore No 1 | 47 54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1 5 | +62 5 | 732 5 |
| 24 | Hudson's Bay St Isidore No 2 | 47 52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1 5 | +73 8 | 642 2 |
| 25 | Hudson's Bay Blanchard No 1 | 47 71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1 5 | +20 7 | 718 9 |
| 26 | Island Development Company Hillsborough No 1 | 46 12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6 4 | 7 3 | 4479.3 |
| 27 | Murphy et al Birch Grove No 1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3 2 | +46 5 | 1343 6 |
| 28 | Hudson's Bay et al Northumberland Strait F-25 | 46 07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9 4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee Fredericton 2 | 45 9322 | -66 6586 | 3-Mar-79 | 26-Apr-79 | 1 5 | +112 5 | 1102.0 |
| 30 | NSDME P-58 | 45 56 | -62 666 | 11-Jun-86 | July, 1986 | 6 0 | +24.0 | 845 0 |




Coal locations are shown by black lines across the well logs.

- marine unit
- shaly sand
- coarse sand
- medium sand red beds
- medium sand
- sandy shale red beds
- shale

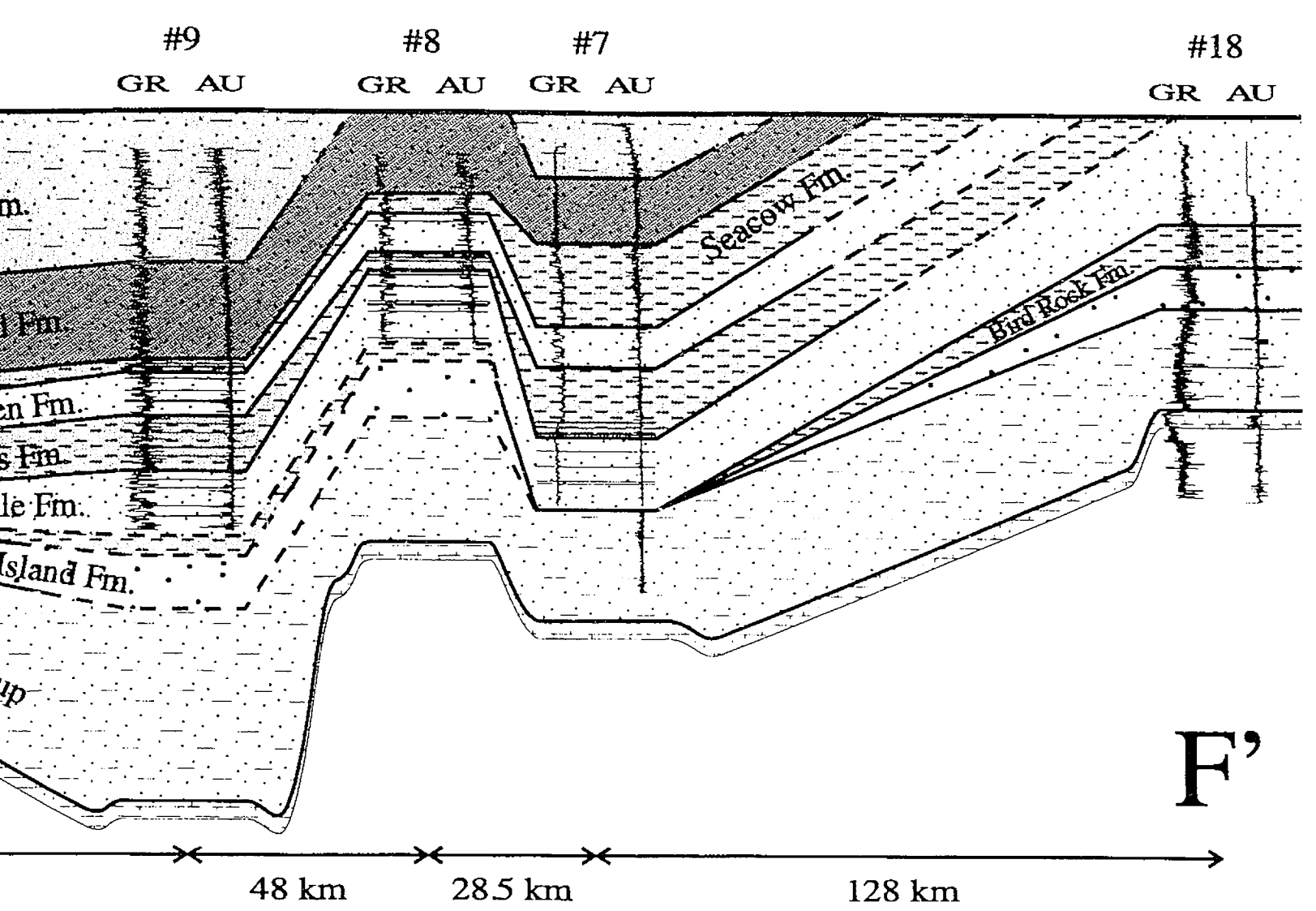
geologic boundary

interpreted geologic boundary

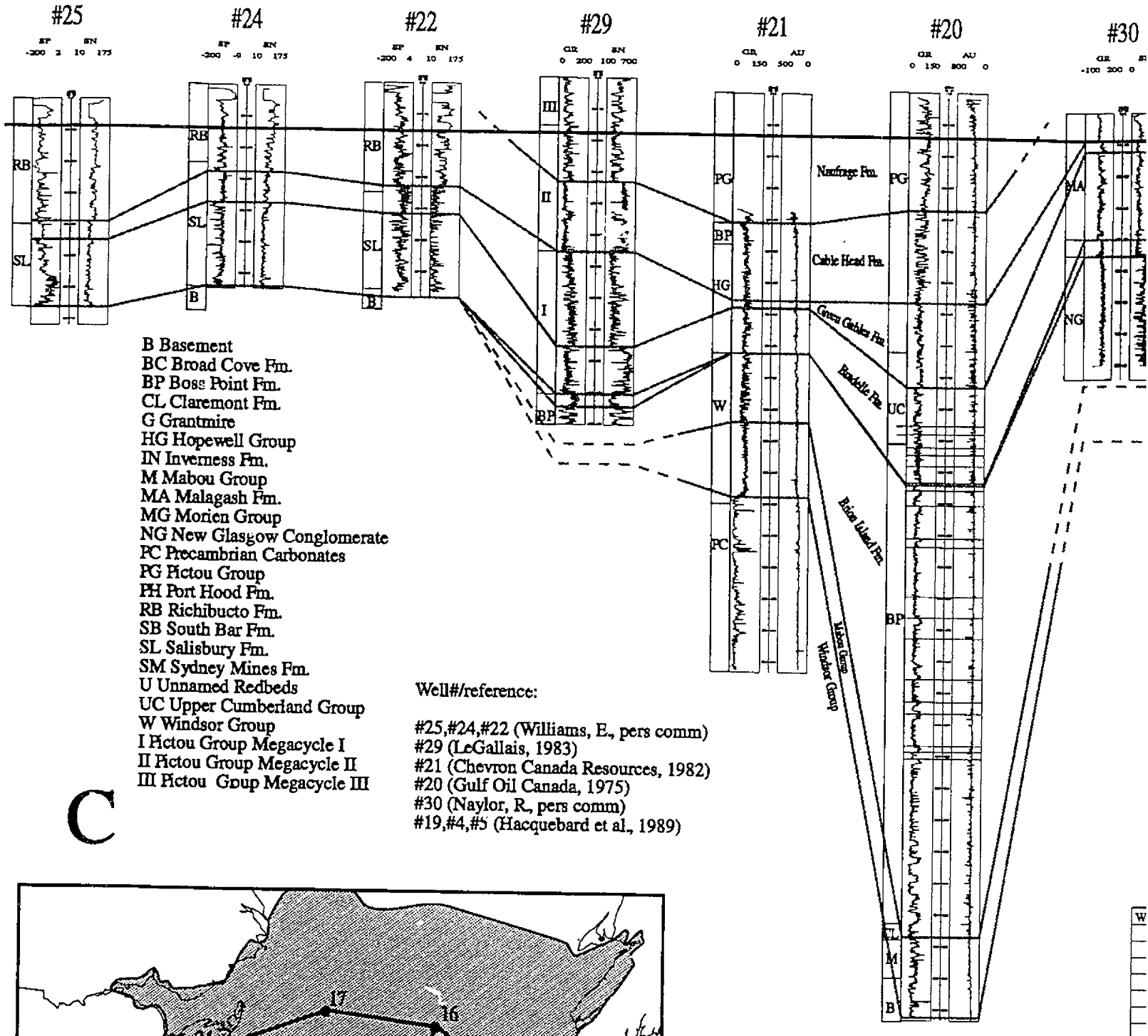
## ENCLOSURE #12

CMB Structural Cross Section
F - F'

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: shown
vertical scale: shown




| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al. North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al. East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.' | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |

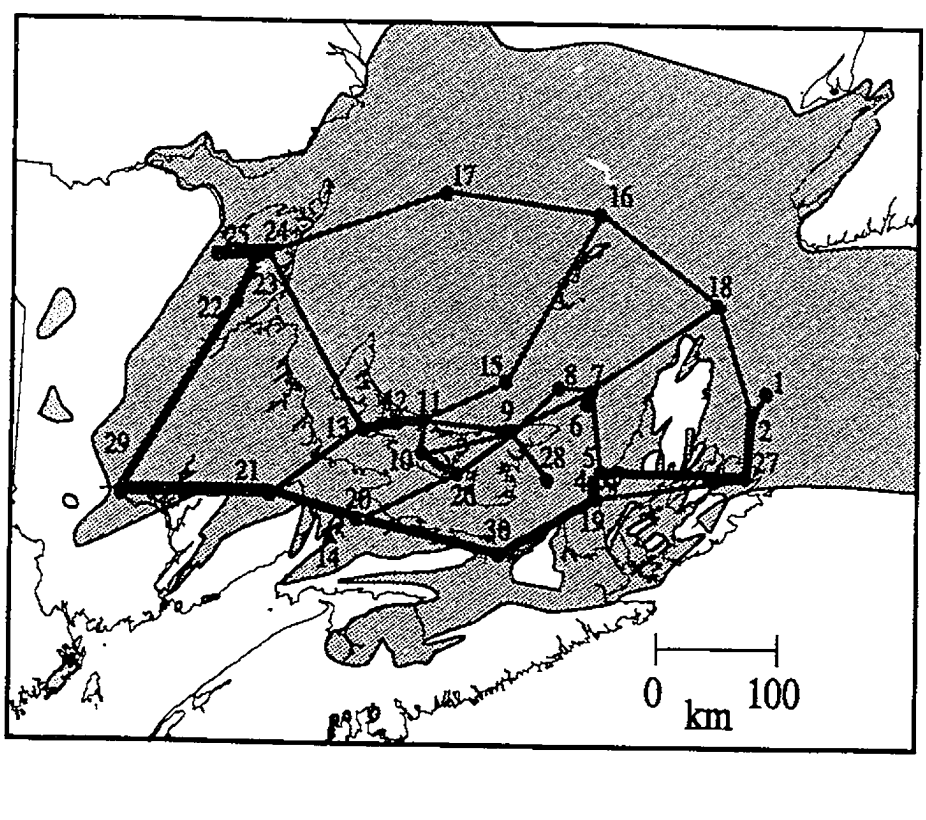



B Basement
BC Broad Cove Fm.
BP Boss Point Fm.
CL Claremont Fm.
G Grantmire
HG Hopewell Group
IN Inverness Fm.
M Mabou Group
MA Malagash Fm.
MG Morien Group
NG New Glasgow Conglomerate
PC Precambrian Carbonates
PG Pictou Group
PH Port Hood Fm.
RB Richibucto Fm.
SB South Bar Fm.
SL Salisbury Fm.
SM Sydney Mines Fm.
U Unnamed Redbeds
UC Upper Cumberland Group
W Windsor Group
I Pictou Group Megacycle I
II Pictou Group Megacycle II
III Pictou Group Megacycle III

Well#/reference:

#25,#24,#22 (Williams, E., pers comm)
#29 (LeGallais, 1983)
#21 (Chevron Canada Resources, 1982)
#20 (Gulf Oil Canada, 1975)
#30 (Naylor, R., pers comm)
#19,#4,#5 (Hacquebard et al., 1989)

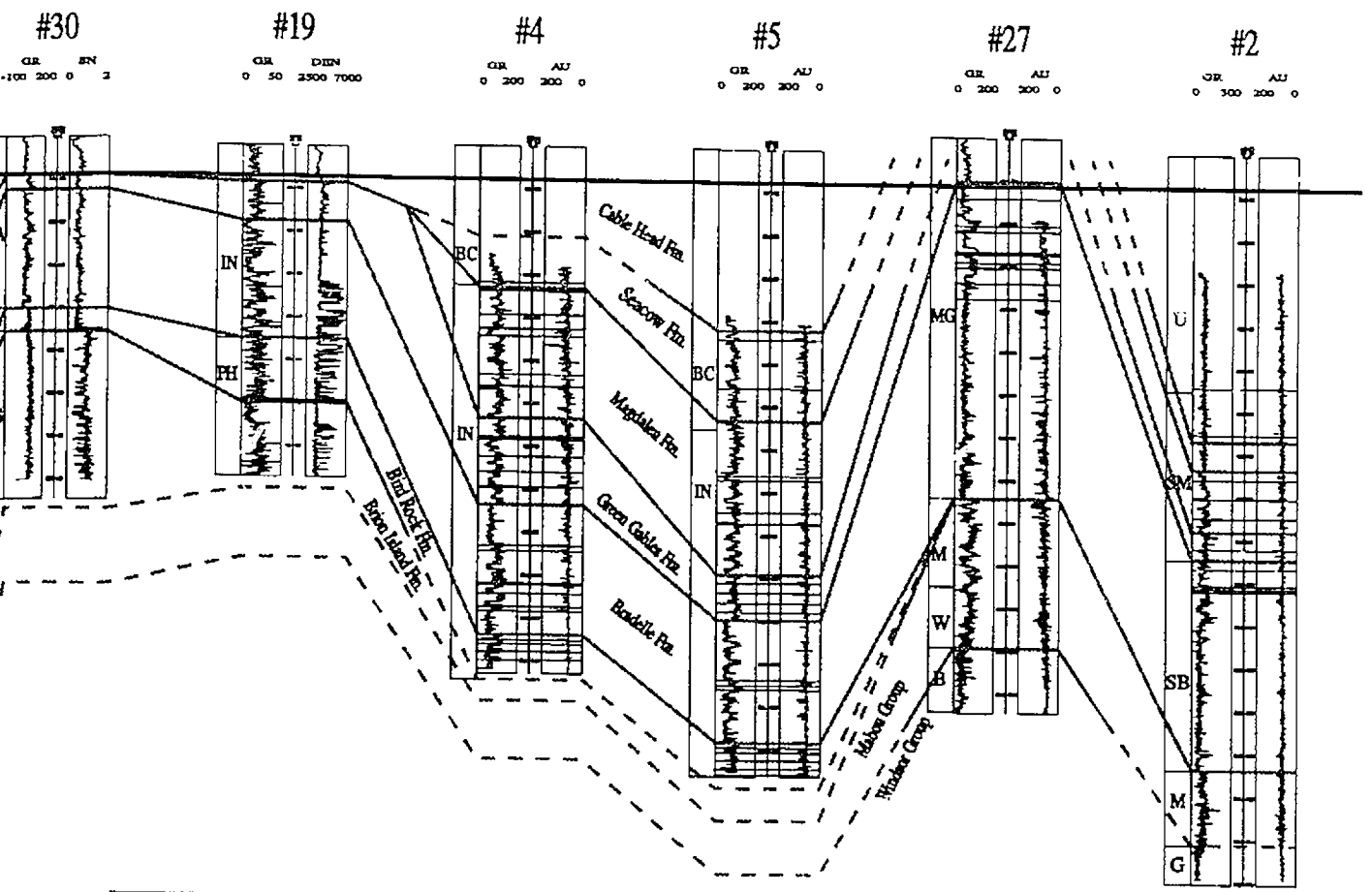
C

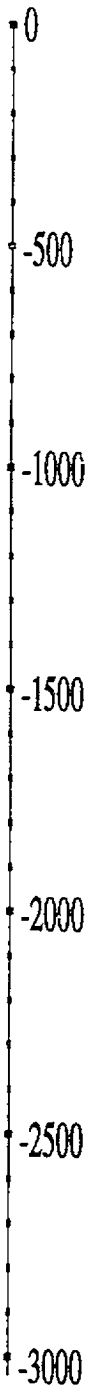



# ENCLOSURE #13

**CMB Bio/Lithostratigraphic Onshore/Offshore Correlations Cross-Section C - C'**

drawn by: Trent A. Rehill
date: January 23, 1996
datum: sea level
horizontal scale: none
vertical scale: shown




Coal locations are shown by black lines across the well logs.

——— geologic boundary

– – – interpreted geologic boundary

C'

| Well # | Well Name | Latitude | Longitude | Spud Date | Rig Release Date | Rotary Table (m) | Water Depth (m) | Total Depth (m) |
|---|---|---|---|---|---|---|---|---|
| 1 | Murphy et al. North Sydney P-05 | 46.57951 | -59.75051 | 10-Aug-74 | 8-Sep-74 | 29.8 | 62.8 | 1641.3 |
| 2 | Shell et al North Sydney F-24 | 46.55642 | -59.81263 | 9-Jun-76 | 14-Jul-76 | 14.6 | 59.7 | 1686.7 |
| 3 | Mabou Mines Coastal Section | | | | | | | |
| 4 | NSDME Borehole M-1 | 46.12183 | -61.48967 | 1978 | 1978 | 10.4 | 76.6 | 1229.0 |
| 5 | NSDME Borehole M-2A | 46.138 | -61.49133 | 1978 | 1978 | 10.4 | 81.0 | 1464.0 |
| 6 | Hudson's Bay et al East Point E-47 | 46.60414 | -61.625 | 9-Jun-80 | 29-Jul-80 | 25.0 | 85.0 | 2662.0 |
| 7 | Hudson's Bay-Fina East Point E-49 | 46.63972 | -61.62389 | 26-Jun-70 | 16-Nov-70 | 9.7 | 61.8 | 3484.6 |
| 8 | Hudson's Bay et al. Beaton Point F-70 | 46.65553 | -61.91247 | 1-Aug-80 | 27-Aug-80 | 27.6 | 56.2 | 1734.0 |
| 9 | Soquip et al. Naufrage No.1 | 46.46833 | -62.46417 | 29-Aug-75 | 23-Oct-75 | 4.1 | +22.2 | 3105.3 |
| 10 | Soquip et al. Tyrone No.1 | 46.26942 | -63.33886 | 26-Feb-75 | 19-Jul-77 | 4.2 | +110.3 | 4166.6 |
| 11 | Hudson's Bay-Fina Green Gables No.1 | 46.47744 | -63.36117 | 4-Jun-72 | 11-Sep-72 | 6.4 | +61.9 | 3389.2 |
| 12 | Hudson's Bay-Fina Irishtown No.1 | 46.50107 | -63.60428 | 24-Jan-72 | 5-Apr-72 | 6.4 | 39.9 | 4107.8 |
| 13 | Imperial Wellington Station No.1 | 46.43611 | -64.02361 | 3-Mar-58 | 3-Jul-58 | 5.1 | +12.8 | 2960.8 |
| 14 | Cumberland Basin Coastal Section | | | | | | | |
| 15 | Irving-Chevron-Texaco Cable Head E-95 | 46.73803 | -62.495 | 26-Jun-83 | 7-Sep-83 | 28.0 | 54.7 | 3235.0 |
| 16 | Sarep H.Q. Brion Island No.1 | 47.78463 | -61.4661 | 18-Sep-70 | 11-Dec-70 | 4.8 | +6.6 | 3168.7 |
| 17 | Shell-Soquip-Amoco Bradelle L-49 | 47.97393 | -63.13841 | 7-Sep-73 | 1-Dec-73 | 29.9 | 56.7 | 4368.4 |
| 18 | Petro-Canada et al. St. Paul P-91 | 47.18278 | -60.22694 | 2-Sep-83 | 31-Dec-83 | 24.9 | 173.6 | 2883.0 |
| 19 | NSDME PH-3 | 45.995 | -61.56 | 1975 | 1975 | 7.5 | +7.5 | 778.0 |
| 20 | Gulf et al. Hastings No.1 | 45.84306 | -64.08139 | 11-Jun-75 | 11-Aug-75 | 18.6 | +74.6 | 2939.5 |
| 21 | Irving Chevron et al. Middlesex #1 | 45.97772 | -65.00256 | 24-Aug-82 | 16-Oct-82 | 7.0 | +63.7 | 1835.0 |
| 22 | Hudson's Bay Bartibog No.1 | 47.21278 | -65.40139 | 6-Aug-67 | 29-Aug-67 | 1.5 | +89.0 | 683.1 |
| 23 | Hudson's Bay St. Isidore No.1 | 47.54472 | -65.05806 | 29-Jun-67 | 16-Jul-67 | 1.5 | +62.5 | 732.5 |
| 24 | Hudson's Bay St. Isidore No.2 | 47.52667 | -65.16056 | 29-Aug-67 | 12-Sep-67 | 1.5 | +73.8 | 642.2 |
| 25 | Hudson's Bay Blanchard No.1 | 47.71333 | -65.89556 | 16-Jul-67 | 4-Aug-67 | 1.5 | +20.7 | 718.9 |
| 26 | Island Development Company Hillsborough No.1 | 46.12417 | -63.08667 | 11-Oct-43 | 5-Dec-44 | 6.4 | 7.3 | 4479.3 |
| 27 | Murphy et al. Birch Grove No.1 | 46.14511 | -59.93473 | 2-Feb-68 | 20-May-68 | 3.2 | +46.5 | 1343.6 |
| 28 | Hudson's Bay et al. Northumberland Strait F-25 | 46.07365 | -62.06268 | 7-Apr-70 | 17-Jun-70 | 9.4 | 29.9 | 2974.7 |
| 29 | Seru Nucleaire Canada Ltee. Fredericton 2 | 45.9322 | -66.6586 | 3-Mar-79 | 26-Apr-79 | 1.5 | +112.5 | 1102.0 |
| 30 | NSDME P-58 | 45.56 | -62.666 | 11-Jun-86 | July, 1986 | 6.0 | +24.0 | 845.0 |