METALLOGENETIC AND THERMAL EVOLUTION OF THE UPPER PALEOZOIC MARITIMES BASIN: EVIDENCE FROM THE CUMBERLAND BASIN OF NOVA SCOTIA

BY

ROBERT JAMES RYAN

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TO MY WIFE ANNE-MARIE AND MY CHILDREN

FIONA, KERRIANNE AND ERIN

For their patience and unde. · ıanding

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ABSTRACT

The Cumberland Basin is the largest onland segment of the Late Paleozoic Maritimes Basin. The Maritimes Basin is made up of up to 7 km of primarily continental clastic strata that presently cover a large area of onshore and offshore Atlantic Canada. The basin is host to significant resources of metallic minerals, industrial minerals and coal. In addition to these resources the basin has recently been the focus of exploration for coal bed methane. A better assessment of the mineral potential is made possible by the clearer understanding of the thermal and metallogenetic evolution of the basin derived from this study. This thesis integrates four separate, but interdependent components: 1) geological constraints from the stratigraphy, sedimentology, and structure, 2) a detailed thermochronological study including apatite fission track analysis, 3) a study of the metallic mineral occurrences of the Cumberland Basin, and 4) an evaluation of time-temperature constraints which were applied to the metallogenetic models.

Quantitative thermochronological evidence presented here suggests that an additional 1 to 4 km of strata were deposited throughout the Maritimes Basin and subsequently eroded. These sediments accumulated to a maximum thickness in the Permian (ca. 280 Ma), and were eroded during an exhumation that preceded the Triassic/Jurassic rifting of the Atlantic margin (ca. 200 Ma).

Redbed hosted Cu-Ag (± U-Pb-Zn) deposits of the Cumberland Basin are genetically related to the process of diagenetic reddening (hematitization) that affected the strata. This reddening developed during the Permo-Triassic exhumation of the basin, when gravity driven oxygenated groundwaters leached metals from the sandstones and conglomerates, and concentrated them in areas rich in reductants.

The time-temperature history reconstructed for the basin poses strict constraints to the time of maximum coalification of peat in Carboniferous strata (280 Ma), and to models of fluid-expulsion and Zn-Pb-barite mineralization in Carboniferous carbonates (pre maximum burial: pre-280 Ma). The peak temperatures in the basin were attained in the Permian, consequently any syn-sedimentary or early diagenetic mineralization that might exist has been thermally modified, and may be difficult to recognize or date accurately.

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CHAPTER I

GEOLOGICAL SETTING

1.1 INTRODUCTION

1.1.1 GENERAL STATEMENT

The Cumberland Basin is a segment of the Maritimes Basin, a large Upper Paleozoic basin in eastern Canada (Fig. 1.1), and host to significant resources of fossil fuels, precious metals, base metals, and industrial minerals. There are numerous mineral occurrences within the Maritimes Basin that are under-explored, suggesting that the basin has excellent potential for extensive undiscovered resources. A better assessment of these resources hinges on a clearer understanding of the thermal evolution and metallogenesis in the basin.

This thesis comprises four main components, each building on the other. The process of developing an understanding of the metallogenetic history of the Maritimes Basin includes: 1) establishing the geological constraints for the time-temperature and metallogenetic evolution of basin by examining the stratigraphy, sedimentology, and structural geology of the Cumberland Basin, and extrapolating these geological constraints, where applicable, to the rest of the Maritimes Basin; 2) a detailed thermochronological study, including apatite fission track analysis, in the Cumberland Basin which was compared with thermochronological data from elsewhere in the Maritimes Basin, and interpreted within the context of the geological constraints (see 1); 3) an investigation of the sediment-hosted mineral occurrences of the Cumberland Basin, with emphasis placed on the thermochronological constraints (see 2) for the Cu deposits; and 4) an evaluation of time-temperature constraints which can be applied to metallogenetic models proposed for the mineral resources in the remainder of the Maritimes Basin (see 3).

The metallic mineral occurrences of the Cumberland Basin thesis area are made up primarily of stratiform redbed Cu occurrences. In order to better understand the metallogenetic implications of this mineralizing style, a detailed investigation of these occurrences was undertaken. Because various other mineralizing styles can also be found within the Cumberland Basin, and have been found to be of great economic value elsewhere in the Maritimes Basin, constraints on these other occurrences were also evaluated.

1.2 THE (COMPOSITE) MARITIMES BASIN

The Permo-Carboniferous system of eastern Canada comprises a post-Acadian molassic suite of coarse- and fine-grained terrestrial and volcanic rocks, as well as shallow marine clastic, carbonate, and evaporite rocks. It underlies an irregular area of lowland extending from the Bay of Fundy through the Gulf of St. Lawrence to offshore Newfoundland. The onshore distribution extends from eastern Maine to Newfoundland and southern mainland Nova Scotia to Quebec (Fig.1.1).

Van de Poll and Ryan (1985) suggested that the Maritimes Basin should not be considered a single post-orogenic basin, but rather a "composite basin", consisting of interconnected fault block basins and horsts, which at various times underwent differing rates of subsidence and uplift. Fragmentation of the main depositional basin into structural basins (sub-basins, such as the Cumberland Basin, Fig. 1.2) took place along a series of faults both during and after basin development.

The present distribution of the Maritimes Basin represents only an erosional remnant of a much larger Permo-Carboniferous basin of deposition (e.g. Van de Poll, 1973). The interpretation of thermal imprint on the extant sedimentary rocks and contained organic matter, may be the only method of determining the thickness of the now eroded sedimentary cover. Models of basin evolution proposed to date (e.g. Ryan et al., 1987; Bradley, 1982; Belt, 1968b; Poole, 1967; Webb, 1963; and others) were not sufficiently constrained by paleothermal data, nor did they take into consideration the erosion and burial history of the basin strata.

1.2.1 THE CUMBERLAND BASIN

The Cumberland Basin is a geographically restricted, thick accumulation of Late Devonian to Early Permian strata in northwestern Nova Scotia and southeastern New Brunswick (Fig. 1.2). The Cumberland Basin, as defined for this study, is bordered as follows: on the south side by the Cobequid Highlands Massif; on the north side by the Northumberland Strait (exact basin limits are unknown); on the east side by the axis of the Scotsburn Anticline; and on the west side by the Caledonia Highlands Massif and Westmorland Uplift (Fig. 1.2). The Cumberland Basin is an east-west trending depocentre which contains a succession of sedimentary strata in excess of 7 km in thickness. The internal structure of the Cumberland Basin is a broad, east-west trending synclinorium enclosing two parallel diapiric anticlinal structures (Fig. 1.2).

The Cumberland Basin of Nova Scotia (Fig. 1.2) has been chosen for detailed study, as it is easily accessible, and is a representative segment of the Maritimes Basin, sharing its metallogenetic and thermal evolution (Ryan and Boehner,1991). The thermochronological data for the Cumberland Basin are integrated with the extensive geological data collected by the author in order to establish geological constraints.

The Cumberland Basin study includes: 1) apatite fission track analysis; 2) paleontological investigation, 3) mapping, sedimentology, and stratigraphy, 4) fluid inclusion microthermometry, vitrinite reflectance, clay mineralogy, paleomagnetic studies of the basin; 5) a compilation of subsurface data; 6) an interpretation of structural, seismic and geophysical data, and 7) an examination of the mineral occurrences. Overviews of these geological aspects are included in this thesis. The Cumberland Basin study is used as a starting point from which the less comprehensive organic maturation and apatite fission track data from the remainder of the Maritimes Basin may be interpreted.

1.3 RATIONALE FOR THE VARIOUS COMPONENTS OF THE STUDY

The overall purpose of this thesis was to acquire, assess, and evaluate as much geological information as possible in order to determine the time-temperature history of the strata contained within the Maritimes Basin. The time-temperature paths for the various stratigraphic units and geographic areas were used to constrain the metallogenetic history of the basin. Unlike many thermal studies, which are dependent on one particular method, this study attempted to assess numerous methods so as to have as many constraints as possible on the thermal history of the strata. An outline of the rationale for the various components of the study is presented here to justify why the various components were included in the thesis.

1.3.1 STRATIGRAPHY (THICKNESS AND AGE)

The stratigraphy of the basin-fill rocks was the starting point of the study. The stratigraphic information permitted accurate thickness estimates to be made for the units in the various areas of the basin. As an intricate part of the background research, the author mapped the largest onland sub-basin of the Maritimes Basin, the Cumberland Basin. To ascertain the age of the strata, a paleontological study was undertaken. The paleontological information provided time constraints for the stratigraphic units. These two pieces of information, the thickness of the strata and the age, are the fundamental building blocks required before modelling of the thermal history can be attempted.

During the course of this investigation it became evident that the stratigraphic nomenclature for the Maritimes Basin was unnecessarily complex. The mixture of chrono-, bio- and litho-stratigraphic terminology made it difficult to correlate strata within the Maritimes Basin, except on the local scale. As a consequence of this study the stratigraphic nomenclature for the basin has been revised (see Ryan et. al, 1991; and Appendix I). The revised stratigraphy, as applied in chapter 2 of this thesis, provides the basis for a more comprehensive understanding of the time-thickness relationships of the strata contained within the basin. When the strata of the basin are correlated using basic group subdivisions, Windsor, Mabou, Cumberland and Pictou, it becomes clear that there is a shared stratigraphic history for the various portions of the basin and that the groups are fairly consistent in thickness and age throughout the region. This information was critical in the interpretation of the thermal history of the basin.

1.3.2 SEDIMENTOLOGY (DISTRIBUTION AND ENVIRONMENTAL SETTING OF THE STRATA)

The next piece of the jigsaw puzzle was the sedimentology of the strata. The sedimentological studies were carried out at the same time as the stratigraphy and paleontology. The sedimentology of the units aids in the understanding of the stratigraphy and permits estimates of thickness of the various units based on the sedimentological environments of deposition. The sedimentological studies also included investigations into the distribution of the various lithostratigraphic units. These data coupled with sediment dispersal patterns can be used to constrain the tectonic evolution of the basin. Information on the environments of deposition of the units forms a basis for modelling of synsedimentary ore deposits.

Sediment dispersal studies carried out as part of this research (Ryan et al.,1988; Gibling et al.,1992) suggest that the source area for much of the basin-fill in the Maritimes Basin lay to the southwest. Detritus was eroded from the Appalachian and Mauritanide Mountains and was transported longitudinally between the mountain ranges to the Maritimes Basin which acted as a receiving basin. Inferences as to the nature and evolution of the Maritimes Basin can be made on the basis this interpretation. The Maritimes Basin may have developed because of a gradient break created by the numerous strike-slip faults in the region. The basin drainage patterns are analogous to basins developing adjacent to the modern Himalayas. This analogy suggests constraints on the geothermal gradients for basins developed in similar settings.

1.3.3 STRUCTURE (REDISTRIBUTION OF THE STRATA AND THERMAL INFLUENCES)

Another important component to the study was an evaluation of the structural geology and tectonic setting of the basin. The structural information used in this study was derived primarily from the mapping and seismic interpretation of the Cumberland Basin. Inferences on the Maritimes Basin as a whole were then drawn from these data. The structure of the basin provides information on the occurrence and timing of uplifts, faulting, down thrown blocks (areas of rapid subsidence), thrusting (non-sedimentary burial) and diapirism. All of these structural features have an effect on the time-temperature path for the adjacent strata.

The structure of the Maritimes Basin is consistent with a continental wrench basin. The most significant structural features of the basin are the east-west strike-slip fault zones and the associated westerly directed thrusts. The structure of the basin when coupled with the stratigraphic record, suggest that the basin-fill of the Maritimes Basin is the result of three tectonically driven sedimentary allocycles (Ryan et al., 1987)(see Chapter 6).

The structural information was used to select areas with minimal structural complexity for detailed thermochronological study. Areas that may have been affected by thermal flux as a result of diapirism or hydrothermal fluid expulsion at fault zones were excluded from the thermal study because the later stage thermal activity may have obscured the overall basin thermal history record.

1.3.4 ORGANIC MATURATION (CONSTRAINTS ON MAXIMUM TEMPERATURE)

Three methods were used in assessing the organic maturation of the kerogens contained within the strata of the Maritimes Basin: (1) vitrinite reflectance (Ro), (2) Thermal Alteration Index (TAI), and (3) Rock Eval pyrolysis. These methods measure the degree to which the kerogens (organic carbon) have been altered (changed) by the maximum temperature experienced and also give some indication as to the duration of the heating. The limitations and reliability of these various methods is discussed in Chapter 5.

Vitrinite reflectance, TAI and Rock-Eval pyrolysis determinations were performed on outcrop and subsurface samples from the Cumberland and Sydney Basins as part of this study. These results were compiled into the regional context by comparison to the work of Hacquebard and Cameron (1989) and Mukhopadhyay (1991b). For the purpose of comparison the results of the various methods were expressed in equivalent Ro max values. The conversion of the results to equivalent Ro was accomplished by using the Barnes et al. (1984) organic maturation comparison table.

Vitrinite reflectance and TAI results are in close agreement. The mean of approximately 0.90 Ro (max) derived from the 283 vitrinite reflectance samples is taken to be an appropriate measure of the organic maturation of the samples near present day surface (see Chapter 5). Rock-Eval pyrolysis of 300 organic rich rocks from throughout the Maritimes Basin have a mean Tmax (temperature of peak S2 hydrocarbon generation during pyrolysis) of 436°C which is equivalent to a Ro (max) of 0.60. The oil-rich shales throughout the Maritimes Basin have vitrinite reflectance values of 0.60 Ro, which is lower than the normal maturation level, and may reflect the type of organic matter in the rock rather than a distinct thermal history.

The organic maturation levels from all of these data indicate that the rocks at the near surface have been covered by additional strata at some time in their history. The vitrinite reflectance Ro/km gradients of the Maritimes Basin as seen in the deeper drilling rarely exceeds 0.65% Ro/km. A comparison of the Ro actual values to the Bustin et al. (1977) coalification curves, suggests a paleogeothermal gradient of less than 30°C/km, where the duration of maximum temperature is longer than 20 million years. Whereas most of the vitrinite gradients are less than 0.40 %Ro/km, even with shorter duration of maximum temperatures, a gradient of 25°C/km would seem sufficient to produce the observed organic maturation profiles. Given this, a minimum of 1 km of additional "ghost stratigraphy" must have been deposited on top of the present day surface.

1.3.5 MINERAL THERMAL INDICATORS (CONSTRAINTS ON MAXIMUM TEMPERATURE AND TIMING OF REDDENING)

Fluid inclusions, clay mineralogy and paleomagnetic studies were also addressed in this thermal study in order to establish additional constraints on the thermal history of the basin. A compilation of previous work on fluid inclusions from mineral deposits in the Maritimes Basin was undertaken. These fluid inclusion studies gave an estimate of maximum temperatures of approximately 200 °C adjacent to the ore deposits. If the mineralizing fluids are derived from the basin (Ravenhurst and Zentilli, 1987), then the rocks at the base of the basin-fill must have been exposed to temperatures of greater than 200°C.

A limited study of clay mineralogy was undertaken as part of this study (15 samples) and then compared to the work of Gall and Sangster (1991) (>60 samples). The mineralogy of the clays (Illite Crystallinity) is temperature dependent, although it is not as reliable as vitrinite reflectance in most instances. Clay mineralogy data is in general agreement with the organic maturation data.

In the Maritimes Basin, many of the red sandstones of the Pictou Group are secondary in origin (Ryan et al., 1989). The sandstones were deposited as grey sandstones, buried, lithified and later diagenetically reddened. The paleomagnetic studies of these red sandstone can date the age of the hematization and given that this reddening probably occurred within 1.5 km of the surface, the date reflects exhumation of the strata. The paleomagnetic studies suggest that the reddening of the sandstones (and therefore the exhumation) occurred 280-240 Ma.

1.3.6 APATITE FISSION TRACK ANALYSIS (TIMING OF EXHUMATION)

The most critical component of the thermal study was the apatite fission track analysis. The fission track study was the thread that tied all of the thermal studies together into a comprehendible package. Apatite fission track analysis is a method of dating a rock by examining the density of spontaneously produced damage zones caused by uranium fission within grains. By comparing the density of spontaneous tracks (damage zones) to the induced tracks (a measure of the total uranium in the grain) it is possible to date a grain. Apatite fission tracks anneal (disappear) at temperatures approaching 100°C and therefore the age of the grain reflects the time at which the grain was last at a temperature of approximately 100°C. This technique gives both time and temperature information, whereas other methods permit only estimates of time or more commonly, of maximum temperature. The method is fully described in chapter 5 of this thesis. Apatite fission track analysis provides information on when a rock was last at approximately 100°C, but also aids in interpreting the cooling history from that point in time to the present. Used in conjunction with the other methods previously discussed this method can be a powerful tool in the modelling of the thermal history of a rock unit.

The fission track study included 33 samples from this thesis, 14 samples from Ryan et al. (1991) and 57 additional apatite fission track age dates compiled from other workers for samples in or adjacent to the Maritimes Basin. All of the samples, with the exception of one high evaluation sample from the Long Range in Newfoundland, have been reset and therefore have been subjected to temperatures greater than 100°C. The overall mean age of the apatites for the Maritimes Basin is 232±55 Ma indicating that the rocks had been cooled through the 100°C isotherm during the late Permian to early Jurassic. This apatite fission track analysis confirms the presence of a "ghost stratigraphy" deposited on top of the basin and indicates that most of this additional strata were eroded prior to the Middle Jurassic.

When this information is applied in conjunction with the organic maturation data it suggests that the additional strata were probably early Permian in age and that erosion (exhumation) began as early as late Permian throughout most of the basin. Older fission track ages are found in the youngest strata exposed near surface in the basin and in the basement rocks adjacent to the basin. These older ages suggest that these rocks experienced exhumation to temperatures of less than 100°C sooner than other rocks in the basin. These observations are consistent with a basin-wide exhumation where the surrounding basement rocks were exhumed soon after the onset of erosion. The timing of the maximum burial and exhumation as defined by the apatite fission track analysis places constraints on the maximum temperatures experienced by the strata. Taking the duration of the maximum burial, as constrained by the fission track study, and using the coalification curve to compare to the observed organic maturation, it is possible to derive a reasonable estimate of the maximum temperatures experienced by the strata (see chapter 5).

1.3.7 THERMAL MODELLING

The primary objective of the thermal modelling of the data from the Maritimes Basin is to attain reasonable approximations of the time-temperature (Tt) paths for the strata from various parts of the basin. This Tt information can be used to constrain the metallogenetic history of the basin. All of the thermal and background geological information described previously has been used to construct burial history plots for the various horizons sampled. The burial history plots are diagrammatic representations of the burial of a stratum constrained by the stratigraphy, sedimentology, structure, and thermal history. These plots provide the information necessary to estimate Tt paths for the rocks under investigation. A detailed discussion of these plots is presented in chapter 5.

Care was taken in this study to avoid creating burial history plots for structurally complicated areas. The avoidance of these areas allowed for a better understanding of the overall thermal and burial history of the basin; in this way anomalies that might have resulted due to structural disturbances were eliminated. Three burial history plots were constructed for the Cumberland Basin, three from the Gulf of St. Lawrence area, and one from each of the Minas Basin, Sydney Basin, Deer Lake Basin, and the Prince Edward Island area. Each of these diagrams is constrained by as many thermal and geological parameters as possible (see Fig. 5.16). After these plots have been constructed it is possible to superimpose isotherms based upon organic maturation gradients from above and below the sampled horizon and from the apatite fission track data.

The burial history plots and isotherms permitted estimation of the time-temperature path for the sampled horizon. As a method to corroborate the Tt path, computer modelling (Trac 3) of the Tt path was undertaken and the modelled apatite fission track age, fission track length distribution, and vitrinite reflectance were compared to the actual measured data from the horizon. In most of the instances the modelling of the Tt path derived from the burial history plots resulted in values which closely approximated the measured values. In the case of the Deer Lake Basin samples, Hendriks (1991) modelled the samples using an inverse model but the results still closely correspond to the measured values. All of the other models in the thesis are from the work of the author.

The implications of the modelling are: (1) the basin underwent rapid sedimentation from 320 to 290 Ma; (2) a basin-wide exhumation took place from 280-170 Ma that removed 2-4 km of strata; (3) most of the basin underwent a slow exhumation from 190 to 100 Ma (Early Triassic to Early Cretaceous); (4) with the exception of the E-49 Well in the Gulf of St. Lawrence, there is no evidence of Triassic sedimentation or thermal activity; (5) the paleogeothermal gradient, as evidenced by the organic maturation data and confirmed by the forward modelling of the apatite fission track data, approximated 25°C/km throughout most of the geological history of 'he area.

1.3.8 MINERAL OCCURRENCES AND METALLOGENETIC EVOLUTION

The final component of this study was the metallic mineral occurrences in the Maritimes Basin. This study focused on the copper-silver occurrences within the Cumberland Basin and collated the other occurrences from throughout the Maritimes Basin (see chapter 7). The work on the Cu-Ag occurrences included mineralogy, geological setting, geochemistry, and sulphur isotopes. Similar work on other deposits in the basin were compiled from various other workers.

In section 1.4 of this thesis the idea of genetic affinities is discussed. The result of the metallic mineral investigation involved the classification of the deposits into three genetic affinities based on empirical observations, probable genetic origins, and environmental settings. The three affinities are: (1) sedimentary exhalative, (2) basin-brine expulsion and (3) groundwater related solution fronts.

These genetic affinities were found to fit the generalized time-temperature path for the basin as derived from the thermal studies and modelling. The sedimentary exhalative type occurred during the period of rapid subsidence prior to 290 Ma. The basin-brine expulsion type occurred prior to the onset of exhumation at 280 Ma. The groundwater related solution front deposits, like the Cu-Ag of the Cumberland Basin, occurred during the exhumation of the strata.

1.4 METALLOGENETIC AFFINITIES

In summary section 1.3.8 of this chapter, the concept of metallogenetic affinities was discussed. This section will better define these terms. Metallogenetic models proposed for base metal and barite deposits of the onshore basin segments include a syngenetic model, controlled by methane seeps (Von Bitter et al., 1989); paleoclimate (Van de Poll, 1978); deeply circulating hydrothermal cells (Russell, 1978); sedimentary exhalative (Hudgins, 1990); early diagenetic-epigenetic (MacLeod, 1975; 1984); or related to episodic basin-fluid-expulsion in the Late Carboniferous (Lydon 1978; Ravenhurst and Zentilli, 1987). Ryan et al. (1989) and Sangster and Vaillancourt (1990) have suggested that the basin contains occurrences related to unconformities and groundwater solution fronts. For the purpose of discussion the author has grouped the different genetic models into three basic genetic affinities (types or groups): (1) those related to sedimentary processes with possible sedimentary exhalative events,including the Von Bitter et al. (1989), Russel (1978), Van de Poll (1978) and the Hudgins (1990) models; (2) those related to large scale basin tectonics and diagenetic hot-fluid migration in the basin, including the Ravenhurst and Zentilli (1987), and Lyndon (1978) models; and (3) those related to near surface groundwater diagenetic processes including the Sangster and Vaillancourt (1989), Ryan et al. (1989), and MacLeod (1975, 1984) models. Although various workers have examined the geology and metallic mineral occurrences in the Maritimes Basin, no study has integrated the metallogenetic constraints posed by a regional thermochronology investigation on the rocks of the entire basin. This study leads to a grouping of mineral occurrences into three main metallogenetic models or affinities (Fig. 1.3), consistent with the empirical observations, probable metallogenetic processes, and environmental parameters (see chapter 7).

1.5 PREVIOUS WORK

Table 1.1 is a compilation of the various authors who have contributed to the understanding of the Maritimes Basin geology. The first geological investigations of the Maritimes Basin were by Jackson and Alger (1828). Brown and Smith (1829) evaluated the coal resource potential and described some of the shoreline sections in the western part of the Cumberland Basin, and remarked on its similarity to the British Carboniferous. Gesner (1836) investigated the Springhill region and made the initial (documentation?) discovery of coal seam occurrences. Lyell (1845) described in detail the fossils collected from the shore section from Minudie to Joggins. Logan (1843) measured bed by bed the strata exposed along the shore at Joggins. Although wave action and erosion have slightly altered the section exposed along the shore, his detailed observations, which resulted in an eight-fold division of the strata, are still applicable today.

Dawson (1855, 1894) examined and identified much of the biota of Logan's section and inferred paleoenvironmental settings. Ells (1885) was the first geologist to compile and synthesize the geology of northern Nova Scotia and southern New Brunswick into a map. In 1892, Fletcher began his sixteen year study of the geology of the Cumberland Basin. Fletcher published a series of geological maps for the area (1892-1909). He also augmented Logan's measured section by including measured section descriptions of strata south of Logan's original Joggins section.

Bell's studies of the strata in northern Nova Scotia started in 1911 and continued for many years (Bell, 1912, 1913, 1924, 1927, 1944, 1958). Many of his observations from the Cumberland Basin were critical to the establishment of the stratigraphic nomenclature for the Carboniferous strata that is still in common usage (Bell, 1944). Shaw (1951a) made the initial attempt at basin analysis in the Cumberland Basin with his observations of facies variations within the strata. Shaw's 1951 map division terminology was still in use when this study was initiated. Copeland

(1959) reexamined and extended the work of Shaw (1951b) and made refinements in stratigraphy based on the paleontology in the western part of the Basin.

Howie and Cumming (1963) used the depth to the basement as a method to define the basin structure. Howie and Barss (1975) used similar geophysical data and methodology to create isopaches of the various stratigraphic units in Atlantic Canada, and Wade et al. (1983) applied these data on the thickness of sediment accumulation to define the various onland and offshore basins of Atlantic Canada. Palynology of Hacquebard and Donaldson (1970) and later Hacquebard (1972, 1986) and Barss and Hacquebard (1967), established and refined age relationships of the various lithostratigraphic units.

In the last thirty years, many workers have made significant contributions to the understanding of the stratigraphy and the sedimentology of the Carboniferous strata of northern Nova Scotia. Amongst these are: Gillis (1964), working in the eastern Cumberland Basin; Belt (1964, 1968) on the lateral variations on a regional scale; Kelley (1967) on the regional aspects of stratigraphic nomenclature; Duff and Walton (1974) on the sedimentology of the Joggins section; Calder (1979-1987) on the Cumberland Group in the Springhill, Joggins and River Hebert area; Van de Poll and Ryan (1985) on the stratigraphy and sedimentology of the Permian-Carboniferous transition; Rust et al. (1984) on the fluvial style of sedimentation in the western part of the Cumberland Basin; and Salas (1986) on the sedimentology in the Apple River area of the western Cumberland Basin.

The structural geology and the sedimentation in response to tectonic movements, have been the subject of many studies in recent years. Eisbacher (1967) published the first comprehensive work on the kinematics of the faulting along the Cobequid Fault system adjacent to the Cumberland Basin. Partly on the basis of Eisbacher's (1967) interpretation of fault movement on a large strike-slip system, Webb (1969) proposed that the Maritimes Basin had formed as a large wrench basin. Fyson (1967) examined the topic of gravity sliding and cross folding in northern Nova Scotia, relating overturned folds to uplift and gravity sliding. White (1972) discussed the concept that the Cumberland Basin was a rift basin, using seismic data and basin-fill characteristics. Bradley (1981) and Keppie (1982) suggested a pull-apart origin, and Keppie (1982) further proposed that this initial pull-apart was followed by a foreland basin phase. Fralick (1980), Fralick and Schenk (1981), Donohoe and Wallace (1985), Yeo and Ruixing (1986) and Ryan et al.(1987) have examined the distribution of facies within the basins of northern Nova Scotia, and proposed possible models of strike-slip basin development.

Significant contributions to the understanding of the economic geology of the Upper Carboniferous of the region were made by Messervey (1929), Papenfus (1931), Shumway (1951), Brummer (1958), MacKay and Zentilli (1976), Dunsmore (1977a, 1977b), Van de Poll (1978), Kirkham (1985), Ravenhurst and Zentilli (1987) and Ryan et al. (1989). In addition, unpublished exploration assessment reports by geologists from numerous mineral and energy exploration companies contain important data (N.S.D.N.R Library). Reynolds et al. (1981, 1987), Ravenhurst and Zentilli (1988), Ravenhurst et al. (1988, 1989, 1990), Muecke et al. (1988), and Hendriks (1991) have made contributions to our understanding of the post-Carboniferous thermal history in Nova Scotia. This study represents the first to integrate the thermal, geological and economic aspects of the mineral occurrences into a comprehensive package.

1.6 HISTORY OF THIS THESIS

This thesis was started at the University of New Brunswick under the supervision of Walter Van de Poll and Ernie Hale. The initial field work was supported by the Geological Survey of Canada through a Department of Supply and Services contract to the author. Subsequent field support was given by the Nova Scotia Department of Natural Resources where the author was employed as a regional geologist conducting a program of geological mapping and resource evaluation in the Cumberland Basin. The death of Dr. Hale and the switch of research emphasis from sedimentology to regional stratigraphy and metallogenesis forced the author to transfer to Dalhousie University. The thermal component of the metallogenetic studies has been emphasized herein as this aspect of the economic geology better reflects the research interests of Marcos Zentilli who has acted as the primary advisor at Dalhousie University.

The thesis reflects the continuous evolution of the research which lead to this document. The reader is referred to Ryan and Boehner (1993) for a more comprehensive report on the geology of the Cumberland Basin component of this study.

TABLE 1.1

SELECTED REFERENCES OF PREVIOUS WORK IN THE MARITIMES BASIN

STRATIGRAPHY AND PALEONTOLOGY	Ami, 1902; Bell, 1912,1914,1924,1926,1929,1938,1944,1945,1958; Belt, 1965, 1968a,1968b,1968c,1969; Belt et al.,1967; Boehner,1977,1980, 1986,1988; Boehner et al.,1986; Calder,1984,1985, 1986,1987,1991; Dawson, 1855; Deal, 1991; Dolby, 1984,1985,1986,1987,1988,1989; Fletcher, 1892,1905,1906,1909; Gibling et al.,1987,1991; Giles et al., 1979; Gussow,1953; Hacquebard, 1972,1979,1983,1984,1986; Hacquebard and Donaldson, 1964,1970; Howie,1974, 1984,1986,1988; Howie and Barss, 1975; Kelley, 1967; Martel,1990; McCutcheon and Robinson, 1987; Moore, 1967; Moore and Ryan, 1976; Roliff,1932,1962; Ryan,1984,1985,1986,1988; Ryan and Boehner,1990,1991,1992; Ryan et al.,1987,1988; Schenk,1969; Shaw, 1951; Utting,1977,1987; Utting et al., 1988; Van de Poll, 1966,1970,1973,1983,1989; Webb, 1963, 1969; Williams, 1974; Yeo, 1985, 1986,1987.
ECONOMIC GEOLOGY	Adams, 1988; Akande, 1982; Akande and Zentilli, 1984; Anderlie et al.,1979; Boyle, 1968,1972; Boyle et al., 1976; Brummer, 1958; Calder, 1985; Chatterjee, 1984; Evans, 1970; Fraser, 1961; Lydon, 1978; MacDonald, 1978; MacKay and Zentilli, 1976; McNabb, 1977; Messervey, 1926, 1930; Mossman and Brown, 1986; Papenfus, 1931; Ravenhurst, 1987; Ravenhurst and Zentilli, 1987; Ravenhurst et al., 1987; Russel, 1978; Ryan and Boehner, 1991; Ryan et al. 1989; Sangster and Vaillancourt, 1990; Stea et al, 1986; Van de Poll, 1978; Von Bitter et al., 1989.

TABLE 1.2 LITHOLOGICAL CRITERIA USED TO DEFINE THE CUMBERLAND AND PICTOU GROUPS

Criteria	Cumberland Group	Pictou Group
Coal-bearing:	generally but not always	rarely
Red lithofacies:	subordinate	dominant
Grey lithofacies:	dominant	subordinate
Conglomerate:	locally abundant	rare
Fine lithofacies:	subordinate-subequal	dominant
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 hetergeneous Cumberland Group and correlatives; unconformable with older Carboniferous strata and basement rocks

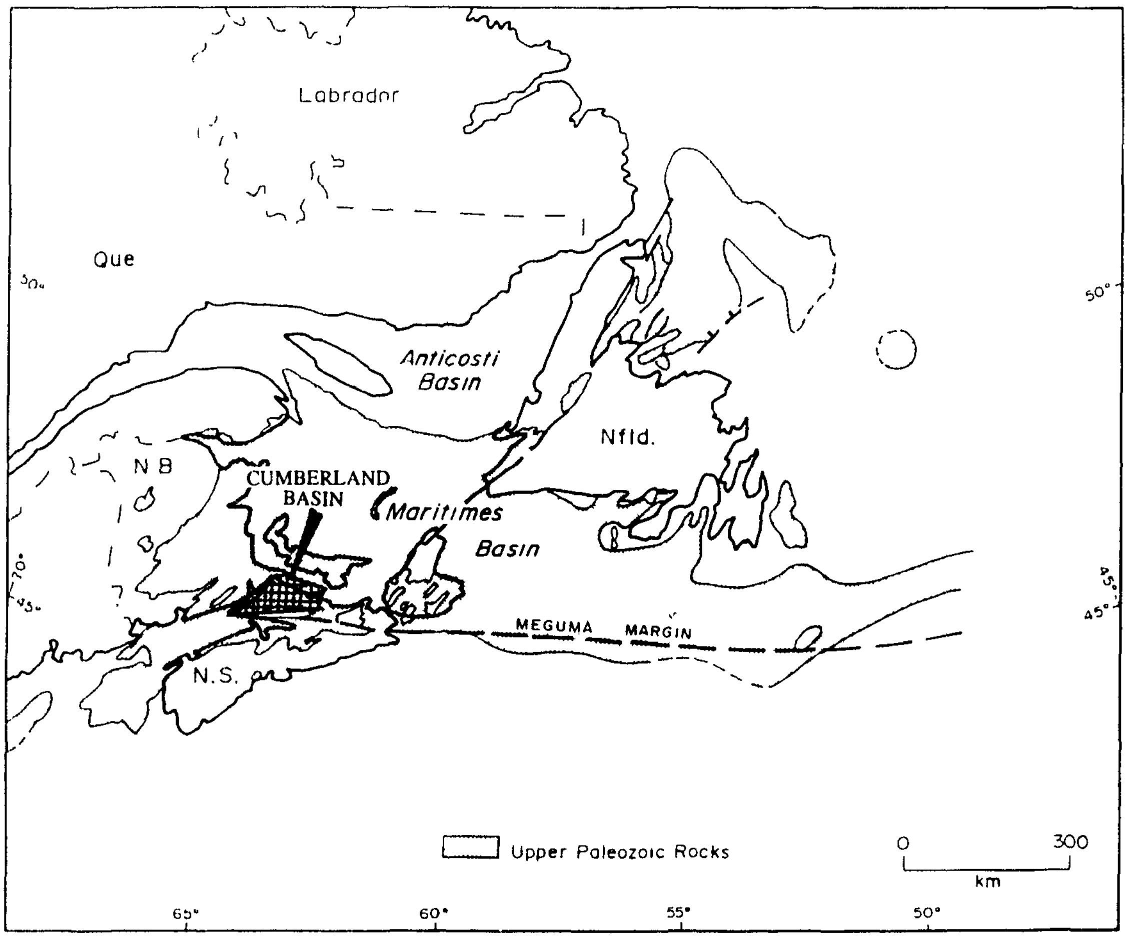


Figure 1.1: Location map for the Upper Paleozoic Cumberland and Maritimes Basins, Eastern Canada. The boxed area on the map is the Cumberland Basin thesis area.

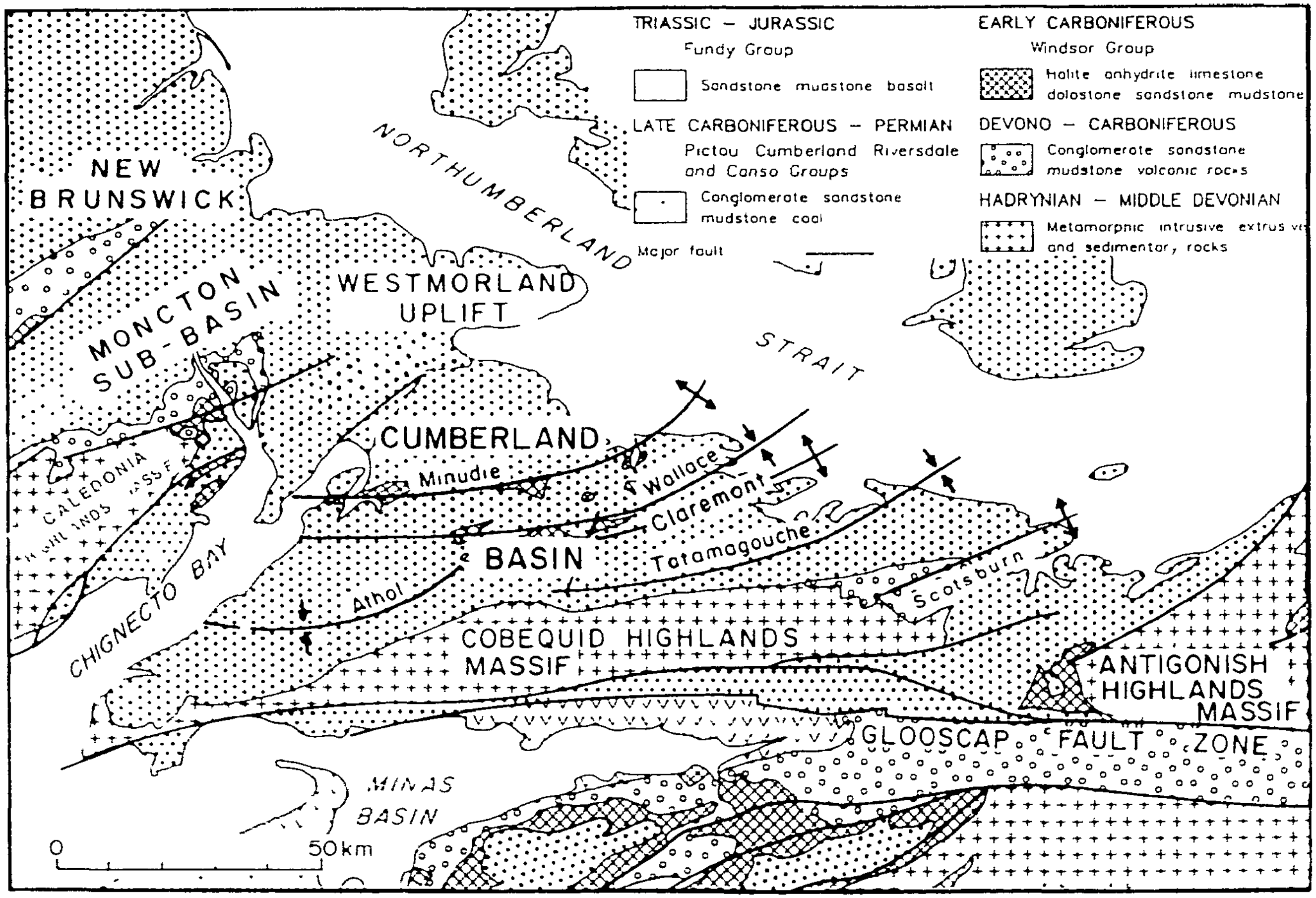


Figure 1.2: Location map and generalized geology of the Cumberland Basin of northern Nova Scotia. The Cumberland Basin is bounded by the Caledonia Highlands Massif, Cobequid Highlands Massif, Northumberland Strait and the Scotsburn Anticline.

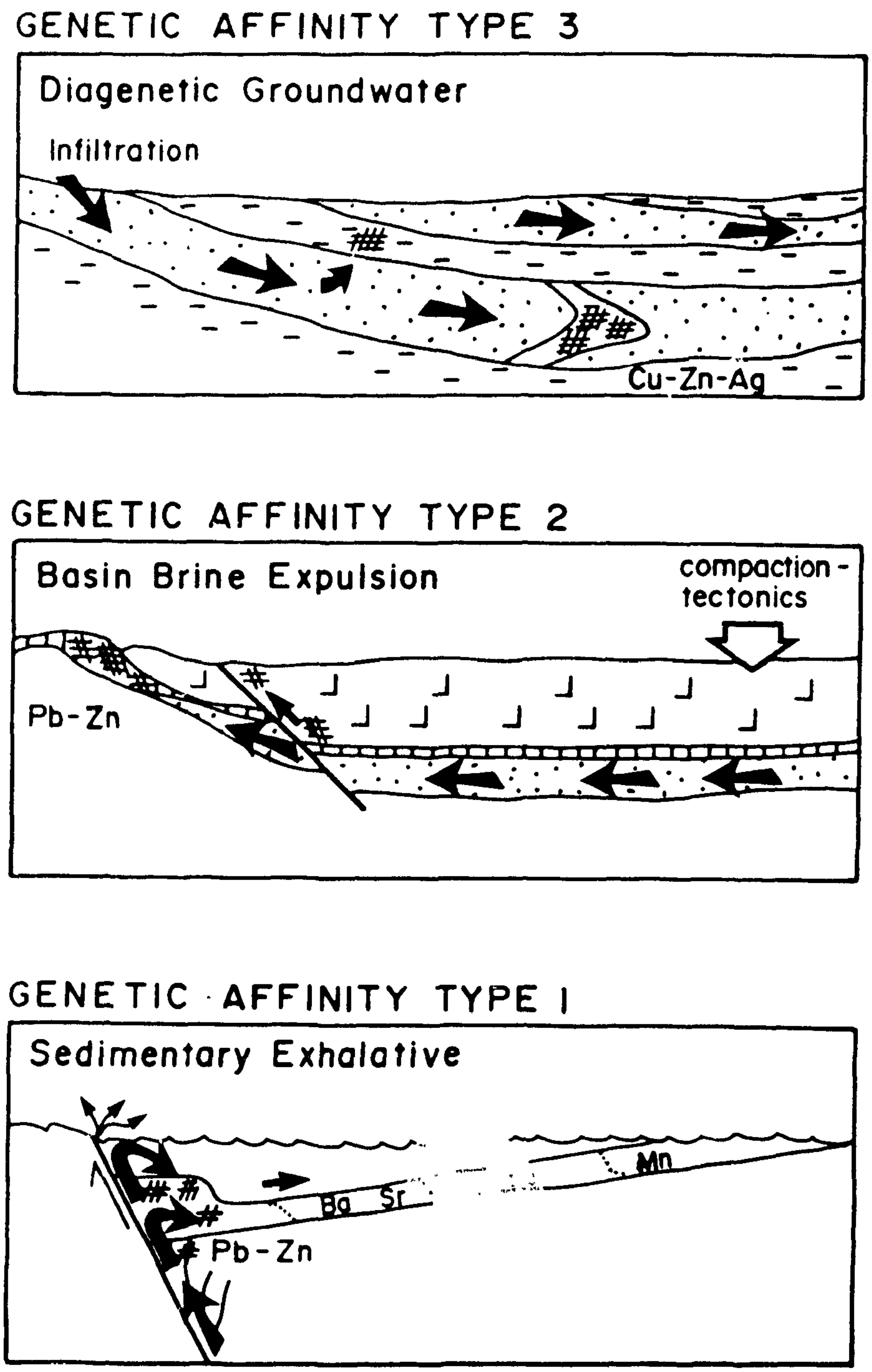


Figure 1.3: Three basic genetic models, groups or affinities have been proposed in this thesis in order to discuss the Permo-Carboniferous hosted mineral occurrences of the Cumberland and Maritimes Basins. Although these affinities are based on inference, the three affinities correspond to empirical and field observations (see chapter 7).

CHAPTER 2

STRATIGRAPHY

The stratigraphy (lithology, thickness and distribution of rock units) and the paleontology (age of the various units) are the essential building blocks for constructing burial histories for the various rocks included in this study. A thermal study of the strata in the Cumberland Basin in particular and the Maritimes Basin in general must be put into a stratigraphic and paleontologic context to permit interpretation. This chapter and Appendix I summarize the stratigraphy and paleontology of the Cumberland Basin, and inferences drawn from the Cumberland Basin geology and stratigraphy have been applied to the larger Maritimes Basin.

2.1 STRATIGRAPHY: CONSTRAINTS ON LITHOLOGY AND THICKNESS

Stratigraphic investigations over the last 150 years have led to complex nomenclature which includes a confusing combination of litho-, chrono- and bio-stratigraphic terminology, and therefore redefinition of some of the units has become necessary. The revised stratigraphy as applied in this thesis simplifies regional correlation and facilitates more coherent interpretation of the thermal history of the Maritimes Basin (Fig. 2.1).

Bell (1944) introduced the basic stratigraphic divisions of the Carboniferous strata in eastern Canada (Fig.2.2) and designated them as "groups", revising the previous assignment of "series". Bell (1944, p.4) stated his reason for doing so as:

> "The economic value of lithological classification of strata has already been mentioned and is generally understood. The value of classification based on age is not so generally appreciated. Yet it is the only classification that permits reliable correlation.'

Bell (1944) believed that all of his groups were separated by unconformities or disconformities of regional time equivalence. Kelley (1967) summarized the evolution of Carboniferous stratigraphic nomenclature, and discussed the inherent problems and confusion where unconformities were not present at group boundaries and paleontological (age) criteria dictated the boundary placement. He pointed out that the designation of these units as "groups" was contrary to the Code of Stratigraphic Nomenclature, and that Bell was assigning lithostratigraphic nomenclature to time stratigraphic units. Although Kelley (1967) was correct in his evaluation of the nomenclature, Bell's basic thesis that time correlation facilitated a better understanding of the geological paleoenvironments, is not without merit. The key lies in the emphasis or degree of confidence placed upon age as a diagnostic characteristic of the unit.

Notwithstanding the inherent problems, Bell's (1944) nomenclature has been so widely accepted and used that it would be imprudent to change all of the nomenclature for the Carboniferous in the Maritimes Basin solely on the basis of this study. Instead, this thesis follows the general trend of previous workers including Shaw (1951a, 1951b), Copeland (1959), Belt (1964 and 1965), Kelley (1967), Howie and Barss (1975a, 1975b), and Ryan et al.(1991a). The trend has been to adapt, develop and improve the stratigraphic nomenclature on a formation level, by documenting and defining mappable lithostratigraphic units and placing them in a more thoroughly defined group nomenclature scheme. In the course of this thesis study, the focus of the investigations was placed on the formations as the fundamental components of the stratigraphic framework. Formations were placed in groups as a secondary priority and are subject to future modification as necessary.

Figure 2.2 is a summary of the evolution of stratigraphic nomenclature for the Cumberland Basin. For a more detailed account of this evolution, see Ryan et al. (1991a) and Ryan and Boehner (1993). The criteria for assignment of formations to the Cumberland and Pictou groups in their type areas in the Cumberland Basin as proposed in this thesis, follow the suggestions of Ryan and Boehner (1989) and are summarized in Table 1.2 and Fig. 2.3. The stratigraphy of the various units in the Cumberland Basin study area are discussed in Appendix I of this thesis.

2.2 PALEONTOLOGY - AGE CONSTRAINTS

The paleontological investigations carried out as part of this study have documented the ages of the various units in the basin (see Ryan and Boehner, 1993). These age determinations are used to constrain the sedimentation rates for the different parts of the basin and by inference they help constrain the time-temperature path of the basin-fill units (see Chapter 5). Some of the conclusions of the detailed paleontological study summarized by Ryan and Boehner (1993) have included here. For detailed descriptions and faunal lists the reader is referred to Ryan and Boehner (1993).

The Windsor Group fauna in the study area indicates an absence of Upper Windsor Group limestones. All of the limestones studied were of B Subzone age suggesting that marine carbonates of the Upper Windsor are not represented in outcrops and were probably not deposited in most of the basin. The faunal assemblage of the Windsor limestones in the area suggest that they were deposited in shallow marine sublittoral zone at/or near wave base.

The presence of thin laterally extensive ostracod- and algae-bearing lacustrine limestones suggests that there was periodic large scale flooding of the alluvial plain during the deposition of the Cumberland and Pictou Groups. The periodic flooding of the alluvial plain may record external eustatic sealevel changes or more probably regional or local tectonic events.

The paleontology and paleobotany of the clastic rocks is obscured by the reddening of the Pictou Group strata in the area. If the present distribution of flora has not been subsequently altered by preferential preservation, it would suggest that much of the vegetation was restricted to the near channel and swamp areas of the floodplain. This restriction of the floral distribution suggests that seasonal drying may have inhibited vegetation development away from water sources. The younger floral assemblages reflect a stressed biome which may be related to a gradual drying of the paleoclimate through time, or to seasonal distribution of precipitation.

Palynology within the study area delineates ten distinct spore assemblage zones within the strata, which range in age from Visean to Stephanian (possibly early Permian). The spore zones correlate with major lithostratigraphic subdivisions within the basin. The palynology results indicate that the range in age of the Cumberland Group should be extended into the Westphalian D from the previous Westphalian C determination, and that the base of the revised Pictou Group in the Cumberland Basin is of Late Westphalian D age. The palynological age dates facilitated regional mapping and correlation in areas where stratigraphic exposure was limited and determination of lithostratigraphic position of beds difficult.

2.3 CHRONOSTRATIC AND CHRONOMETRIC AGES

There is a margin of error in the geological boundary placement when comparing chronostratic and chronometric scales, therefore it is necessary to define the geological time scale used for this study. The Carboniferous to Triassic boundaries as defined by Harland et al. (1989) are the most widely used in the literature and are used here to compare apatite fission track ages to the stratigraphic record. Although other time scales such as the International Union of Geological Sciences (1989) scale exist, they are for the most part in agreement with, or adapted from, the Harland et al. (1989) scale for the Carboniferous to Jurassic, and therefore the Harland scale was used exclusively in this study.

2.4 IMPLICATIONS OF THE STRATIGRAPHY AND PALEONTOLOGY ON THE MARITIMES BASIN THERMAL STUDY

The stratigraphic and paleontologic information derived from this study have direct implications for the thermal and tectonic evolution of the Maritimes Basin.

The revised stratigraphic nomenclature for the Cumberland Basin, when applied to the Maritimes Basin, greatly simplifies the stratigraphic nomenclature of the larger basin. The new division of the Carboniferous basin-fill, as proposed by this study, into 5 groups, each with distinct lithological characteristics, has important ramifications for our understanding of the basin. The regional correlation of the units is summarized in Figure 2.1 and 2.4. These revisions eliminate redundancies in terms applied to stratigraphic equivalent units occurring within local basins or sub-basins (Fig. 2.1).

The paleontology of the Cumberland Basin establishes time constraints for these units and the Cumberland Basin information aids interpretation of paleontological data from elsewhere in the Maritimes Basin. The paleontological and stratigraphic observations from this study have provided information from which time versus thickness plots for the basin (Fig. 2.5) have been constructed. This study provides the opportunity to visualize the lithological characteristics and sedimentation rate for the units at various times in the basin history. These observations yield valuable information which permit construction of burial history plots (see Chapter 5). The burial history plots are used as the starting point for the thermochronological modelling of the basin strata.

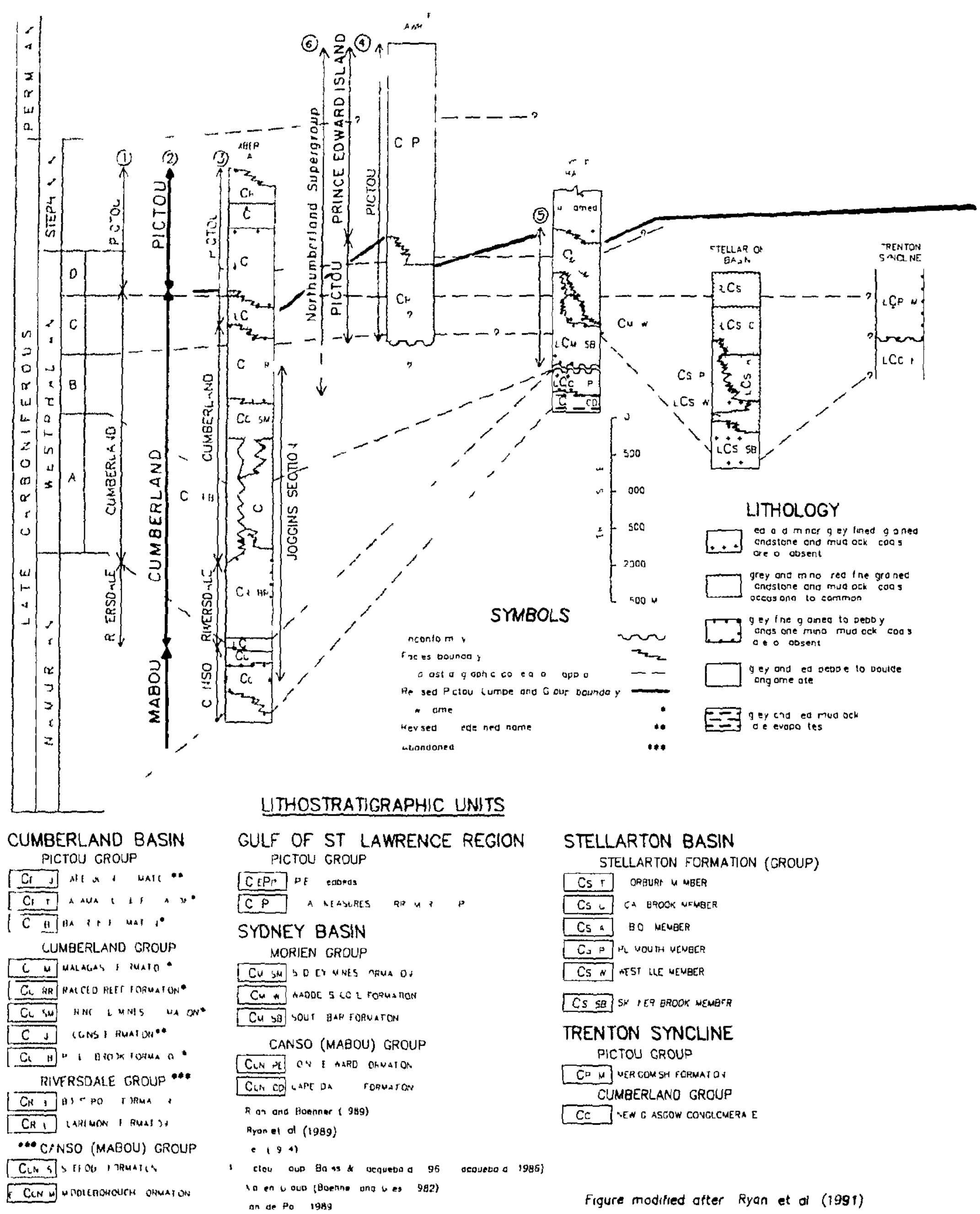
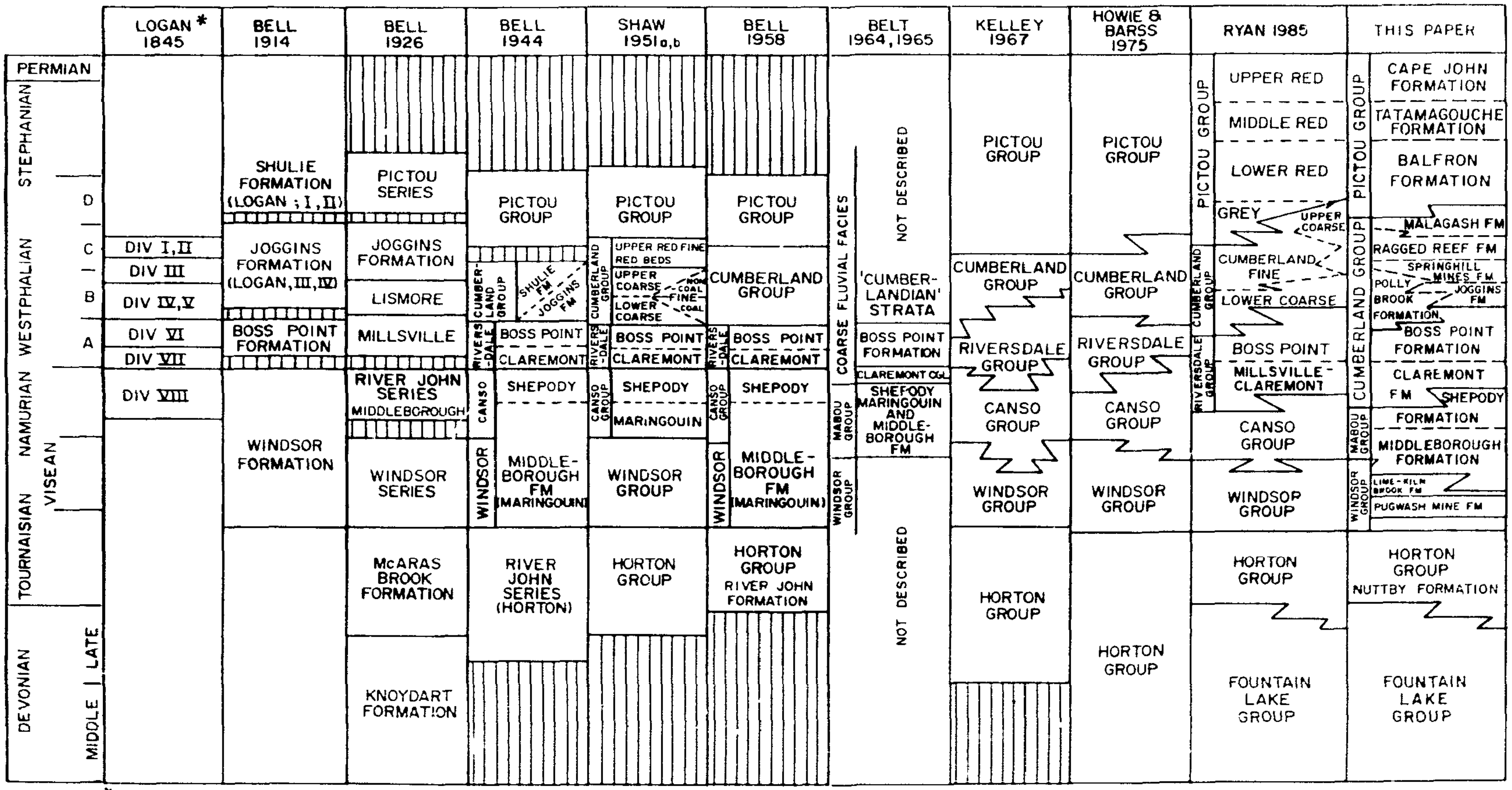


Figure 2.1 Revised stratigraphy of the Cumberland Basin and the regional correlation with other areas of the Maritimes Basin (after Ryan et al., 1991). Correlation of time lines suggests variations of sedimentation through time in the basin, the Westphalian C-D line correlates well with the Cumberland to Pictou Group boundary.



*Joggins section, tied to the lithostratigraphic assignments of this study.

Figure 2.2: Evolution of stratigraphic nomenclature in the Cumberland Basin. The figure demonstrates evolution of the various group and formation names applied to the various units over the years.

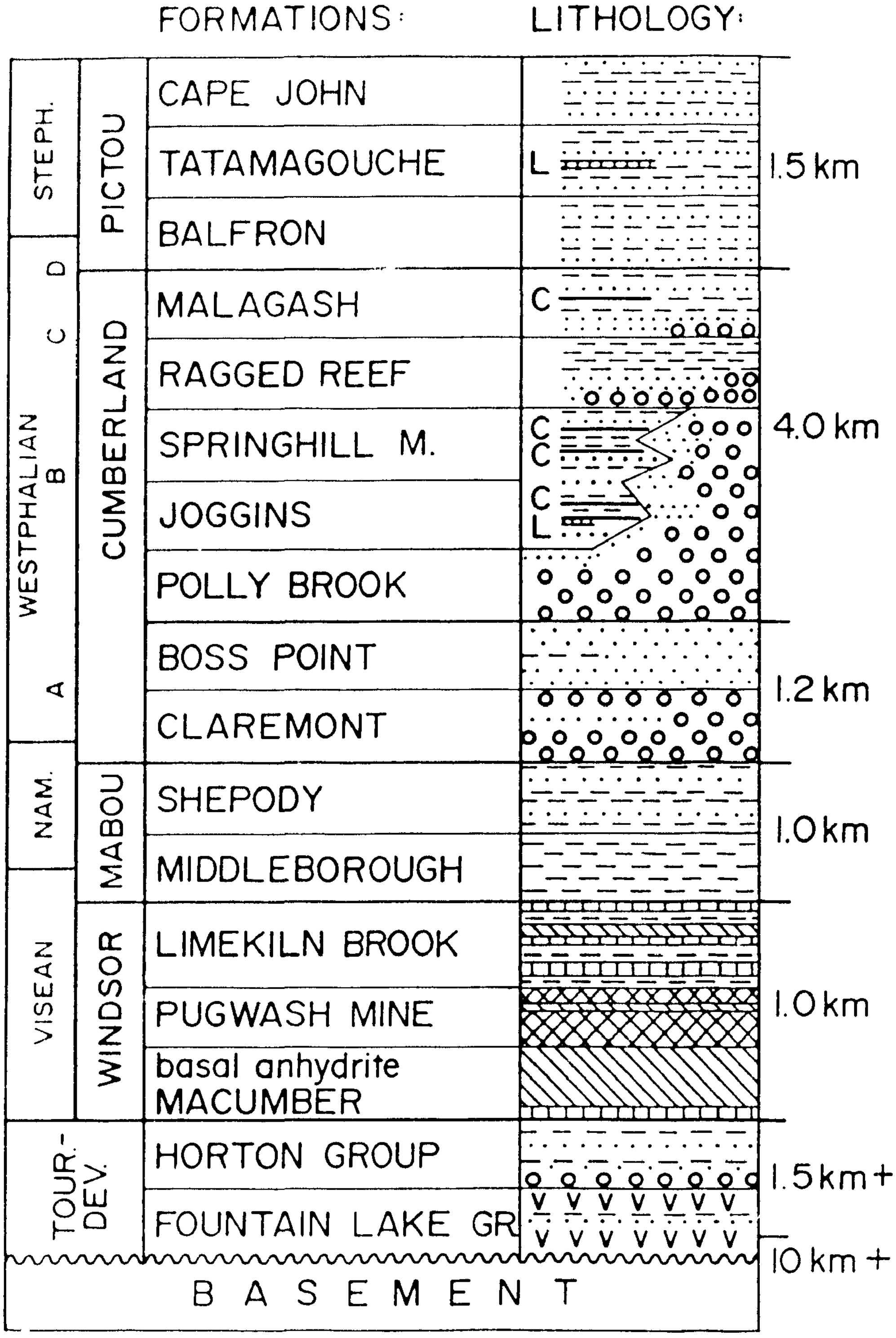


Figure 2.3: Late Devonian to Early Permian stratigraphic column and approximate thicknesses for the Cumberland Basin, revised by Ryan et al., 1991. C = coal, L = limestone, cross hatch = salt, diagonal lines = gypsum/anhydrite, circles = conglomerates, vertical lines = carbonates, V's = volcanics, stipple = sandstones, horizontal dashes = mudrocks.

CORRELATION OF STRATIGRAPHIC GROUP NOMENCLURE

REVISED	OLD CUMBERLAND	OLD STELLARTON	OLD SYDNEY
PICTOU	PICTOU	STELLARTON (PART)	MORIEN (RED)
CUMBERLAND	CUMBERLAND+ RIVERSDALE	STELLARTON+ RIVERSDALE	MORIEN (GREY)+ RIVERSDALE
MABOU	CANSO	CANSO	CANSO

Figure 2.4: The correlation of the revised group nomenclature with the group names used by older literature for the Cumberland, Stellarton and Sydney Basins. The revised nomenclature is after Ryan et al.(1991a).

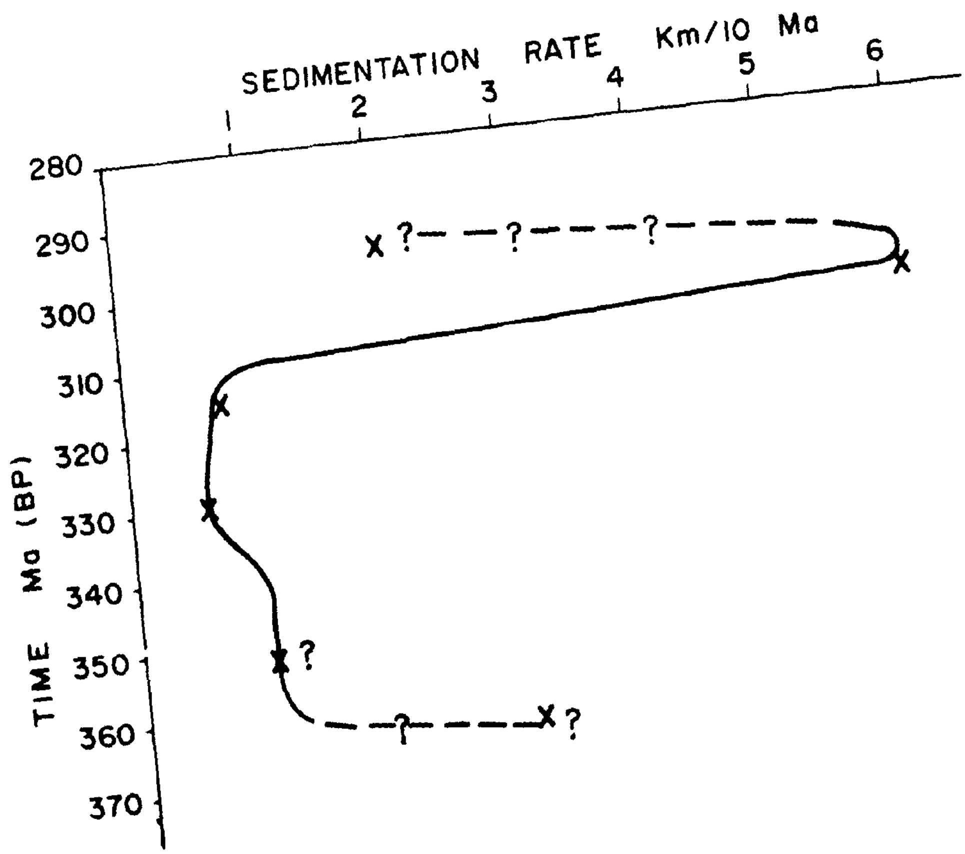


Figure 2.5: Time versus sediment thickness plots for the Cumberland Basin. The plots are maximum inferred thickness from seismic profiles and drilling within the basin. Formations which are facies equivalents were treated as a single unit. The areas of question marks are from parts of the section that are not completely exposed in the basin.

CHAPTER 3

SEDIMENTOLOGY

3.1 INTRODUCTION

Various aspects of the sedimentology of the strata in the Cumberland Basin area are discussed in this chapter, in order to establish the sedimentological parameters related to burial and erosion which are used to interpret the thermochronology, and the structural and economic geology of the Cumberland Basin. The sedimentological parameters which apply to the Cumberland Basin also apply in a general sense to the larger Maritimes Basin.

The sedimentology can be used to verify the following geological constraints : (1) sediment source and dispersal patterns which can be used to ascertain the geomorphic configuration of the basin, and areas of relative uplift and subsidence; (2) the lithofacies distribution of the strata help to define the environments of deposition for the various rock packages, and their inter-relationships make it possible to interpret internal basin features such as local sub-basins and areas of rapid sedimentation; (3) the presence of recycled basin material indicates uplift of part of the basin area; and (4) the basin-fill detritus which constitutes the rocks is a potential source for the metals and gangue found in the mineral deposits of the basin. The various observations are dovetailed with the stratigraphy (Chapter 2) in an effort to create burial history plots for the basin (see Chapter 5).

Lithofacies and lithofacies associations are described in Ryan and Boehner (1993) and therefore are not included here. The sediment dispersal trends for the Cumberland Basin and the Maritimes Basin have been summarized by Ryan et al. (1988) and Gibling et al. (1992) (Fig. 3.1). The reader is referred to these papers for a detailed discussion of the paleoflow during the Carboniferous in Atlantic Canada.

3.2 SEDIMENTOLOGICAL ENVIRONMENTS OF DEPOSITION

This section provides a brief discussion of the environments of deposition for the various units from the Windsor Group to the Pictou Group. The Horton and the Fountain Lake groups are not discussed here because they are poorly exposed in the Cumberland Basin.

3.2.1 WINDSOR GROUP

The evaporites, mudrocks and carbonates of the Windsor Group are grouped together into a marine facies assemblage for the purpose of this study. The exact depositional environment of the evaporite sequence is difficult to determine, however it is clearly marine in origin. The carbonates of the Windsor Group, which are thin and interbedded with the evaporites and clastics, were deposited in shallow waters. The fauna and flora of the various carbonates studied within the Cumberland Basin all indicate deposition under stressed conditions (possibly hypersaline) at or near the wave base.

3.2.2 MIDDLEBOROUGH FORMATION

Strata of this formation are poorly exposed in the area which makes interpretation of the depositional environment very tenuous. McCabe and Schenk (1982) suggested that most of the Middleborough Formation (or its equivalent Maringouin) had been deposited on a floodplain during sheetfloods and within shallow ephemeral streams. The overall sequence of the formation is mostly composed of very fine grained sandstones and mudrocks which would support such a paleoenvironmental interpretation (Fig. 3.2). The fine grained rocks commonly have pedogenic horizons as well as desiccation features. Rare lateral accretion beds can be found within the thicker sandstone units indicating that a few less seasonal streams also traversed the floodplain. In general the formation coarsens upward, perhaps in response to an increased supply of water due to the transition from an arid paleoclimate, as suggested by the underlying Windsor Group evaporites at the base of the formation, to a more humid paleoclimate at the top.

3.2.3 SHEPODY FORMATION

This formation is a sandstone-dominated sequence with subordinate fine grained rocks. The sandstone bodies are usually single story at the base of the formation but within short distances develop upwards into multi-storied channel sequences (Fig.3.3). Unimodal paleocurrents predominate in the upper parts of the formation. Lateral accretion beds occur primarily in the lower parts of the formation although a few persist into the upper beds. This formation is interpreted to represent a transition from meandering streams at the base of the unit to a sandy braided system at the top (Ryan and Boehner, 1990). The uppermost beds of the formation are interbedded with polymictic alluvial fan conglomerates of the Claremont Formation.

3.2.4 CLAREMONT FORMATION

In the study area, alluvial fan deposition occurred during the Namurian. The alluvial fan deposition is recorded by the Claremont Formation which is characterized by poorly sorted boulder to pebble polymictic conglomerates. The presence of planar bedded intervals indicate episodic deposition by sheet flow. Less commonly conglomerates are matrix supported, and may have been deposited by debris flows (Fig. 3.4). The presence of alluvial fans is usually taken to indicate syndepositional tectonic activity, such fans develop only in areas of relatively high relief (Davies, 1983). A similar link between tectonic movements and alluvial fan deposition in the Cumberland Basin has been proposed by various workers (Bell, 1944; Fralick and Schenk, 1981; Ryan et al., 1987). The source for the detritus which composes these conglomerates is the Cobequid Highlands Massif, although to the northwest, the Caledonia Highlands Massif may also have contributed coarse detrital material. The thickness of the formation and the size of the clasts both diminish to the north. Conglomerates exposed at the axes of the anticlines, away from the basin margins, are commonly trough cross-stratified, whereas the conglomerates at the basin margins are dominated by planar or massive bedding. The areas along the margin of the Cobequid Highlands Massif are interpreted as proximal fans, and to the north near the axes of the anticlines, the formation was apparently deposited in the mid-fan area (Ryan, 1985,1986; Ryan et al., 1987).

3.2.5 BOSS POINT FORMATION

The sandstone-dominated strata of this formation have strongly unimodal sediment dispersal trends. The sandstone and mud-chip conglomerate channel deposits are multi-storied and multi-lateral, and have flat channel bases (Fig.3.5). On the basis of these criteria and the presence of horizontal stratification at the top of some of the channel sequences of this formation, the Boss Point Formation has been interpreted as representing a braided stream facies assemblage (Ryan, 1985,1986; Browne, 1990). In addition, the sandstones are commonly interbedded with alluvial fan polymictic conglomerates along the margin of the Cobequid Highlands Massif which also suggest a braided stream environment.

3.2.6 POLLY BROOK FORMATION

This formation is made up of coarsening upward cycles of polymictic cobble to pebble conglomerates, which exhibit a northward decrease in the thickness of the unit, thickness of the individual beds, and the size of the clasts (Fig. 3.6). Along the margin of the basin, adjacent to the Cobequid Highlands Massif, the conglomerates are very crudely horizontally stratified. Downflow, to the north, the conglomerates exhibit trough and tabular cross stratification and are interbedded with coarse grained arkosic sandstones (Ryan, 1986). The distribution, lithofacies assemblages, and lateral transitions of the unit, indicate that deposition took place in proximal to distal alluvial fans which emanated from the Cobequid Highlands Massif to the south (Calder, 1984a, 1991; Ryan,1986; Ryan et al., 1987).

3.2.7 JOGGINS FORMATION

Ryan et al (1987) suggested that the sandstone body configurations and sedimentary features of the Joggins Formation, indicate that the sands were deposited by an anastomosing to meandering stream transition system (Fig. 3.7). Rhythmites (alternating beds of 1 m thick sandstones, thicker mudrocks and thin beds of coal and limestone), which are interbedded with channel sandstones, have been used to suggest deltaic sedimentation may also have taken place (Duff and Walton, 1973). The number of lacustrine limestones interbedded with the fine grained rocks of the rhythmite sequences suggests that deposition occurred marginal to a large (up to several hundred km^2) inland lake system (cf. Copeland, 1959). Perhaps the setting for the deposition of the Joggins Formation strata is best described as a low gradient floodplain - lacustrine delta plain which was traversed by numerous small streams, positioned between the southern highlands with their adjacent alluvial fans, and a large inland lake near the centre of the basin.

3.2.8. SPRINGHILL MINES FORMATION

The coal-bearing strata of the Springhill Mines Formation accumulated in an inland river valley setting bordering a mature piedmont of coalesced alluvial fans derived from the Cobequid Highlands Massif, to the south (Calder,1991). Streams of the northeasterly trending trunk system differ in configuration from the streams derived from the Cobequids. Multi-lateral channel sandstones occur within the formation, and multi-storied channels with stepped bases are common (Fig. 3.8). The trunk system has been interpreted as anastomosed where it is exposed at the Joggins Shore (Rust et al., 1984). The streams exhibit moderate sinuosity in the Springhill area and have been described as anastomosing systems (Calder, 1991). Ephemeral discharge input from smaller streams entering the basin from the south merge into the larger trunk system (Calder, 1986; Boehner et al., 1986). The presence of alluvial fans which have built out for several kilometres into the basin could possibly have impeded drainage of the trunk system, a subsequent rise in water table level may have resulted in peat accumulation and development of anastomosing stream patterns in the trunk rivers (Boehner et al.,1986; cf. Calder, 1991). Calder (1991) suggests that the groundwater recharge from the fanglomerates along the basin margin may have been an important controlling factor in the development of the peat mires which are represented in the rock record as coals.

3.2.9 RAGGED REEF FORMATION

The Ragged Reef Formation has two end members with dramatically different coarse to fine ratios. In the western Cumberland Basin, and in the Roslin area north of Springhill, the formation is composed primarily of cobble- to pebble-conglomerates and coarse grained sandstones with subordinate mudrocks. In the centrai part of the Athol Syncline the strata of this formation are much finer grained and only a few thin conglomeratic horizons occur. The coarse end member of the formation was deposited by high-gradient braided streams draining from the southwest (Salas, 1986; Deal, 1991)(Fig. 3.9). The finer grained end member of the Ragged Reef Formation has been interpreted as being deposited in an area where the stream gradient has been significantly reduced (Deal, 1991). Towards the top of the Formation, both in the east and the west, there is a significant lacustrine environment recorded by the presence of thin coals and limestones (Deal, 1991). The upper parts of the formation change over a short distance from coarse strata into a grey mudstone dominated coal-bearing package (Ryan et al. 1990; Deal, 1991) . The Ragged Reef Formation therefore represents a transition from braided streams near the basin margins to meandering streams associated with lakes or ponds in the central (lower gradient) parts of the basin.

3.2.10 MALAGASH FORMATION

The strata of this formation are composed of sandstone dominated sequences with a sand/silt ratio of 0.5 . The sandstone and mud-chip conglomerate channel deposits are multi-lateral and multi-storied. The channel deposits exhibit only crude fining-upward cycles. There is little evidence of upward decrease in the scale of the sedimentary structures (Fig.3.10). The sediment dispersal trends of the unit are unimodal. Levee deposits are rare but splays are common. Fresh water limestones are commonly interbedded with the fine grained overbank deposits. Based on the biota present (see Ryan and Boehner, 1993), these carbonates are interpreted as being deposited in shallow water near the shore of the lake. The depositional setting of this formation is as sandy braided streams with associated shallow lacustrine deposits (Ryan, 1985, 1986; Ryan et al., 1987).

3.2.11 BALFRON AND TATAMAGOUCHE FORMATIONS

These formations are well exposed in the study area and intersected by numerous drill holes. The overbank mudrocks of these formations are interbedded with shallow lacustrine carbonates and mudrocks which Ryan (1986) suggested were deposited near the inner mudflat zone of large inland lakes (Figs. 3.11 and 3.12).

Although the streams of the Balfron and the Tatamagouche Formations might be classified as either low sinuosity meandering or anastomosing, they probably represent some intermediate pattern (Ryan and Boehner, 1993). The channel sequences within the Balfron and Tatamagouche Formations are up to 50 m thick and correlative for distances of 20 km or more (Fig. 3.13). The sand to silt ratio of this succession is estimated from cross-sections as approximately 1:4 . Field observations, drillhole descriptions, and lithofacies transition matrices were combined to create a hypothetical fluvial cycle for the stream deposits of the strata. The idealized cycle fines upwards from a calcareous mud-chip conglomerate, through medium- to fine-grained sandstone, to laminated siltstone at the top. The beds exhibit a concomitant decrease in the scale of the sedimentary structures. The associated transition of sedimentary structures upwards is: (1) large scale trough cross-beds, (2) small scale trough cross-beds, (3) low angle foresets, (4) ripple drift cross-lamination, and (5) planar laminated bedding (Fig. 3.14).

Crevasse splays are common and represented by thin (less than 70 cm) tabular sandstones enveloped by the overbank mudstone and siltstone (Ryan, 1986). Splay sandstones exhibit obscure coarsening-upward cycles, planar bedding, or more rarely, small scale trough cross-stratified beds.

The multi-lateral nature of the sand bodies is confusing, given the strongly unimodal paleocurrent data. The presence of laterally extensive interbedded lacustrine limestones indicates that the enclosing floodplains of these streams must have had low gradients to facilitate the episodic establishment of relatively large inland lakes. Smith and Smith (1979) suggested that a variation in sea level (lake level) or damming of the streams may have been a significant controlling factor in the establishment of anastomosing patterns. A similar effect, perhaps triggered by sudden basin subsidence which resulted in lake transgression, may have been a controlling factor in the Cumberland Basin. Tectono-allocyclic events have been documented for megasequences occurring within the Maritimes Basin (Ryan et al., 1987; Chapters 4 & 6) and similar but smaller scale occurrences of episodic subsidence may account for lake transgression events.

The depositional setting has been interpreted by Ryan (1986) as a floodplain cut by coalescing anastomosing streams, however deposition is best described as taking place on a large floodplain traversed by numerous nearly parallel straight streams with large seasonal discharge variability. These streams may have emptied into inland lakes as evidenced by the laterally consistent lacustrine limestones present in the strata.

3.2.12 CAPE JOHN FORMATION

The strata of the Cape John Formation are dominated by mudrocks interbedded with multi-storied channel deposits (Fig. 3.15). The bases of the channel deposits are commonly stepped and concave upward. The channel sequence has a poorly developed upward decrease in the scale of the sedimentary structures and the grain size fines upward. Crevasse splays are common and levees are more abundant than in the other units of the area. A few thin shallow lacustrine carbonates occur within the mudrocks, however they are not as laterally continuous as those of the Balfron and the Tatamagouche Formations. The sediment dispersal is crudely unimodal, however variations in the flow directions are much more common than in the older units. Ryan (1985, 1986) suggested that this formation was deposited on a floodplain traversed by mud-rich anastomosing streams (cf. Galloway and Hobday, 1983) with small lakes occurring between the channels on the floodplain.

3.3 SPATIAL RELATIONSHIPS OF THE FORMATIONS

Many of the environments of deposition described above were contemporaneous. This is particularly true in the Cumberland Group of western Cumberland Basin. Naylor et al. (1992) and Ryan et al. (1990) have attempted to visually portray these inter-relationships of rock units and paleoenvironments. Figure 3.16 demonstrates the relationships between the formations of the Cumberland Group. The basin margin facies are dominated by alluvial fan deposition of the poorly sorted conglomerates. The conglomerate deposition at the basin margin is coincident with fine grained sand and mud deposition away from the margins. The presence of lacustrine beds within the coal-bearing sequence of the Joggins Formation reflect rapid subsidence at the same time as alluvial fans were developed near the basin margins.

The correlation of the sedimentology of the various formations of the Cumberland Basin with the tectonics is discussed in Chapter 6 (Section 6.2) of this thesis.

3.4 IMPLICATIONS OF THE SEDIMENTOLOGY

This study, Ryan et al. (1987) and Boehner et al. (1986) have demonstrated how the sedimentology and the spatial relationships of the various facies assemblages can be used to aid interpretation of the tectonic history for Carboniferous Basins in eastern Canada (Chapter 4 & 6). For example, the occurrence of basin margin fanglomerates which are time equivalent to basinward lacustrine strata indicates a period of rapid basin subsidence or basin margin uplift. Similarly the sediment dispersal patterns for such a time interval would reflect the effects of local uplifts and concurrent basin subsidence. The lithologic patterns found within the Cumberland Basin suggest that the strata were deposited as large scale allocycles (driven by tectonic events), similar allocycles can be extrapolated to much of the Maritimes Basin.

The relationship and nature of these tectonically induced allocycles are examined in detail in Chapter 4 in relation to the structural geology, in Chapter 5 in relation to the burial and exhumation history of the strata and therefore the thermal history, and in Chapter 6 in regard to the basin development.

The presence of thick multi-storied and multi-lateral sand bodies which form permeable sheet-like deposits have important implications for the transmittal of metal-bearing fluids within the basin. Similarly the presence of ferromagnesian silicates and fresh feldspar within the rocks of the study area suggests that intrabasinal source of metalliferous fluids is plausible. These aspects of the sedimentology are discussed in the context of the economic geology in Chapter 7.

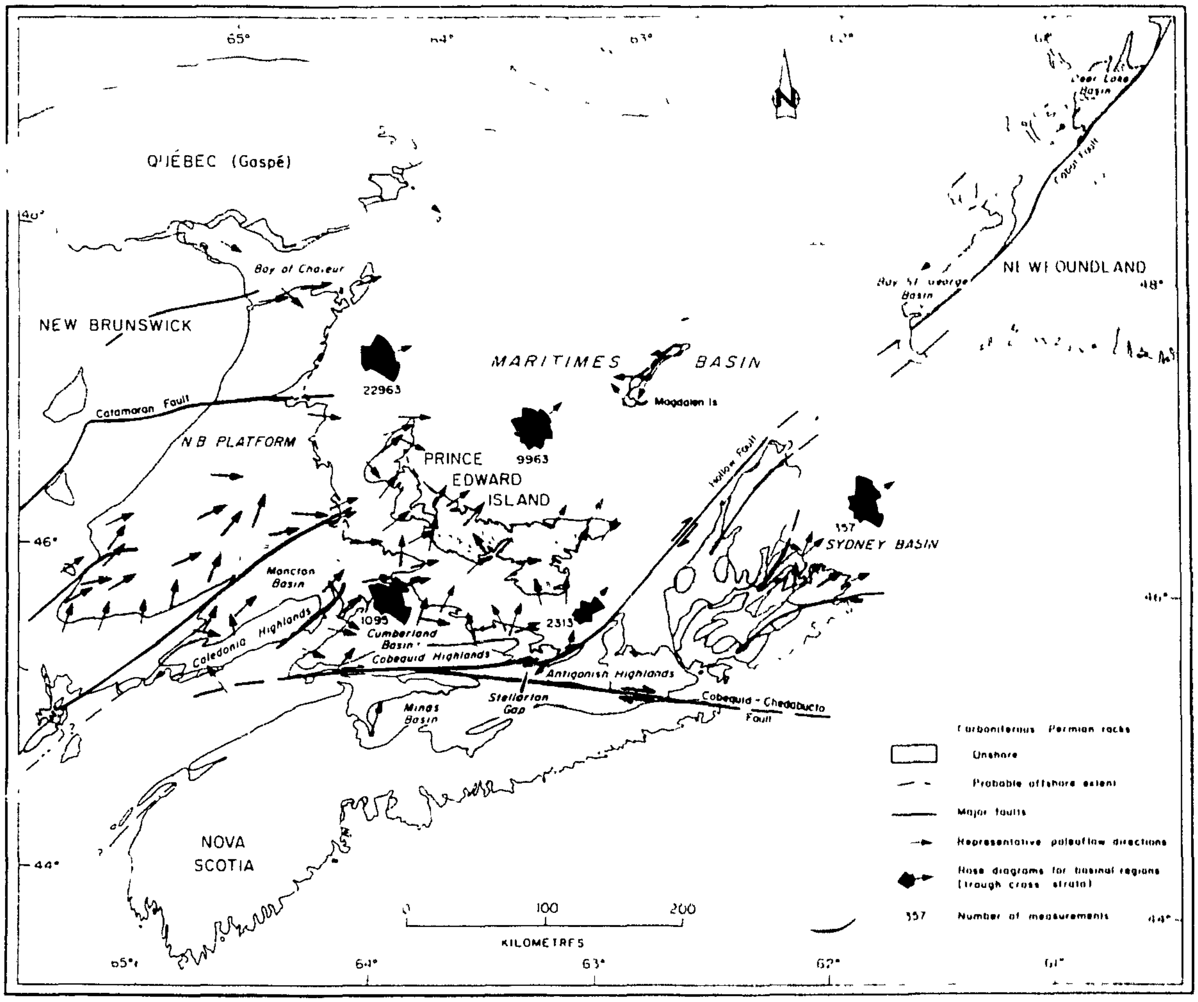


Figure 3.1: Sediment dispersal trends in the Upper Carboniferous and Permian strata of the Maritimes Basin, after Gibling et al., 1991. This diagram is a compilation of over 30,000 paleocurrent measurements, the overall trend is toward basin centre, near the Magdalen Islands, although some east-west flow along the basin axis is probable.

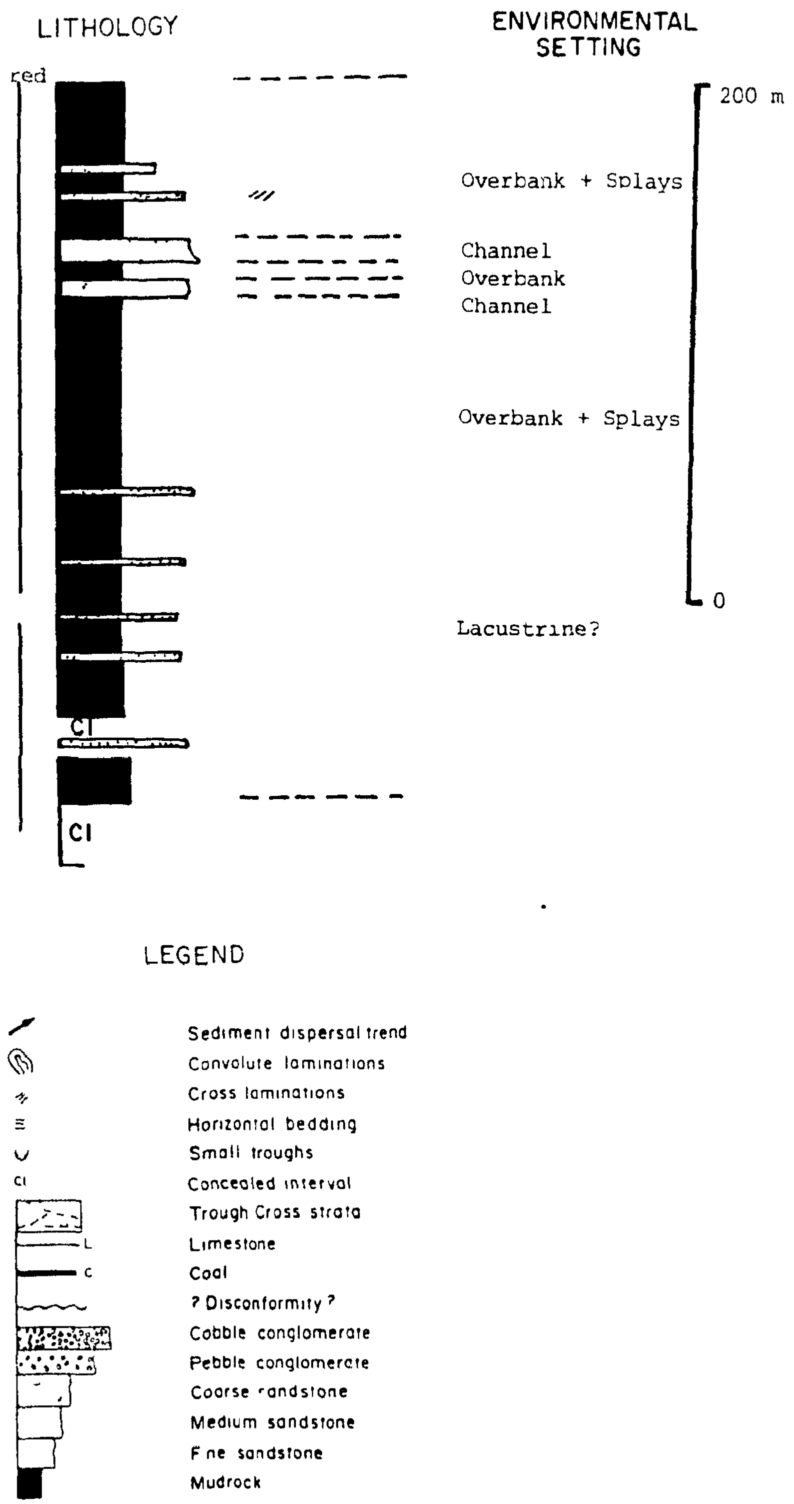


Figure 3 2: Detailed log of the Middleborough Formation, as exposed along the Joggins section, and suggested environmental setting for the various rock packages. McCabe and Schenk (1982) suggested that most of the formation was deposited on a floodplain during sheet flow and by ephemeral streams.

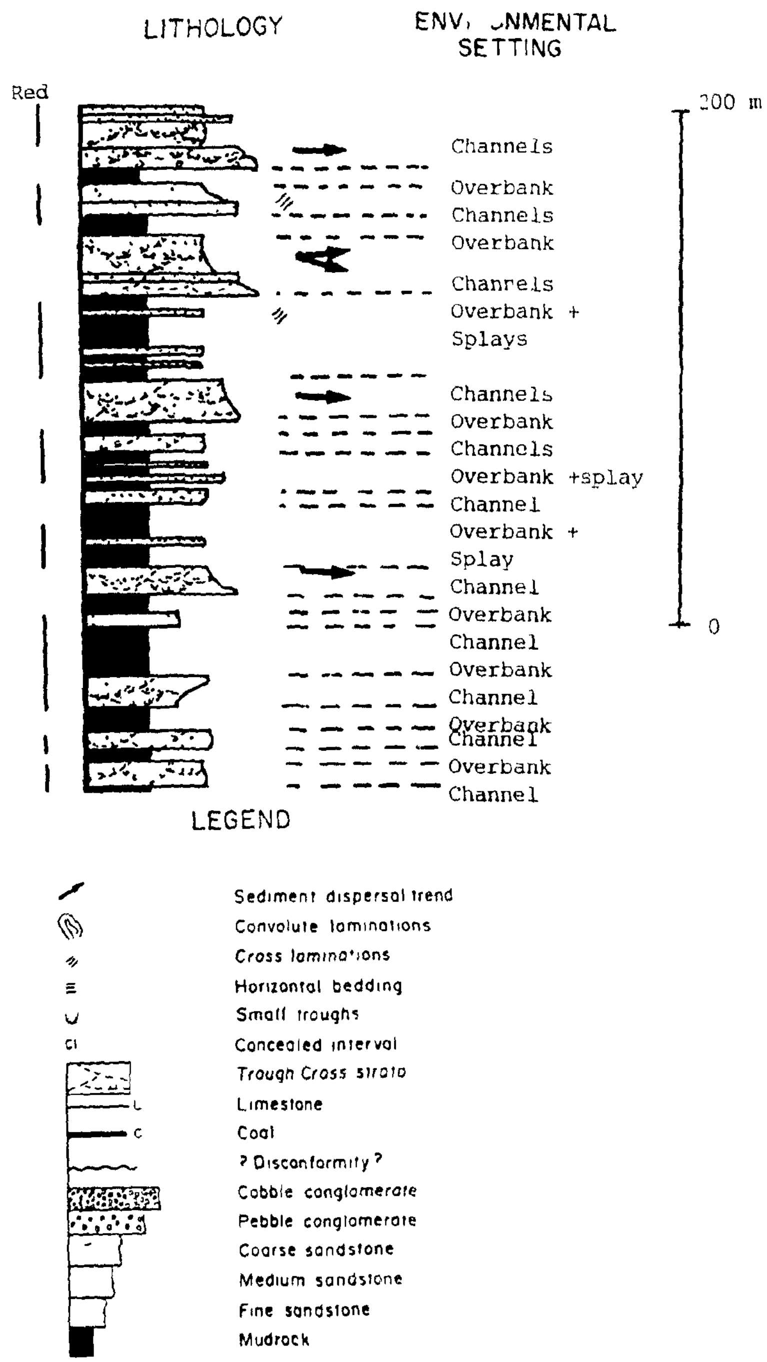


Figure 3.3: *Detailed log of the Shepody Formation, as exposed along the Joggins shore,* with the environmental interpretations of the lithofacies packages. This formation is interpreted to represent deposition in a transition between meandering streams at the base and braided streams near the top.

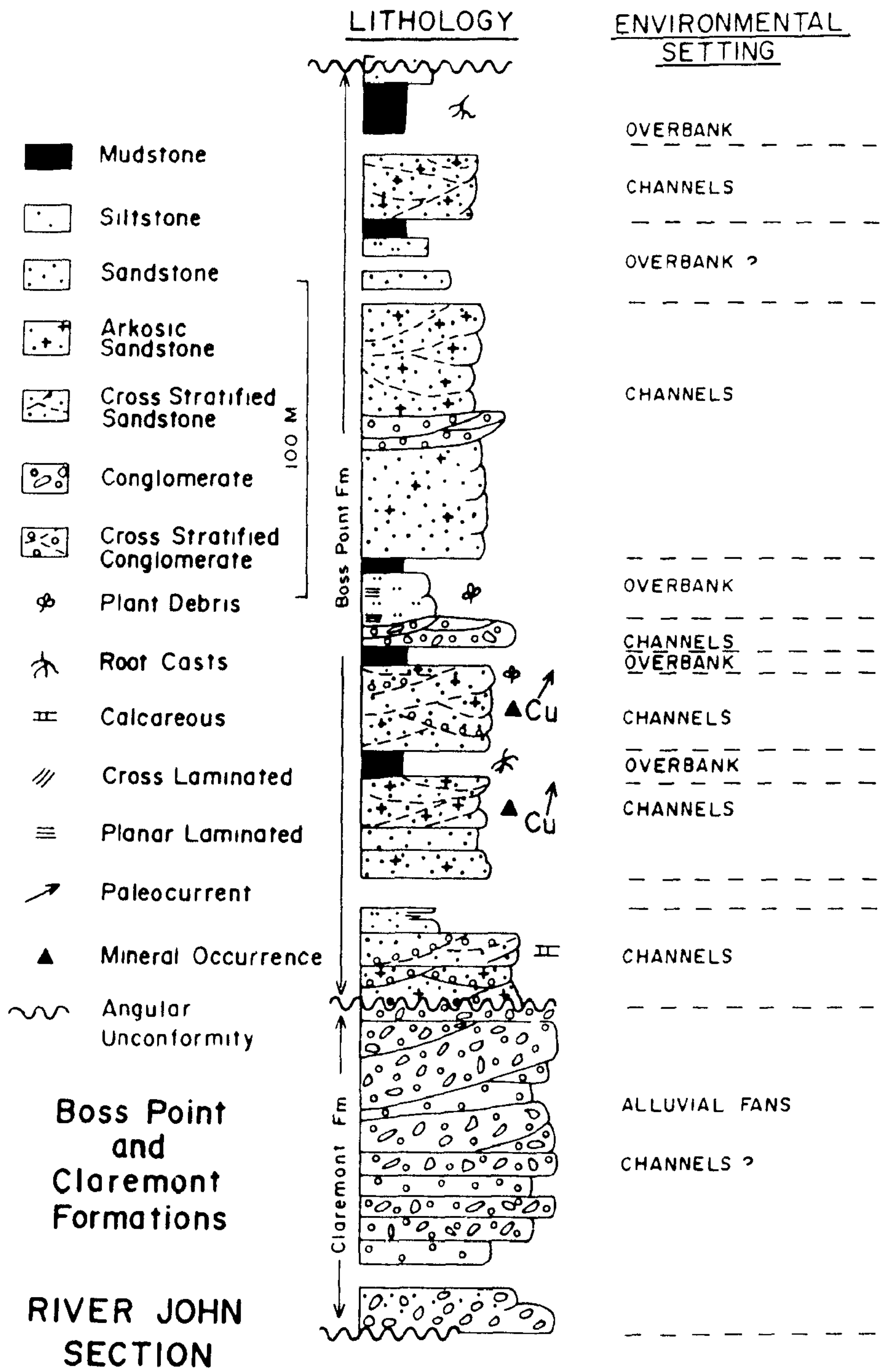


Figure 3.4: Column of the Claremont and the Boss Point formations, as exposed on the River John section, with environmental interpretations for the various lithologies. This section demonstrates the differences between the alluvial fan deposition of the Claremont Formation and the braided stream deposition of the Boss Point Formation.

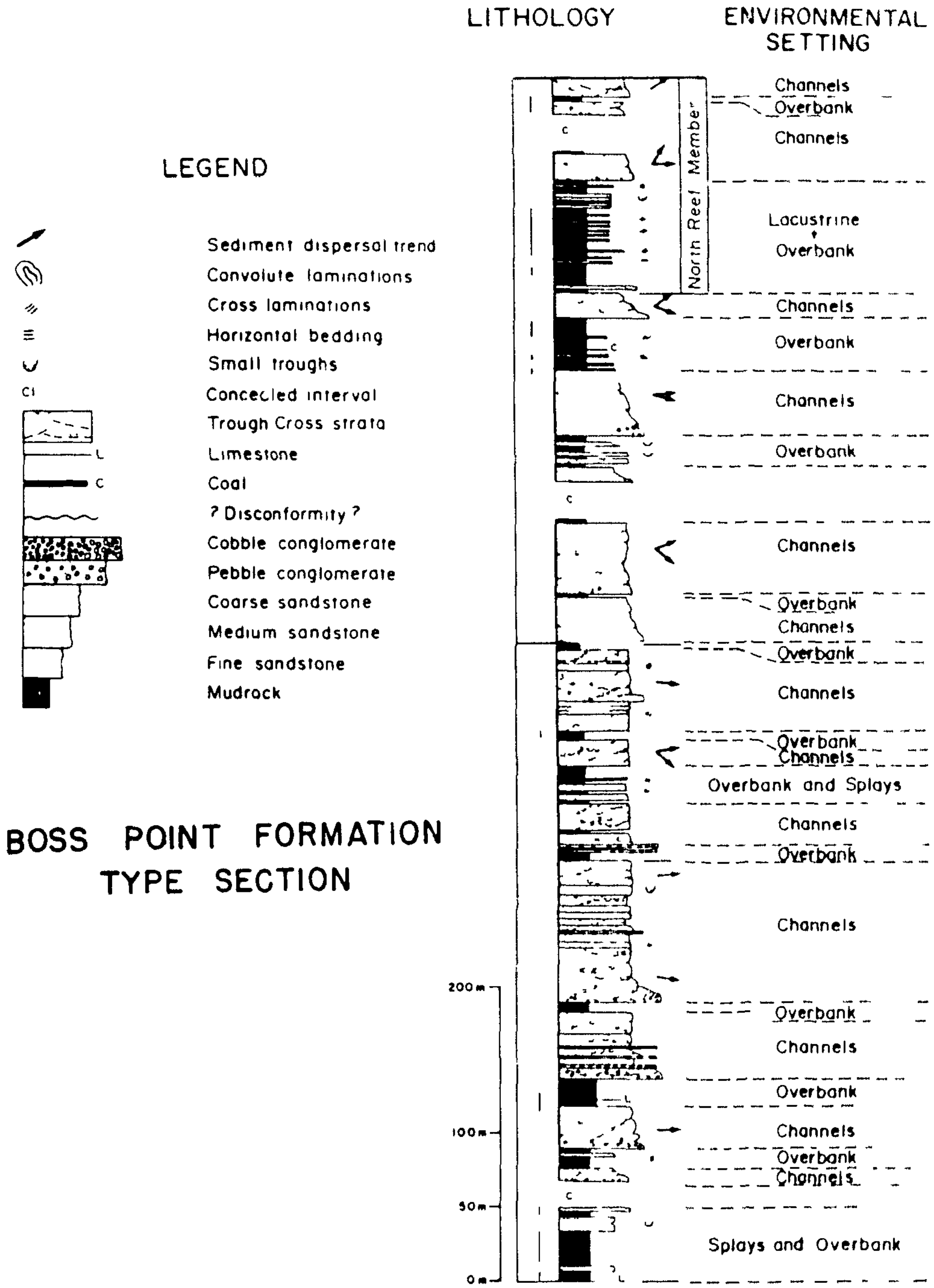


Figure 3.5: Stratigraphic column and paleoenvironmental interpretations of the various units, Boss Point Formation Type Section, Joggins section. The Boss Point Formation was deposited within braided streams.

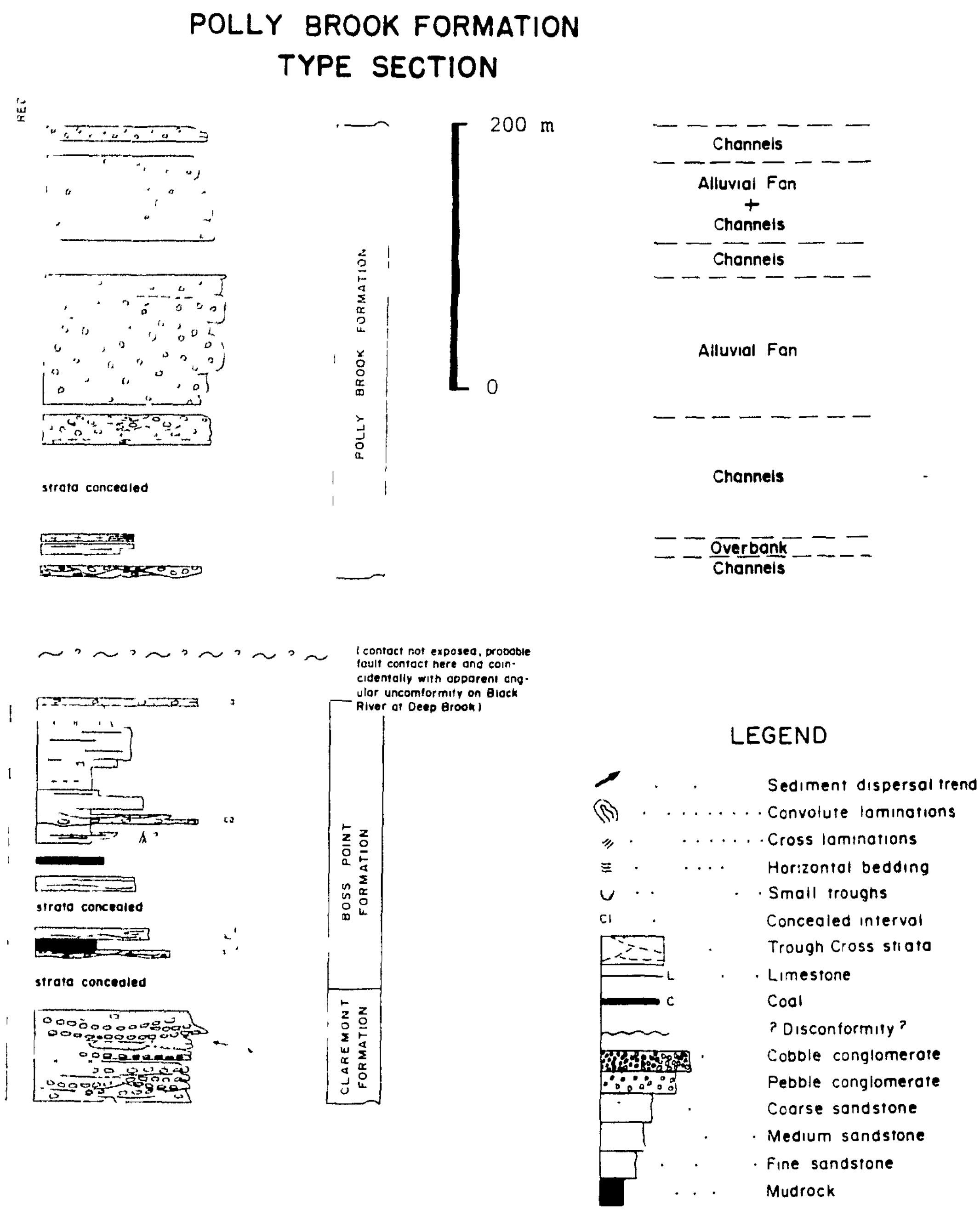


Figure 3.6: Type section of the Polly Brook Formation, Springhill area, with paleoenvironmental interpretations of the Polly Brook, Boss Point and Claremont formations in the area. Deposition of the Polly Brook Formation took place in the proximal to distal fans which emanated from the Cobequid Highlands Massif.

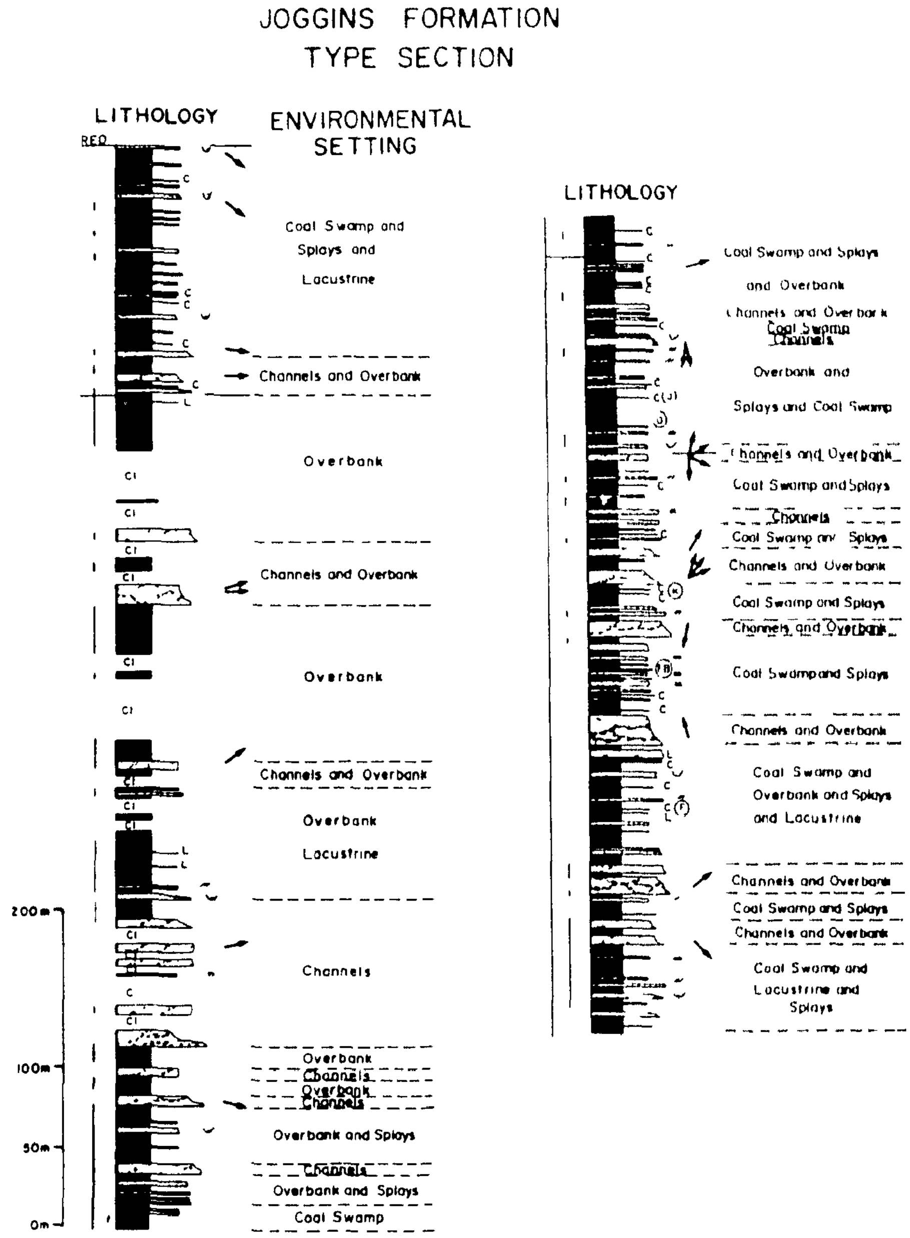


Figure 3.7: Detailed stratigraphy of the Joggins Formation Type Section and the paleoenvironmental interpretations of the various lithofacies associations. The Joggins formation was probably deposited in a low gradient floodplain-lacustrine delta plain which was traversed by numerous small streams.

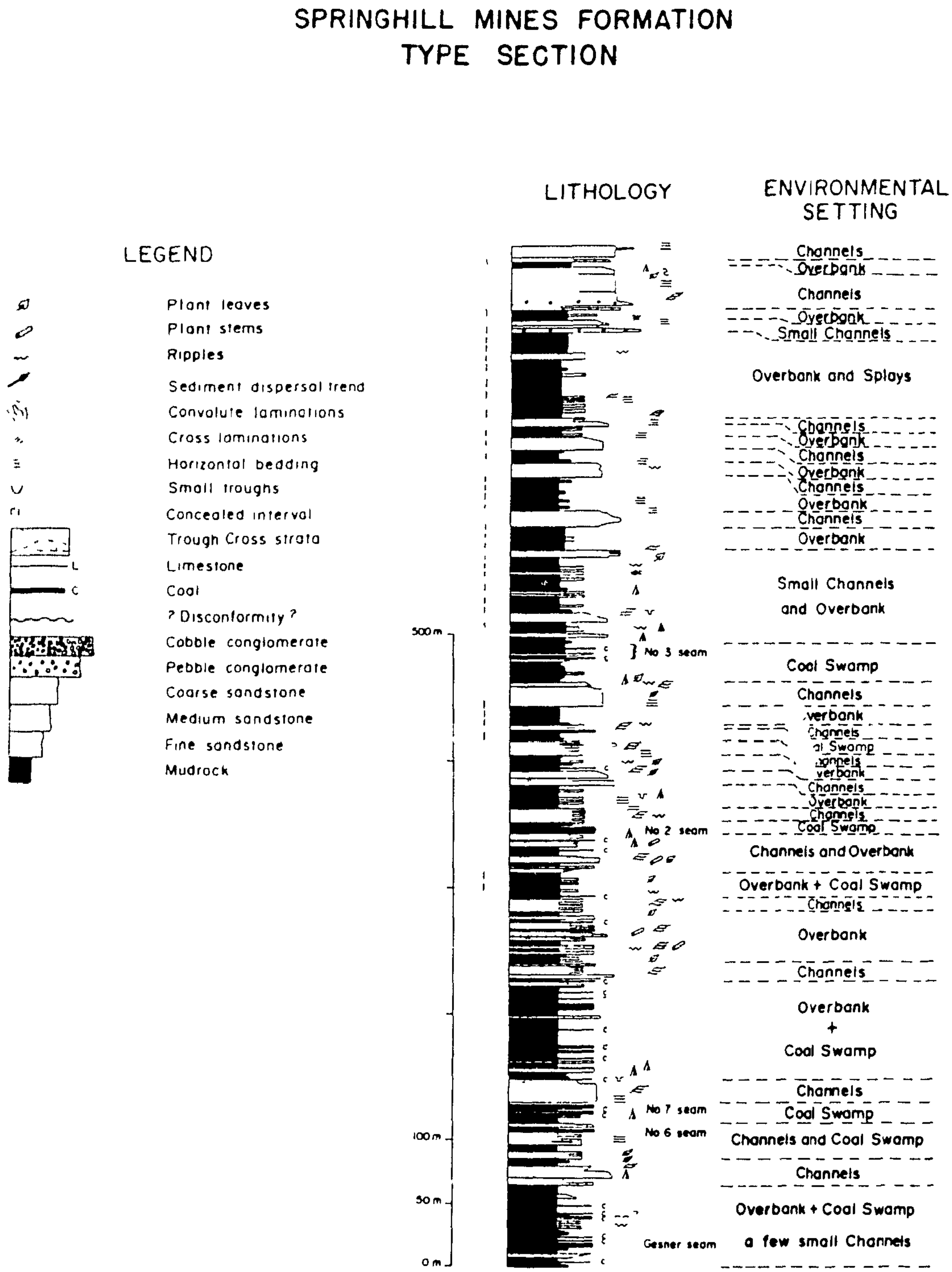


Figure 3.8: Springhill Mines Formation Type Section, Springhill area, environmental setting of the various units. Calder (1991) suggested that this formation was deposited by anastomosing streams.

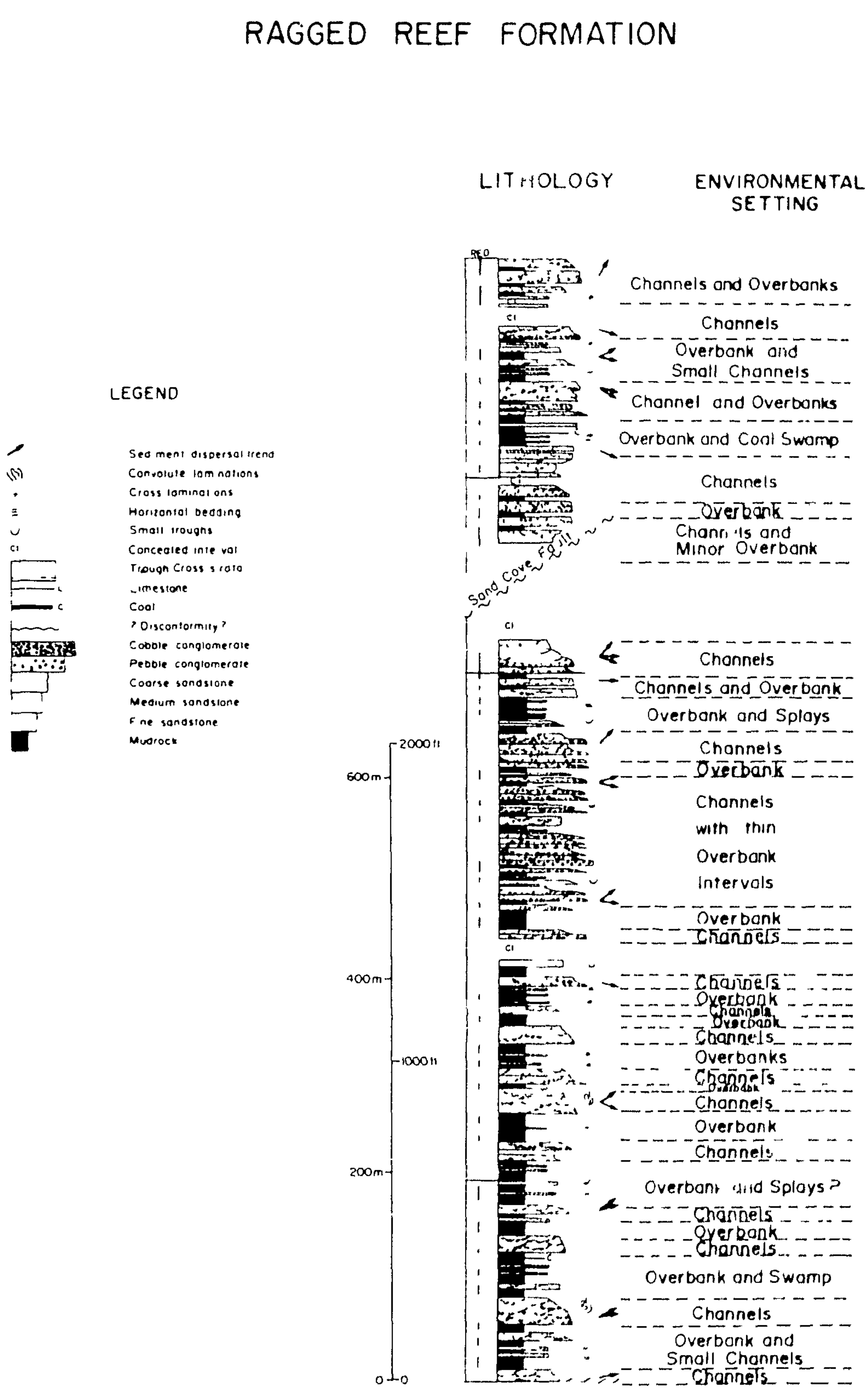


Figure 3.9: Ragged Reef Formation Type Section, Joggins section, and the environmental interpretation of the various units in the formation. This formation represents a transition from braided stream near the basin margins to meandering streams in the central parts of the basin.

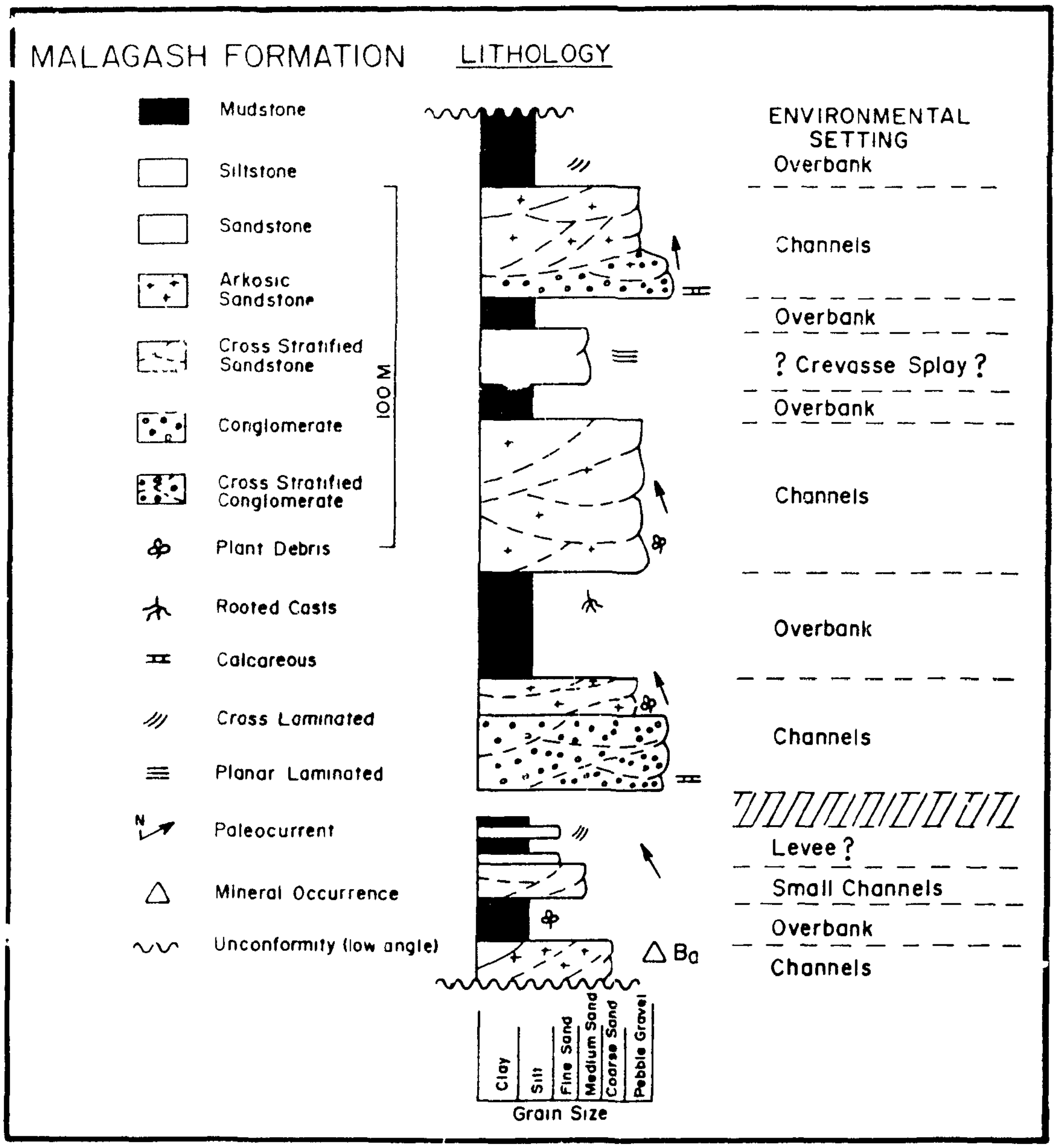


Figure 3.10: Stratigraphic column of the Malagash Formation Reference Section, River John area, and the paleoenvironmental interpretations of the various units. Note that the Type section contains lacustrine limestones (Fig. 1.6) which are not exposed at River John.

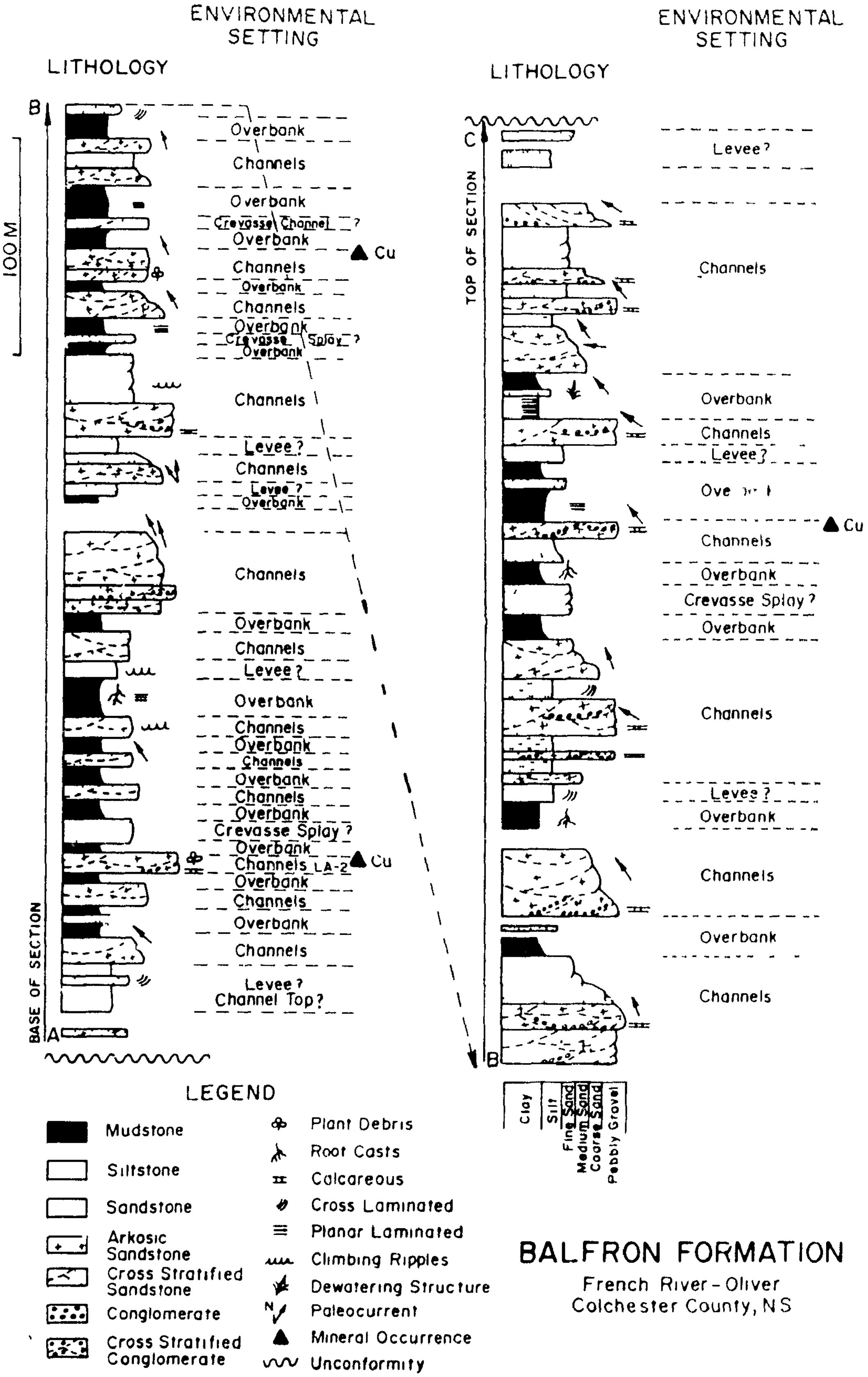


Figure 3.11: Reference section, French River, of the Balfron Formation and the environmental interpretations of the various units of the formation. The deposition of this formation probably took place in an intermediate type of stream between a low sinuosity meandering and an anastomosing stream.

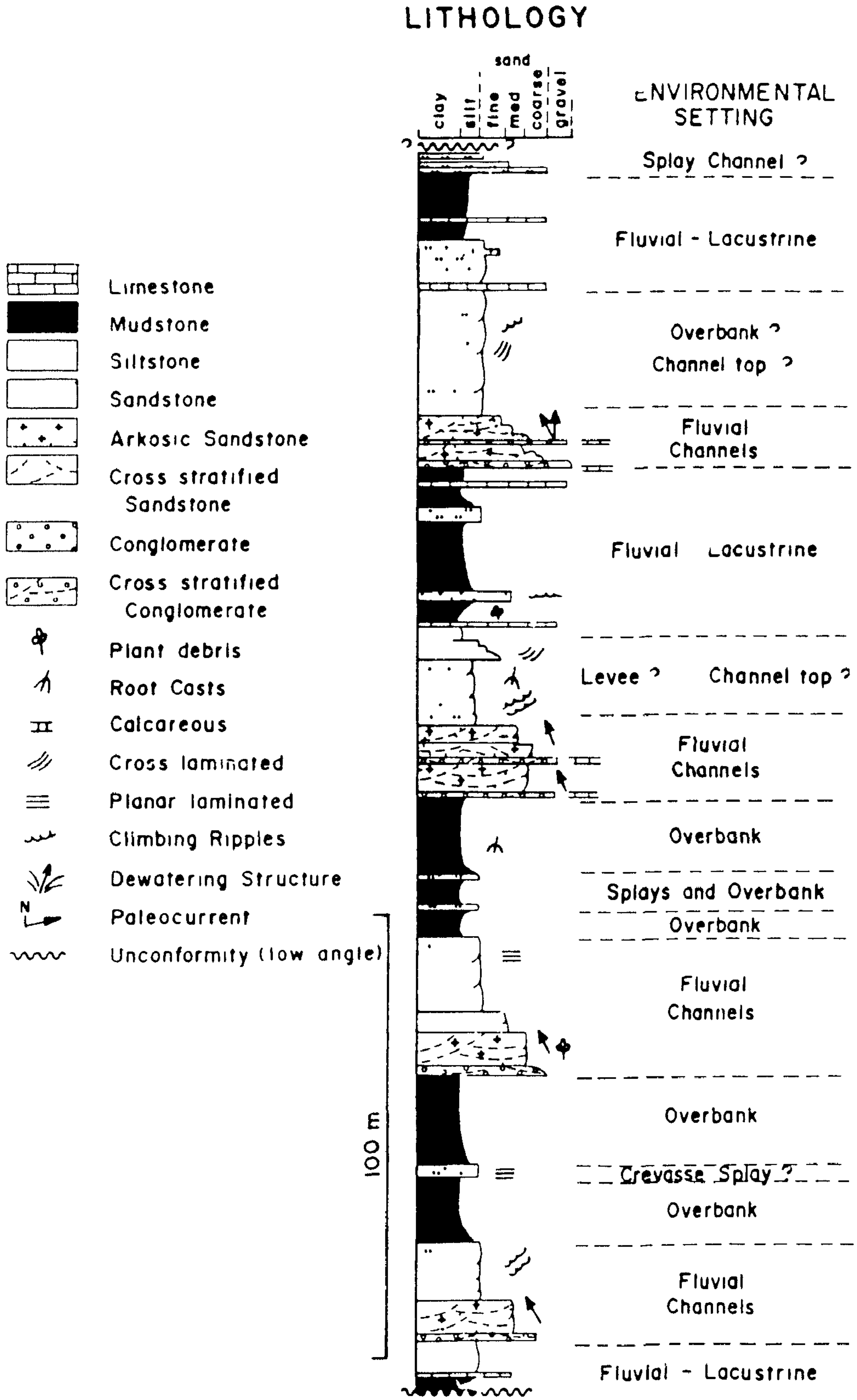


Figure 3.12. Lithologies and environmental interpretations for the Tatamagouche Formation reference section from drillhole NT-47 (Fig. 1.9) near Tatamagouche. As in previous units, reference section are used if they are better exposed or more completely represented in drilling. The environment of deposition is similar to that of the Balfron Formation.

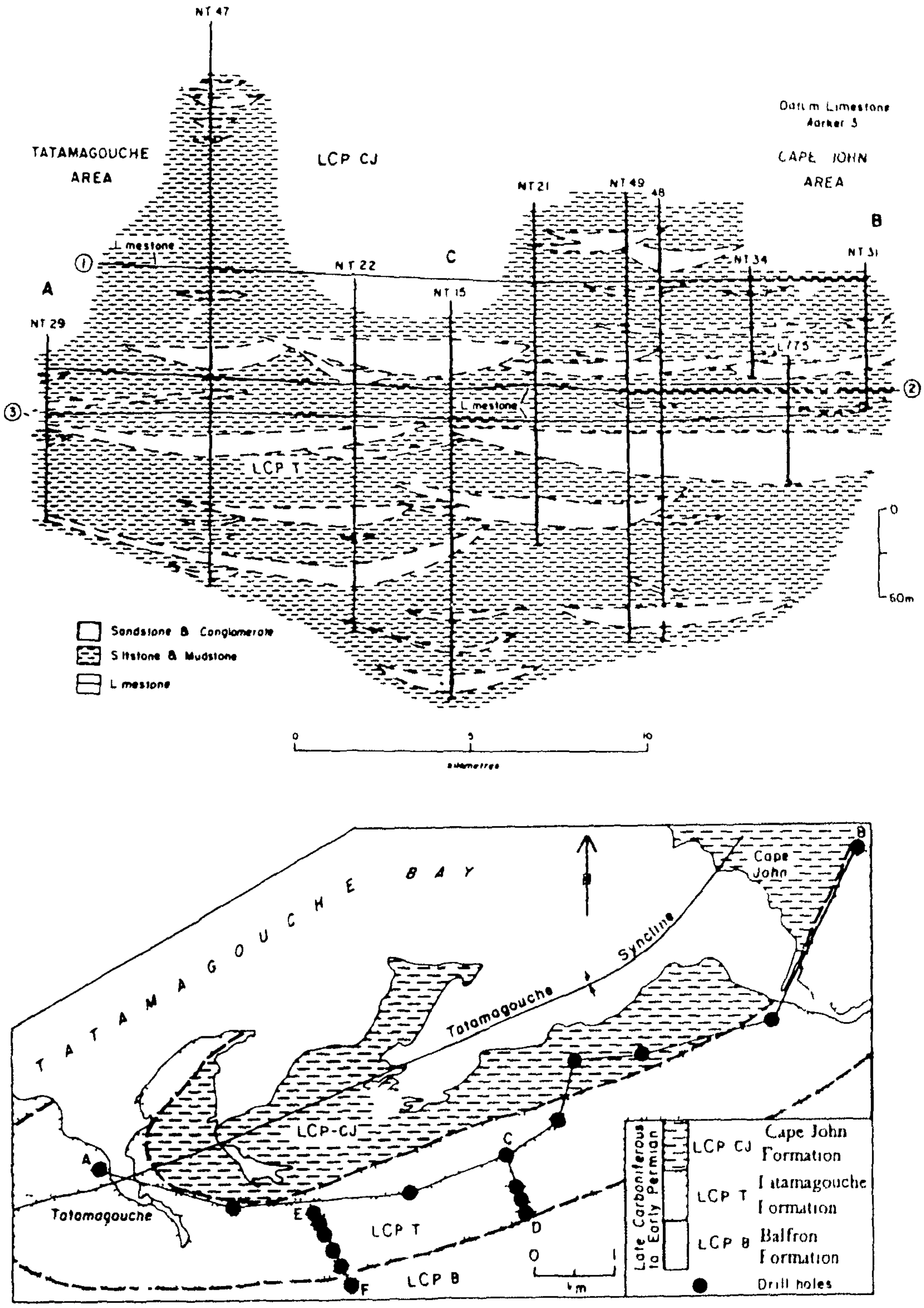


Figure 3.13: Drillhole correlation of the Tatamagouche and the lower part of the Cape John formations in the Tatamagouche area. Simplified from Ryan and Boehner (1990) NSDME Open File Illustration 90-004. Note the multi-lateral nature of the sand bodies.

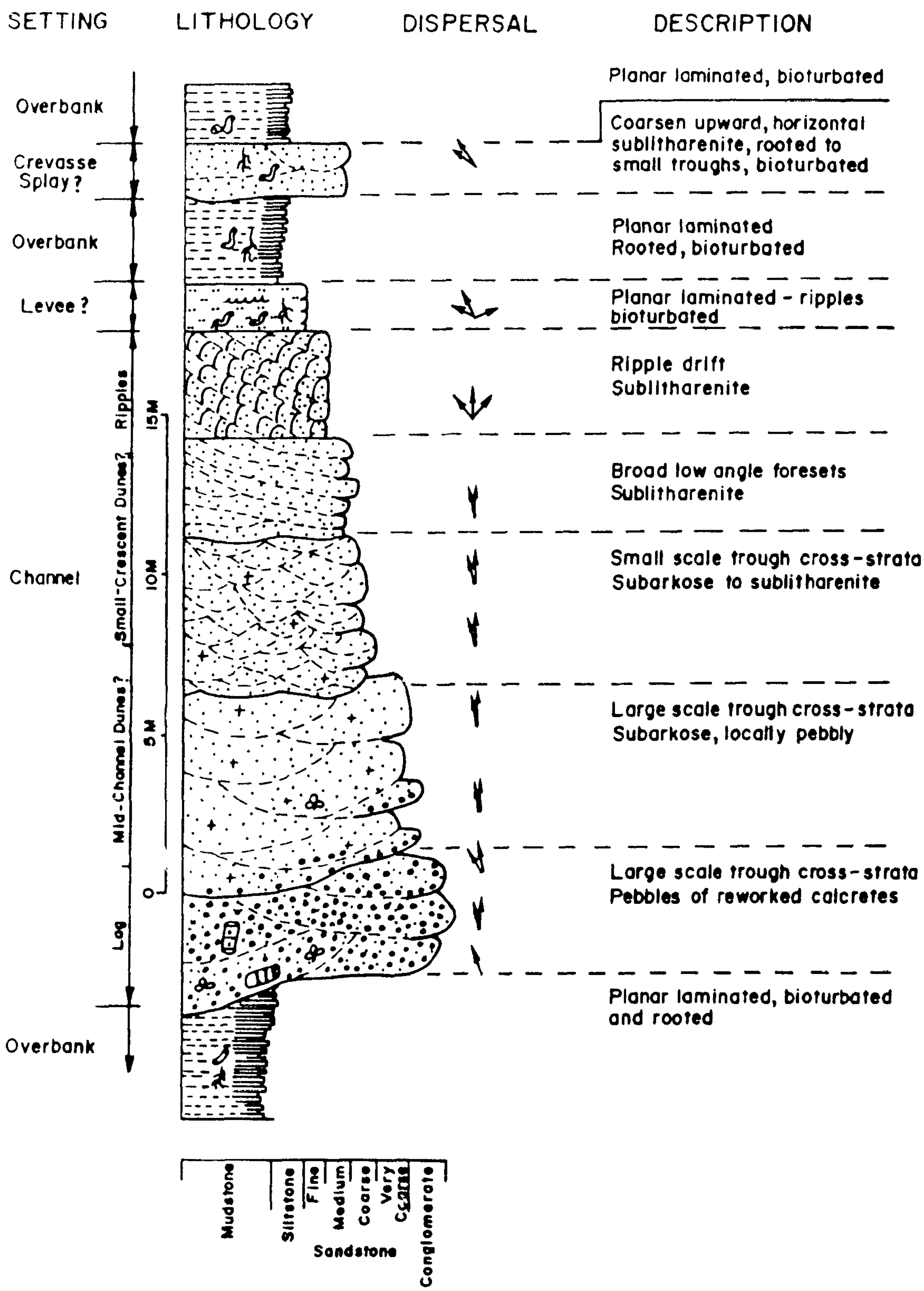


Figure 3.14: Idealized stratigraphic sequence (fluvial cycle) found within the Tatamagouche and Balfron Formations, the fluvial cycle is based on transition matrices from the formations (see Ryan and Boehner, 1992).

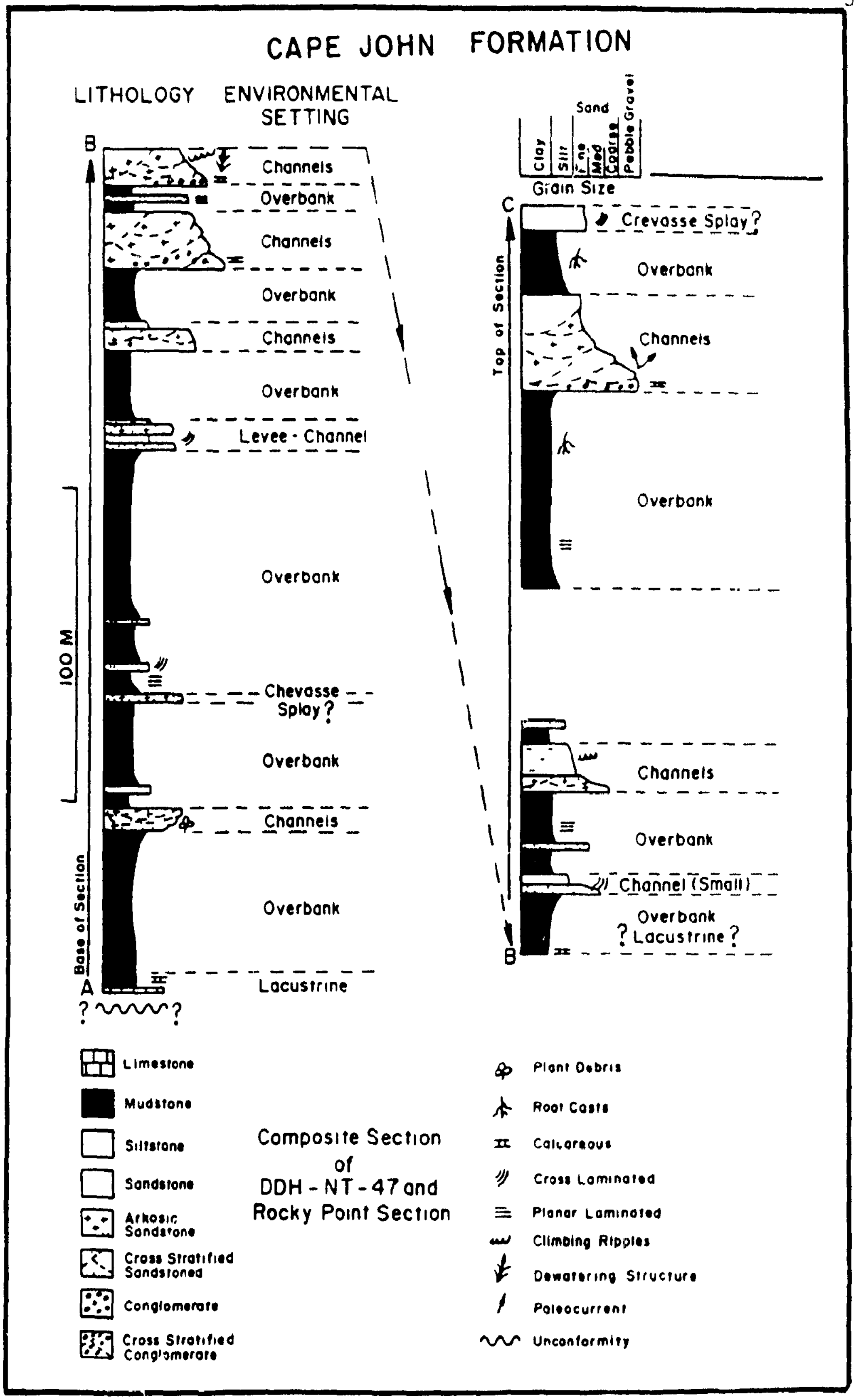


Figure 3.15: Composite reference section from DDH NT-47 and Rocky Point, paleoenvironmental interpretations of the various units. The reference section was used because it contains a more complete section.

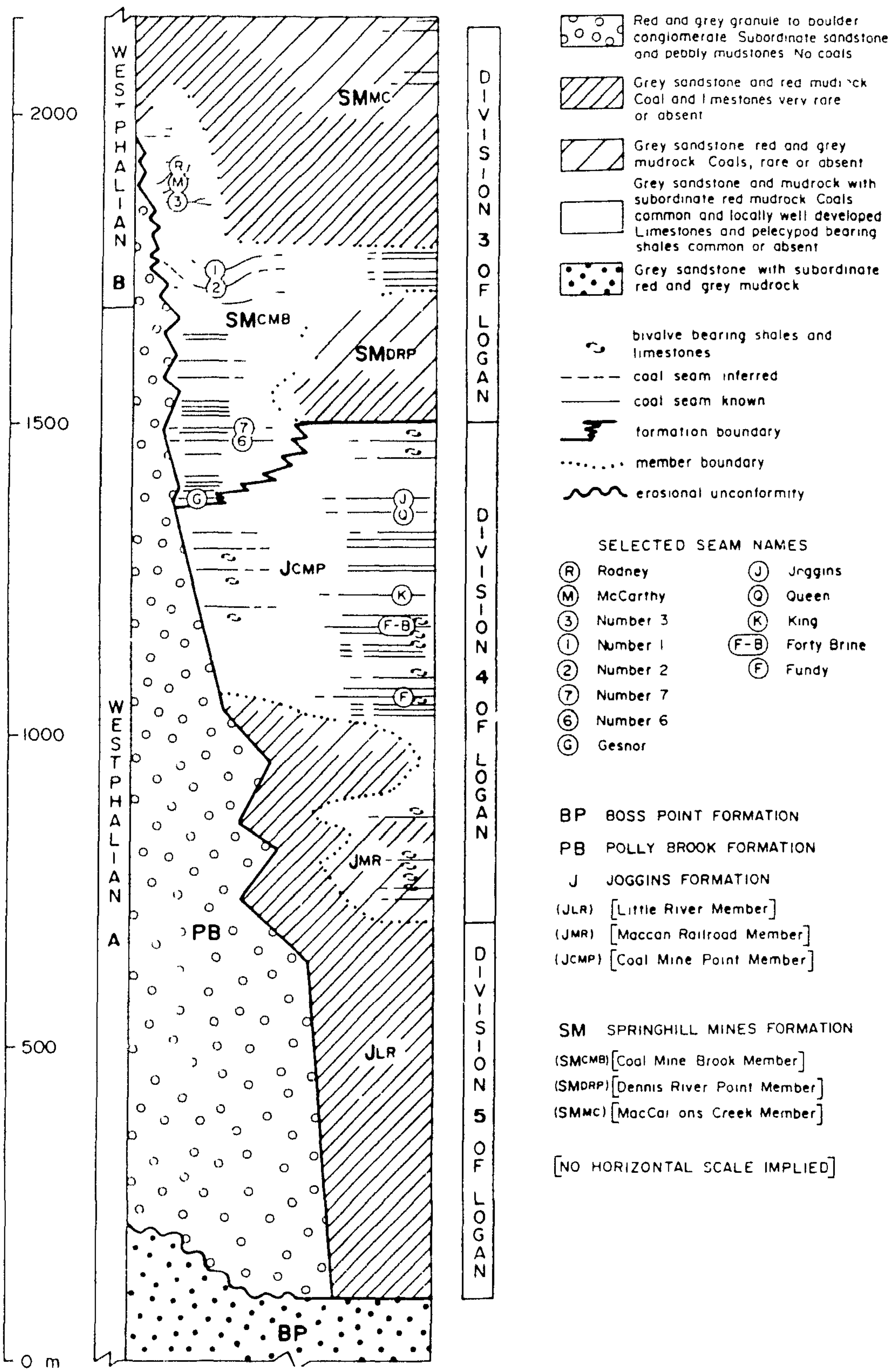


Figure 3.16: Diagrammatic representation of the relationship of various Cumberland Group formations and members in the western part of the Cumberland Basin (modified after Naylor et al., 1992). This diagram attempts to show the time-space relationships of the various formations of the Cumberland Group in the basin.

CHAPTER 4
STRUCTURE

4.1 INTRODUCTION

The structural geology of the Cumberland and Maritimes Basins is intricately interwoven with the metallogenesis and thermal history of the region. The structural and tectonic history of the basin is important to interpret with respect to: (1) relationships between tectonic and thermal events within the basins; (2) basin-forming mechanisms and how they influence the possibility of sedimentary exhalative deposits; (3) the effects of uplift and erosion (exhumation) on the likelihood of late diagenetic groundwater-related mineralization; and (4) the role of faults as conduits and hosts for diagenetic and epigenetic mineral deposits. This chapter and Appendix II outlines the structural features of the Cumberland Basin. Because tectonics can influence the movement of mineralizing fluids in sedimentary basins (eg. Oliver, 1986; Jowett 1986, 1989), this aspect of the metallogenetic history is addressed here. Structural information is combined with the geological and thermal constraints in order to suggest a possible tectonic and basin development history for the larger Maritimes Basin within the context of global tectonics (see Chapter 6).

4.2 MARITIMES BASIN OVERVIEW

Essentially two tectonic models for the development of the Maritimes Basin have emerged from a multitude of hypotheses: 1) a rift model on a wrench system proposed by Belt (1968a) and 2) a dextral strike-slip pull-apart model proposed by Bradley (1982). McCutcheon and Robinson (1987) suggested that the key to understanding the tectonics lies in a better understanding of the kinetics of the Cobequid-Chedabucto and the Belleisle faults. These faults, together with the Long Range, Taylors Brook, Green Bay, Hollow, Aspy, Norumbega, and Fredericton faults (Fig. 4.1), hold the key to understanding the tectonic framework. A detailed investigation of all of these structural features is beyond the scope of this thesis, however valuable information about movement along the Cobequid-Chedabucto Fault and its subsidiaries, which can be derived from the Cumberland Basin study area, is included here. The information from the Cumberland Basin can be combined with other recent studies (eg. Yeo and Ruixiang, 1987) on the fault movements in the Maritimes Basin in order to propose new constraints on the basin-forming mechanisms.

4.3 CUMBERLAND BASIN STRUCTURAL STUDY

The most significant structural features contained within or directly influencing the Cumberland Basin are: (1) the Cobequid - Chedabucto Fault System (Minas Geofracture); (2) the North Fault (Keppie, 1976) along the northern margin of the Cobequid Highlands Massif; and (3) the Cumberland Basin and its internal structures (Fig.4.2). In this chapter these features are examined and inferences as to their origin are used to reconstruct the tectonic and resultant sedimentological history of the Cumberland Basin. This information is dove-tailed with thermal constraints (presented in Chapter 5) in order to assess basin development models (Chapter 6). The smaller scale more detailed information on the structure of the Cumberland Basin are presented in Appendix II.

4.4 COBEQUID - CHEDABUCTO FAULT SYSTEM

4.4.1 LOCATION AND DISPLACEMENT

The Cobequid - Chedabucto Fault System (Minas Geofracture) is an east-west trending series of faults with a complex movement history, separating the Meguma Terrane from the Avalon Terrane in northern Nova Scotia (Fig.4.1) (Donohoe and Wallace, 1985). The on-land trace of the fault system is over 300 km long (Mawer and White, 1987), extending from Chedabucto Bay in the east to Chignecto Bay in the west. To the west beneath the Bay of Fundy the Cobequid-Chedabucto Fault System curves to a southwesterly trend and changes to a complex flower structure (Nance, 1988). The fault zone is linked to Late Carboniferous convergent thrust faulting and metamorphism which occurred in southern New Brunswick. The structure is further complicated in the Bay of Fundy area by the superimposed Mesozoic Fundy Rift, and by northeast trending regional faults in southern and south-central New Brunswick. To the east, the fault system is similarly complicated by the Mesozoic Orpheus Graben structure extending eastward from Chedabucto Bay (Fig. 4.1).

Individual faults within the system have been described as having normal, reverse, dextral, or sinistral displacement (Eisbacher, 1969, 1971; Keppie, 1982; Mawer and White, 1987). Mawer and White (1987) concluded that displacements are expected to vary within a fault zone that is of strike-slip origin. Most of the workers over the last thirty years, have suggested that the Cobequid-Chedabucto Fault System is a strike-slip movement zone (Eisbacher, 1969, 1971; Webb, 1969; Bradley, 1981; Keppie, 1982; Donohoe and Wallace, 1985, Mawer and White, 1987), whereas earlier workers such as Bell (1944, 1958), suggested that normal faulting took place along the fault zone at the basin margins. Net dip-slip movements occurred along the faults, as evidenced by the basin margin fanglomerates, however these movements may have been relatively minor in comparison with the interpreted strike-slip displacements.

Keppie (1982) suggested that during the Mesozoic the fault system had a complete reversal in displacement sense from dextral to sinistral strike-slip movement. Mawer and White (1987), on the basis of their research of the microstructures in the fault zone at either end of the on-land trace, concluded that the fault zone had a protracted history of dextral strike-slip movement. No evidence for major sinistral movement was documented. Yeo and Ruixiang (1986) and Fralick and Schenk (1981) suggested, based upon structural and sedimentological studies in and adjacent to the Hollow and Cobequid Fault zones in the Stellarton area, that these faults underwent dextral offset. The Hollow and the Cobequid Faults are both part of the Cobequid - Chedabucto Fault System. Dextral movement along the faults is well documented and it seems reasonable to assume that some degree of sinistral accommodation was possible in the Mesozoic, however the sinistral offset may have been taken up by smaller subsidiary faults within the zone.

The actual amount of displacement along the fault zone is not well documented. Donohoe and Wallace (1985) suggested that there was between 20 and 85 km of post-Devonian dextral offset on the system along the Cobequid Highlands Massif, based on the offset of rhyolitic and granitic rocks on either side of the fault zone. Keppie (pers. comm.) suggested that the dextral offset may be as much as 200 km, based on the occurrence of Torbrook Formation clasts in the Middle Devonian rocks. These clasts, contained in strata near Chedabucto Bay at the eastern end of the on-land trace of the fault system, are 200 km east of the nearest Torbrook Formation outcrops south of the fault zone. Yeo and Ruixiang (1987) suggest that 20 to 35 km of dextral displacement took place along the fault during the Late Carboniferous.

In summary, it can be concluded that a minimum of 20 km of strike-slip offset occurred and perhaps as much as 200 km. In addition to the strike-slip movement there has been episodic dip-slip movement as evidenced by the local fanglomerates adjacent to highland areas near the fault zone.

4.4.2 TIMING OF THE MOVEMENTS

Faulting within the Cobequid-Chedabucto Fault System is interpreted as beginning by the Middle Devonian or earlier (Schenk, 1971; Keppie, 1982; Donohoe and Wallace, 1985), and continuing intermittently (recorded locally by episodic coarse sedimentation) throughout the Carboniferous (Donohoe and Wallace, 1985; Yeo and Ruixiang, 1986; Ryan et al, 1987). Donohoe and Wallace (1985), and Ryan et al. (1987) estimated the timing of the net dip-slip movements along the fault zone, on the basis of the presence of thick fanglomerates adjacent to the faults, as Namurian and Early Westphalian. These dip-slip movements may have occurred without any associated strike-slip movements, or more likely, as a component of the strike-slip displacement (Donohoe and Wallace, 1985). The Namurian to early Westphalian age of the fanglomerates constrain the timing of the tectonic events within the Maritimes Basin adjacent to the Cobequid - Chedabucto Fault, serving as an aid in modelling of the basin evolution (cf. Fralick and Schenk, 1981; Yeo and Ruixiang, 1987; Ryan et al., 1987).

The author has compared the movements along this fault zone with those of the North fault and the results are discussed in section 4.3.2 of this chapter. Additional discussion of the timing of the faulting and the implications of the fault movements, is integrated into a discussion of basin evolution in chapter 6.

4.5 NORTH FAULT

4.5.1 LOCATION AND DISPLACEMENT

The term "North Fault" was introduced by Keppie (1976) to define the zone of faulting (including the Spicers Cove Fault) which occurs on the northern flank of the Cobequid Highlands Massif (Fig.4.3). The fault zone forms part of the southern boundary of the Cumberland Basin. The on-land fault trace is locally overlapped by Upper Carboniferous rocks (ie. south limb of the Tatamagouche Syncline) and at other places it clearly displaces rocks of similar age, indicating a complex movement history. Radar imagery shows the fault as a series of linears, extending from River Philip to Earltown (Keppie, 1976). The zone can be traced in the subsurface, using seismic profiles, as far east as River John. West of River Philip the fault trace becomes irregular, and is apparently represented in the west by the Spicers Cove Fault and the Athol, Sand River and Sand Cove faults. Keppie (1976) concluded that the irregular configuration in the west was due in part to overstepping Upper Carboniferous cover south of the fault trace. He suggested that there must have been a Late Carboniferous to Permian reactivation of the fault which accounted for the presence of the lineation in the Carboniferous cover rock. Field mapping in the western part of the basin indicates that the fault is not overlapped by Upper Carboniferous strata and that the fault at surface separates Devonian (or possibly Early Carboniferous) conglomerates on the south from Upper Carboniferous strata north of the fault. Moderate to shallow dips on the fault, thick glacial cover, and cross-faulting may account for the more irregular trace of the fault. Seismic lines which transect this fault are interpreted by Chevron Standard (Nantais, pers. comm.) as indicating a thrust component to the faulting. Although older strata may overlie the Upper Carboniferous basin-fill units at some localities along the fault, a low angle (<45) strike-slip displacement could also result in a similar configuration of the strata (Fig.4.4).

Most of the seismic data for the area are confidential (as of summer 1992) and therefore unavailable for publication at this time. However, insights into the nature of the faulting along the Cumberland Basin margins based upon these data, as well as from the GSC seismic data (Calder and Bromley, 1988), are incorporated into the geological cross sections (Fig.4.5). In the western part of the Cumberland Basin the North Fault is not one fault occurring in isolation but is a composite of numerous splays that displace Upper Carboniferous strata in the basin. The nature and location of these associated faults are discussed in section 4.4.4.4 of this chapter. The North Fault is parallel to the Cobequid-Chedabucto Fault System and the faulted axes of the Minudie and Claremont anticlines. Piper et al. (1988) described a (?) pre-Cumberland Group (late Westphalian A to B) northward overthrust structure in mylonitic zones in the western part of the Cobequid Highlands. They related this to convergent tectonics along portions of the Cobequid-Chedabucto Fault System. These ductile structures were apparently overprinted by later brittle faults of Mesozoic age. In summary, the North fault is the northern boundary fault of the Cobequid Highlands Massif which has been onlapped by Carboniferous strata of the Cumberland Basin. This fault was active from the Namurian until the Mesozoic.

4.5.2 TIMING OF DISPLACEMENT

Ryan et al. (1987) examined the timing of fanglomerate deposition on the Cobequid and North Faults and suggest that the timing of net dip-slip movements on the faults were almost identical with the major movements taking place in the Namurian and Early Westphalian (Fig.4.6). The subsequent displacement of the Upper Carboniferous strata indicates that a post Carboniferous (Permian to Mesozoic?) movement has also occurred and impacted on the structure within the basin (Fig.4.5).

In the Tatamagouche area in the eastern Cumberland Basin, dips of the Lower Carboniferous strata along the southern margin of the basin adjacent to the North Fault are approximately 25-35 degrees north. The younger Pictou Group strata have a dip of only 5-15 degrees north, at the same distance from the fault trace. This angular discordance suggests that net dip-slip movement occurred in the east during the Early Westphalian, even though Early

Westphalian fanglomerate deposition did not occur in this area of the basin In the extreme western part of the Cumberland Basin there are no Pictou group strata overlying the Cumberland strata and therefore no inference can be made.

4.6 IMPLICATIONS

The structural geology of the Cumberland Basin (see Appendix II) demonstrates that there have been numerous tectonic events affecting the strata in the area. The tectonic events span a long period of time, from syn-depositional through to the Mesozoic Structural features in the study area can be divided into 1) major terrain features (eg. Cobequid-Chedabucto Fault System), 2) small scale basin development faults and folds, 3) evaporite diapirs and salt removal structures, 4) post Permian brittle deformation related to the Triassic rifting, as evidenced by the Triassic fill in Chignecto Bay By combining the structural data on the relative movement and the timing of the movements with the stratigraphic information in Chapter 2, it is possible to suggest limits to the types and extent of tectonics which have occurred throughout the basin history In the chapters to follow, the structural geology plays a key role in the interpretation of the thermal history of the basin, the basin forming mechanism and development, and finally the metallogenetic evolution of the basin. Faults are numerous and may have acted as conduits for mineralizing fluids at various times in the basin history.

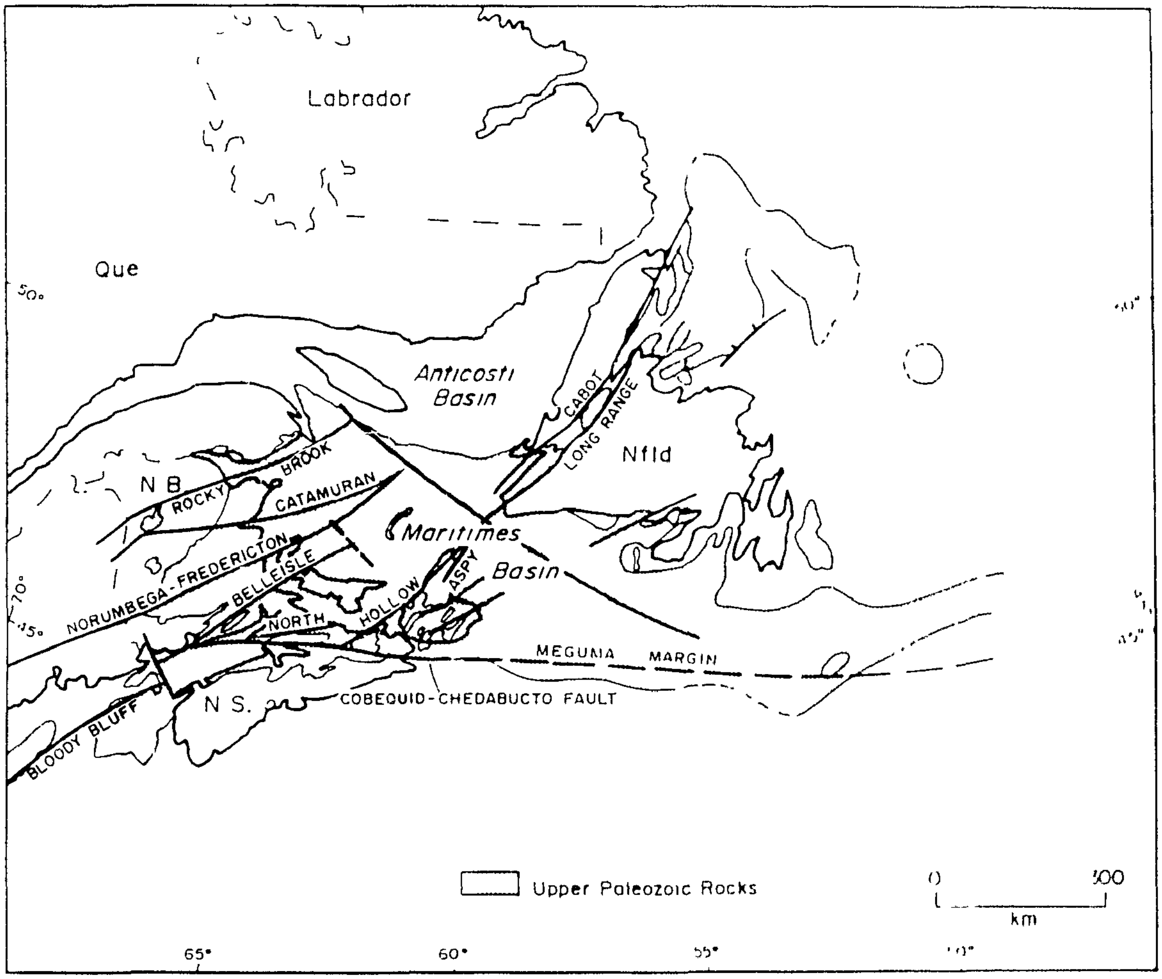


Figure 4.1: Simplified structural features of the Maritimes Basin in Atlantic Canada. The main features are the strike-slip and thrust faults.

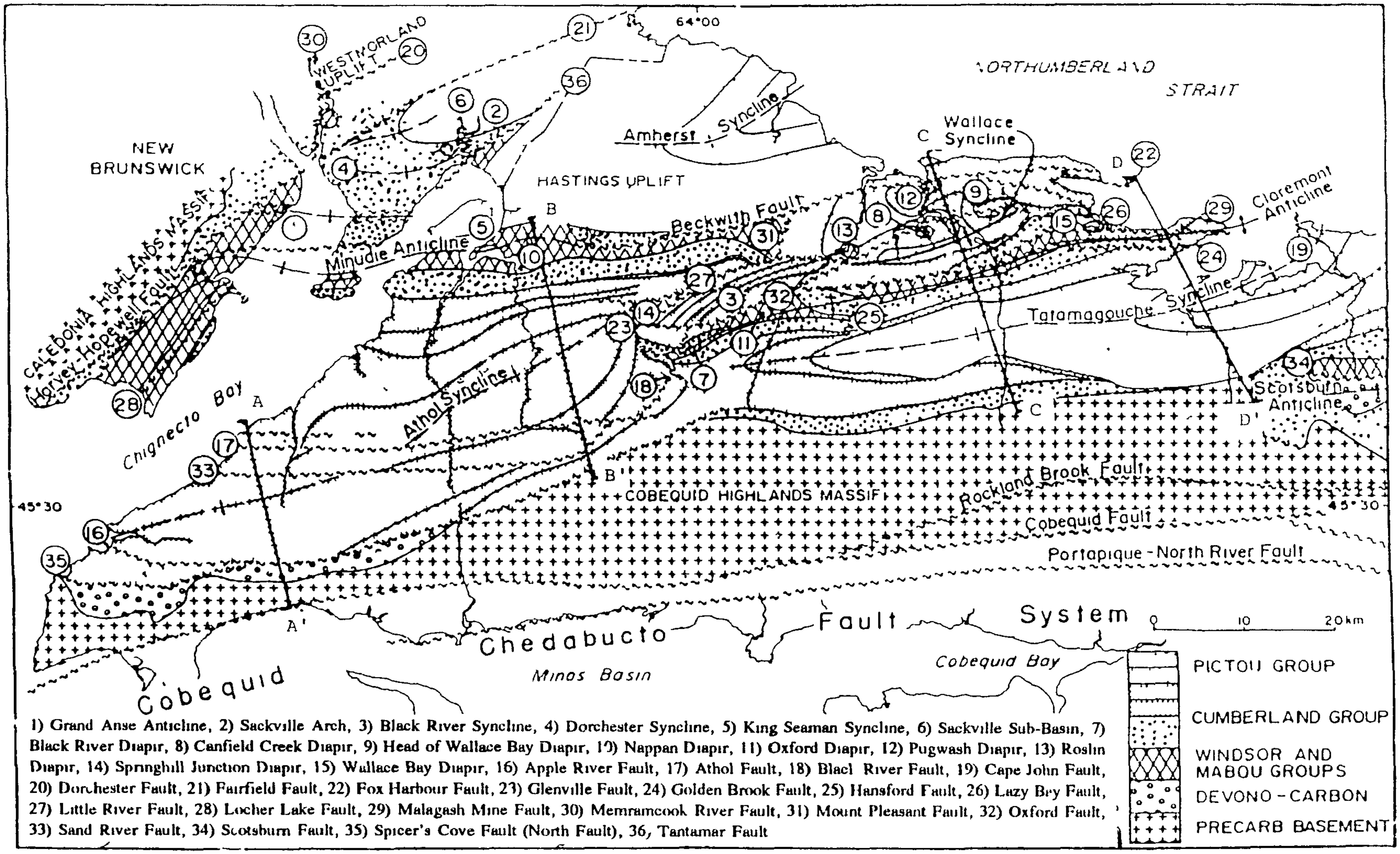


Figure 4.2: Geology and structure of the Cumberland Basin. Locations for cross sections (see Fig. 4.5).

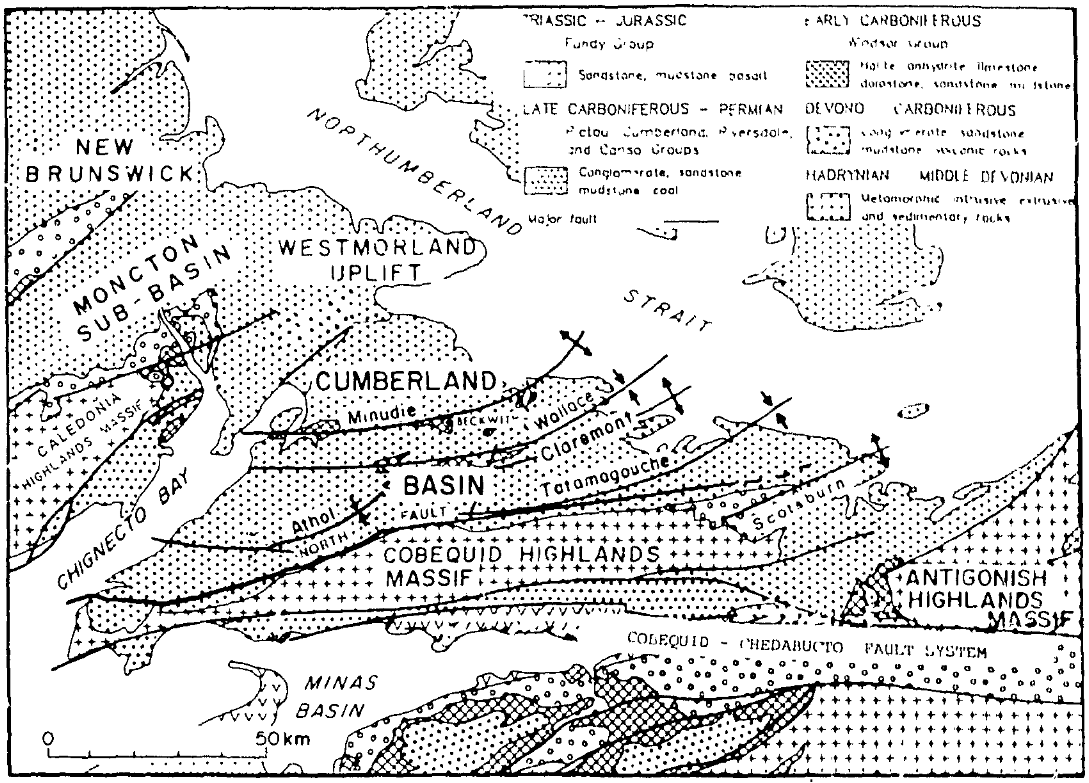


Figure 4.3: Major structural elements of the Cumberland Basin area and the trace of the North Fault along the southern part of the Cumberland Basin.

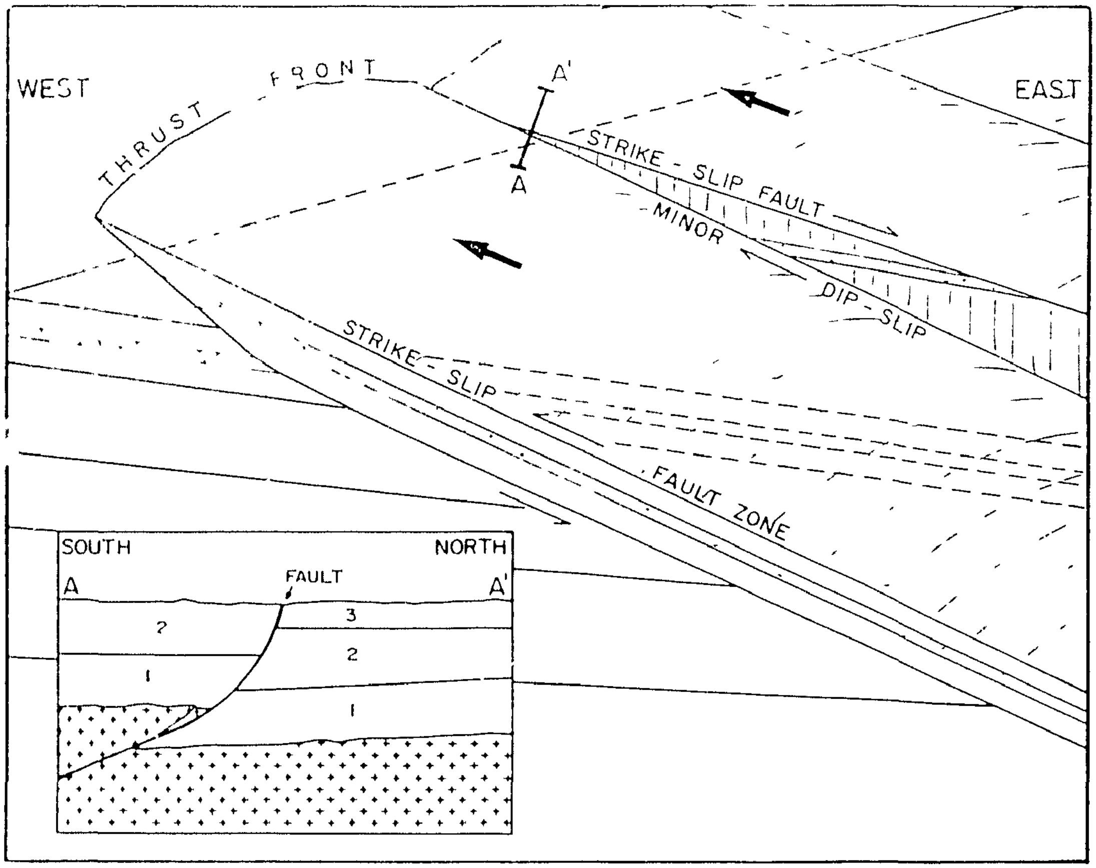


Figure 4.4. Diagrammatic representation of the nature of strike-slip faults in the western Cumberland Basin. Cross section A-A' suggests how strike-slip movement along lateral margins of shovel-like westerly directed thrusts can give the illusion of northerly directed thrusting.

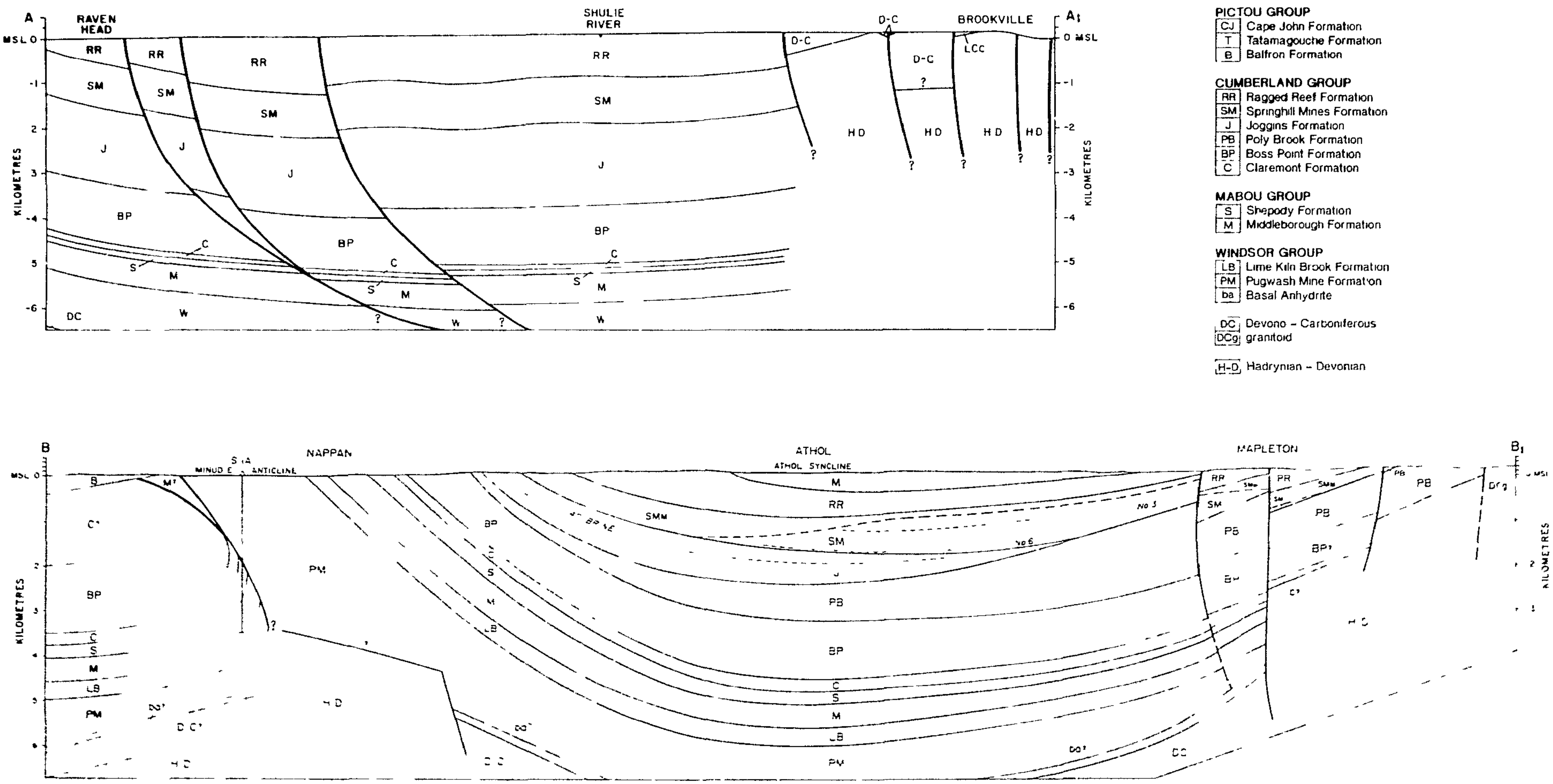


Figure 4.5: Cross sections of the Cumberland Basin (see Fig. 4.2 for locations) the cross sections are more or less north-south.

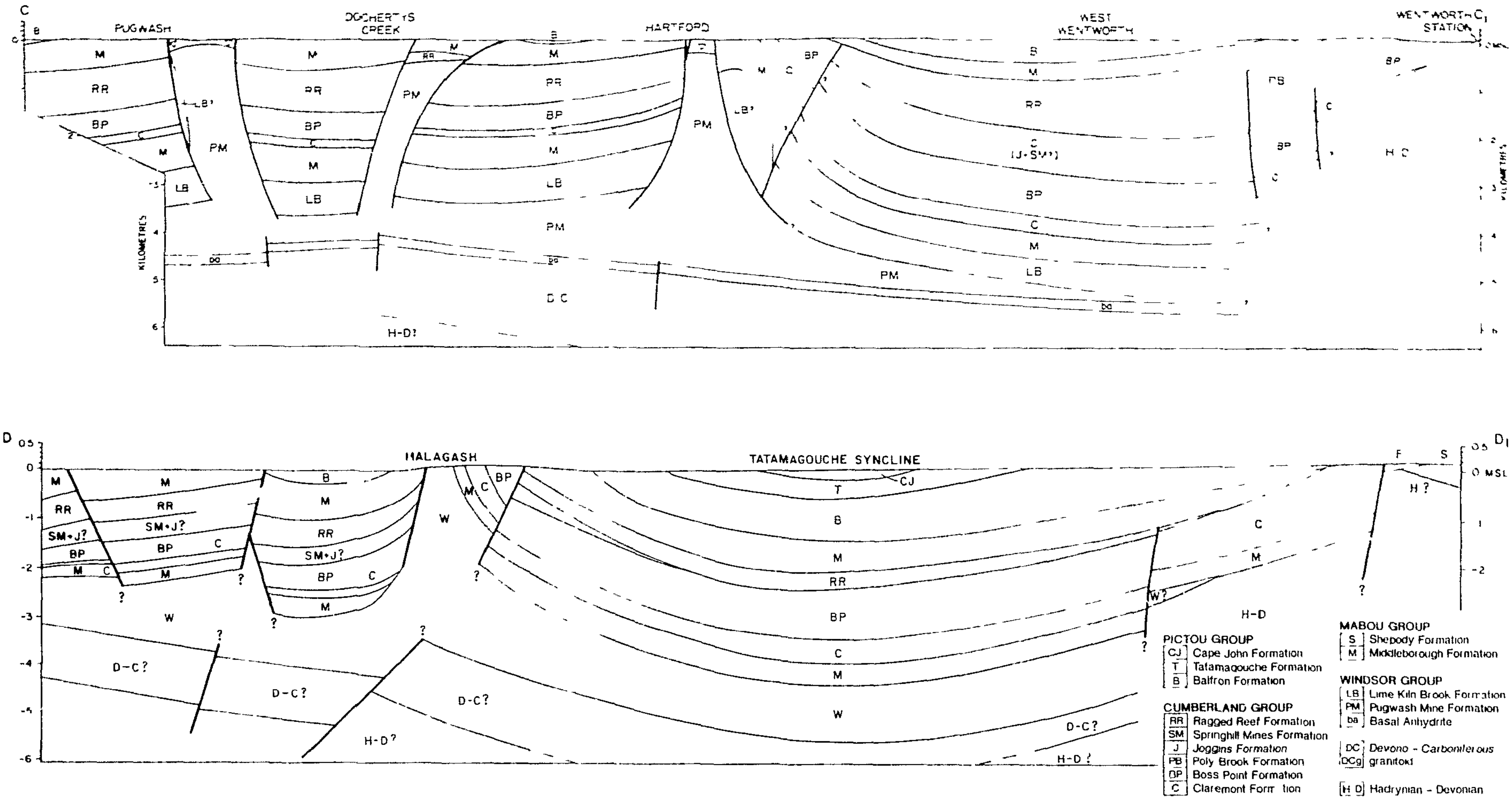


Figure 4.5: Cross sections of the Cumberland Basin (see Fig. 4.2 for locations) the cross sections are more or less north-south.

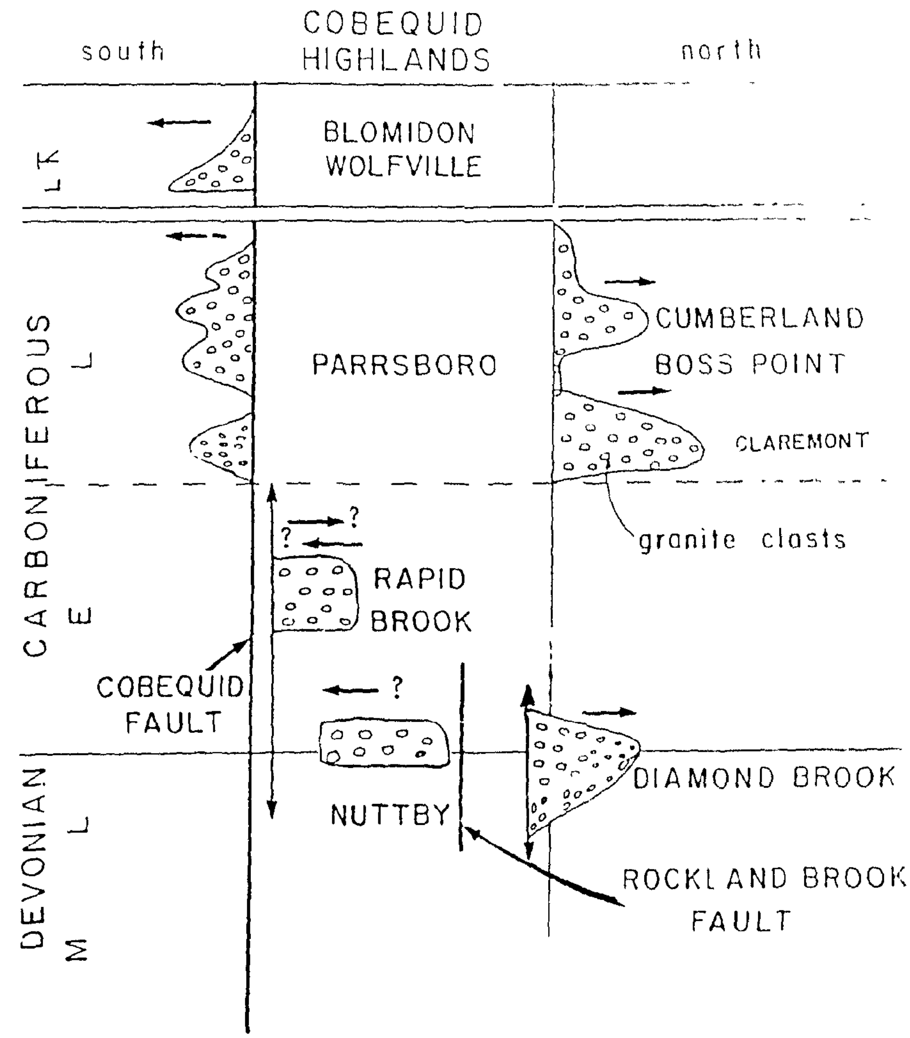


Figure 4.6: Timing of conglomeratic deposition adjacent to the Cobequid Highland Massif (after Ryan et al., 1987). Note the similarity of ages of the conglomeratic units especially in the younger units, indicating that the entire Cobequid Highlands Massif was uplifted relative to the basins to the north and south.

CHAPTER 5

THE THERMAL EVOLUTION OF THE MARITIMES BASIN

5.1 INTRODUCTION

The objective of this chapter is to quantify and interpret the thermal history of the Cumberland Basin, and the greater Maritimes Basin, on the basis of paleothermometric data, including fission-track thermochronology.

The thermal indicators to be used in this study can be divided into two distinct categories: 1) organic indicators including i) vitrinite reflectance (Ro), ii) thermal alteration index (TAI) of sporinite material, iii) rock-eval pyrolysis, and 2) mineral indicators including i) apatite fission-track analysis (AFTA), ii) fluid inclusion microthermometry, iii) clay mineralogy, iv) paleomagnetic studies. Primary emphasis for this study was placed on the apatite fission track analysis (AFTA) and the solid organic indicators, with secondary emphasis placed on the other mineral indicators. AFTA was emphasized in this study because it provides both <u>temperature and time</u> information and therefore it provides the means of tying all of the thermal information together. The apatite fission track analysis was so important to the thermal study that it warranted discussion in a separate section (see section 5.4) within this chapter. Etchable fission track length distributions also allow inferences to be made on the post-annealing thermal history of the rocks. Solid organic indicators, in particular vitrinite reflectance, are the most commonly used thermal methods for study of sedimentary basins. Vitrinite reflectance constitutes a significant percentage of the data used for this study. The conversion of values derived from other maturation indicators to equivalent Ro max values was accomplished by using the Barnes et al. (1984) organic maturation comparison table.

Specifics of how each of the thermal indicators was used in the modelling of thermal data for individual sub-basins is explained in the burial history plot section 5.6 of this chapter. The following summaries apply to the thermal indicator results for the Maritimes Basin as a whole. By examining the overall trends within the Maritimes Basin it is possible to draw conclusions on the overall basin thermal history before modelling the individual study areas in detail.

5.2 SOLID ORGANIC INDICATORS

The techniques used in this study and the results are described below. Implications of the organic maturation studies are discussed together in section 5.2.7 of this chapter.

5.2.1 VITRINITE REFLECTANCE:

Vitrinite reflectance (Ro) is a measure of the reflectivity from a polished surface of vitrinite, the most common coal maceral. Vitrinite reflectance is perhaps the most precise method for the quantification of organic maturation (Mukhopadhyay, 1991a; Bustin, 1989; Barnes et al., 1984; Waples, 1980; Teichmuller, 1979; Bostick et al., 1978; Dow, 1977; etc.).

Bustin (1989) lists the advantages of vitrinite reflectance as a thermal maturation indicator: 1) it is a broadly accepted and standardized procedure (ASTM,1980); 2) vitrinite is sensitive to small changes in the diagenetic level; 3) it is a microscopic method and as such it is easier to maintain a constant set of analytical parameters; 4) vitrinite is a common component of many sedimentary rocks and it can be easily isolated; 5) the method is applicable to a wide range of diagenetic conditions, from unconsolidated sediments to low temperature metamorphic rocks.

The limitations of the vitrinite reflectance technique have been evaluated by several workers (Mukhopadhyay,1991a; Heroux et al., 1979; Barker, 1989, Bustin, 1989, Barnes et al., 1984; etc.) and although interpretation of the Ro values is not straight forward, it is usually possible to interpret datasets. Vitrinite reflectance data often show a scatter of results that would be considered unacceptable to many workers from other disciplines (McCulloh and Naeser, 1989). It has been demonstrated, however, that the scatter of the data is not due to analytical or statistical errors but are the result of geologically significant mechanisms (Mukhopadhyay, 1991a; Heroux and Sangster, 1989; Wenger and Baker, 1986; Kalkreuth and Macauley, 1984; etc.). Major contributors to variance of Ro data have been identified as: 1) type of organic matter analyzed, resulting in a variance of 0.35 within a single sample, 2) the presence of reworked vitrinite; 3) coalification jumps at unconformities caused by erosion of cover after maximum burial has occurred; 4) overpressured zones, causing suppression of Ro values; 5) presence of liquid hydrocarbons, tending to lower values, 6) oxidation, which can lower or raise Ro values, and 7) the effects of chemical alteration of the vitrinite.

Although Hacquebard and Donaldson (1970), Hacquebard and Cameron (1989), Mukhopadhyay (1991b),and Hyde et al. (1991), have previously compiled much of the vitrinite data from the Maritimes Basin, little consideration has been given to the causes of Ro variations. Of particular significance to this study, are the problems related to reworked vitrinite and oxidation and chemical alteration. It was noted that the shales containing significant oil in the Maritimes Basin have anomalous low Ro values (cf. Cook, 1980; Kalkreuth and MacAuley, 1984). One of the problems in the utilization of vitrinite reflectance in the Maritimes Basin is that much of the stratigraphic record is dominated by sandstones or vitrinite-barren redbeds. The effects of oxidation and chemical alteration are most commonly observed in the porous sandstones, unfortunately in much of the basin these rocks are the only strata containing vitrinite, and therefore significant variations in Ro values are observed. For the purpose of comparison the results of the various methods and vitrinite reflectance studies were expressed in equivalent Ro max values. A note of caution is expressed here not to interpret reflectance data at increments of less than 0.2% Ro as this is the approximate error inherent in the dataset because of the geological influences explained previously and because the analyses were carried out by a variety of labs.

5.2.2 RESULTS AND INTERPRETATION OF THE VITRINITE REFLECTANCE

The following sections summarize the results of this study and examine the results obtained by Hacquebard and Cameron (1989) and Mukhopadhyay (1991b). The vitrinite reflectance data are presented in two parts: 1) the Cumberland Basin and northern Nova Scotia samples, and (2) an overview of the Carboniferous samples for the entire Maritimes Basin. The vitrinite reflectance for the other individual sub-basins is not presented here, however the vitrinite reflectance data for these areas was used in the process of creating the burial history plots in section 5.6 of this chapter. The thermal modelling also included a comparison of the modelled versus the measured vitrinite reflectance for horizons adjacent to fission track samples.

5.2.2.1 Cumberland Basin and Northern Nova Scotia

Approximately 80 samples (compiled from Ryan and Boehner, 1993; and Mukhopadhyay, 1991b) have yielded vitrinite reflectance data from the Cumberland Basin area. These samples included outcrop samples and downhole profiles. The results are presented as a contour map of northern Nova Scotia (Fig. 5.1). Rock type plays an important role in Ro value obtained. Oil shales, or coals interbedded with hydrocarbon-rich shales, constitute all of the low Ro values (approximately 0.5% Ro max) in the Cumberland Basin (Fig. 5.1). The oil-rich shales throughout the Maritimes Basin have vitrinite reflectance values of approximately 0.60% Ro, which is lower than the normal maturation level, and may reflect the type of organic matter in the rock rather than a distinct thermal history. Another striking feature is the apparent lack of stratigraphic control on the Ro max value for a given sample (Fig 5.2). This characteristic may be the result of acquisition of the Ro max value by burial after faulting, tilting , and possible erosion (exhumation) of the strata during the Late Carboniferous. This suggests that the timing of the maximum burial postdates the youngest sedimentary rocks exposed in the basin. A similar conclusion was reached by Hacquebard and Cameron (1989) for the coals in the Sydney Basin. Most of the surface or near surface values fall between 0.65 to 0.95 Ro, with the lower values occurring towards the northwest (Fig. 5.1).

The histograms of the vitrinite data from the Pictou Group redbeds often exhibit bimodal populations (Fig. 5.3) which have been interpreted as resulting from secondary oxidation (White, 1988). In these bimodal samples there are often rims of slightly higher reflectance around the vitrinite grains suggesting oxidation is the probable cause. The histograms in Figure 5.3 are from localities where secondary oxidation of the strata occurred coincident with Cu-Ag redbed mineralization.

5.2.2.2 Maritimes Basin Compilation

A total of 345 vitrinite reflectance samples have been compiled by Mukhopadhyay (1991b) from the Carboniferous rocks in the province of Nova Scotia. Hacquebard and Donaldson (1970) and Hacquebard and Cameron (1989) have compiled most of the vitrinite reflectance data for the Maritimes Basin in eastern Canada (approx. 500 samples). A contour map of the reflectance values (Fig. 5.4) synthesizes their data with more recent studies such as those of Mukhopadhyay (1991b), Hyde et al.(1991), and Ryan and Boehner (1993).

Anomalous Ro values occur within the northern part of the Minas Basin area. The vitrinite reflectance values increase dramatically towards the north. This trend may reflect extremely thick sedimentary cover or alternatively thermal anomalies associated with either hydrothermal fluids along the Cobequid-Chedabucto Fault Zone or with Triassic volcanism.

Local anomalies exist in New Brunswick, but overall the data show a tendency toward reduction in the Ro max up the stratigraphic column. Hacquebard and Cameron (1989) suggested that the anomalous coal rank in New Brunswick was the result of volcanic/plutonic influences. The decrease in Ro values up the stratigraphic column is generally interpreted to represent simple sedimentary load acquisition of the reflectance, thus suggesting that the post-deformational vitrinite reflectance acquisition is a local phenomenon. Because the local anomalies are interpreted as resulting from syndepositional structural development, it is not surprising that on a more regional scale, these anomalies are statistically overwhelmed by the vitrinite reflectance attained through sedimentary burial.

Figure 5.5 is a histogram of 286 near surface vitrinite reflectance measurements from throughout the Maritimes Basin (including the Cumberland Basin). The mean value for the basin is 0.89 Ro, with a standard deviation of 0.32. The distribution suggests that the values > 1.50 Ro are most likely the result of mechanisms other than sedimentary burial.

5.2.3 THERMAL ALTERATION INDEX (SPORE COLORATION)

The thermal alteration index (TAI) is a measure of the spore or pollen colour variation with increasing organic maturation. An arbitrary numeric scale was assigned to the colour variations, and a series of reference samples provide standards for comparison (Staplin, 1969, 1982). The most widely used of these scales is the Thermal Alteration Index (TAI) proposed by Jones and Edison (1978).

Bustin (1989) suggested that the advantages of TAI are: 1) only standard palynological preparation techniques and microscopic examination are required; 2) palynmorphs are very common in most fine grained sedimentary rocks; and 3) the colour variations range over levels of diagenesis equivalent to 0.35% to 2.4% vitrinite reflectance, and therefore they quantify thermal maturation levels from oil generation through to cracking. Barnes et al. (1984) and Bustin (1989) point out that the limitations of the method are: 1) the method is subjective and therefore not as reliable as vitrinite reflectance; 2) reworking of palynmorphs is common and sometimes difficult to detect, and 3) the colour of the spores and pollens may be dependent on the species, thickness of kerogen, and initial pigmentation. McCulloh and Naeser (1989) suggest, because of the operator error possible in this method, it should only be used in conjunction with other methods. Peterson and Hickey (1985) point out that TAI, like all of the organic methods, can be used as long as the limitations are well understood before application.

5.2.4 TAI RESULTS AND INTERPRETATION

A total of 50 $\pm$ localities were sampled at various depths within drill holes and wells to make up the ±300 samples analyzed for TAI within the Maritimes Basin (Fig. 5.6). Approximately 60 TAI measurements compose the database for the Cumberland Basin study. Ryan et al. (1990a) have pointed out that recycling of palynmorphs is common in the strata of the Cumberland Basin, and therefore care must be taken in the interpretation of the results. Most of the samples from the study area have at least one adjacent vitrinite Ro value to use as a calibration. The samples also represent a variety of sample depths within the drill holes, and therefore minor variations in the measurements may reflect increasing maturation with depth Cumberland Basin TAI determinations were compared to nearly 300 samples compiled from elsewhere in the Maritimes Basin

Figure 5 6 summarizes the TAI data for the Maritimes Basin, and the results reflect the less precise nature of the technique Most of the TAI data, when converted to equivalent Ro max values using the Barnes et al (1984) conversion table, correspond very well to vitrinite reflectance samples in adjacent strata In a few of the drillholes (eg SA-1, 82-1) (Fig. 5.7) single sample anomalies in the vitrinite values are not reproduced in the TAI determinations These localities are therefore interpreted as areas where the vitrinite has been altered by chemical reactions with fluids or by oxidation, however spore material was apparently not altered by the process Spore samples and vitrinite reflectance samples from areas adjacent to salt diapirs have extremely high maturation levels This can be explained as the result of abnormal heat flow related to the diapiric structures, although chemical alteration due to chloride-rich solutions cannot be ruled out In section 5 4 3 the information from TAI studies is combined with other maturation indicators and used to constrain thermal modelling In areas where there are vitrinite reflectance measurements the TAI data add little information except to verify the vitrinite data. The TAI data were used to help constrain the burial history plots in section 5.6 of this chapter

5 2 5 ROCK-EVAL PYROLYSIS

Pyrolytic methods involves heating samples of kerogen at a given rate to specified temperatures, and measuring the type and amount of gas generated by the process The most widely used pyrolysis technique is Rock-eval (Espitalie et al , 1977; Peters, 1986), which refers to the use of a furnace with an on-line ionization detector The sample is heated to 600 degrees C, simulating maturation, and three types of gas are measured: 1) S1 hydrocarbons already in the sample which are generated at temperatures less than 300 degrees C, 2) S2 hydrocarbons generated by thermal cracking between 300-600 degrees C, and 3) S3 carbon dioxide (Bustin,1989). The TOC (total organic carbon) is also measured. The level of maturation is obtained from the S1/S2 ratio and the maximum temperature (Tmax) at which there is maximum generation of S2 hydrocarbons.

The advantage of the Rock-Eval method is that it can be used to estimate maturation levels in hydrocarbon-rich shales that give inconsistent Ro values. The method also has the advantage of being a good measure of the hydrocarbon source rock potential for a sample, and it requires little preparation of the sample, except for crushing. Problems related to the method include: 1) mixed kerogen types tend to give inconsistent results; 2) groundwater flow can sometimes extract hydrocarbons from the rock and give low S1 values and incorrect maturation ratios S1/S2; 3) the presence of carbonate in the sample yields invalid carbon dioxide values (Peters, 1986); and 4) a certain amount of operator bias is involved in the technique (although this is less of a problem in automated systems) and therefore it is not always possible to combine data from different labs. McCulloh and Naeser (1989) suggest that the method is less accurate and more variable than vitrinite reflectance and therefore the data should always be integrated (or calibrated) with other maturation methods.

In the Cumberland Basin many of the bituminous (oil-bearing) shales have low Ro values in contrast to the adjacent strata, and Rock-eval pyrolysis is an appropriate method for deriving a more precise maturation level for these rocks. Approximately 80 Rock-eval analyses are available for the Cumberland Basin, and these can be compared to 507 samples from elsewhere in the Maritimes Basin. All samples used here had total organic carbon greater than 0.3%, permitting interpretation. Almost all of this database has been compiled from the work of the Petroleum Division of the Nova Scotia Department of Mines and Energy (Mukhopadhyay,1991b).

5.2.6 RESULTS AND INTERPRETATION OF THE ROCK-EVAL PYROLYSIS

Mukhopadhyay (1991b) described in detail the Rock-eval data for the Nova Scotia portion of the Maritimes Basin. The reader is referred to this for the discussion of the petroleum potential of the strata. Tmax can be correlated with Ro only in samples considered to be Kerogen Type II-III, with S2 greater than 0.2 mg. Figure 5.7 is a compilation of 301 Rock-Eval Tmax measurements from the Maritimes Basin having over 0.3% TOC and > 0.2 mg of S2.

When all the acceptable data are plotted, an overall mean for Tmax is 436°C with a standard deviation of 25°C. Although both overmature and immature samples occur, the majority of the samples are consistent with the vitrinite reflectance values at the same localities. Approximately 85% of the samples have equivalent Ro values of less than 1.0% (see Bustin et al., 1985; for conversion). The mean value of the data (436 °C) is approximately equivalent to an vitrinite reflectance value of 0.6 Ro. These data correspond well to the vitrinite data from the same stratigraphic horizons. The oil shales and organic-rich shales throughout the Maritimes Basin all exhibit lower maturation levels than the adjacent strata. The cause of this is discussed in section 5.2.2.1 of this chapter. The maturation information from the Rock-Eval analysis was incorporated into the thermal database used in the modelling processes later in this chapter (see section 5.4.3).

5.2.7 IMPLICATIONS OF ORGANIC MATURATION INVESTIGATIONS

The information on the organic maturation indicators generated and compiled as a result of this study must be used with caution. Variations of measured values exist within each of the methods described above and conversion of the non-vitrinite reflectance methods to equivalent Ro % values are not exact therefore these data should be used bearing in mind that the values are only accurate to 0.20% Ro at best. The organic maturation levels from all of these data indicate that the rocks at the near surface have been covered by additional strata at some time in their history. The vitrinite reflectance Ro/km gradients of the Maritimes Basin as seen in the deeper drilling rarely exceeds 0.65% Ro/km. A comparison of the Ro actual values to the Bustin et al. (1977) coalification curves, suggests a paleogeothermal gradient of less than 30°C/km, where the duration of maximum temperature is longer than 20 million years. Whereas most of the vitrinite gradients are less than 0.40 %Ro/km, even with shorter duration of maximum temperatures, a gradient of 25°C/km would seem sufficient to produce the observed organic maturation profiles. Given this, a minimum of 1 km of additional "ghost stratigraphy" must have been deposited on top of the present day surface. In the Cumberland Basin the Pictou Group strata near surface have vitrinite reflectance values of 0.95% Ro max, given a gradient of 0.40 Ro/km (Fig. 5.6) a minimum of 2 km additional cover is estimated. Based on observed vitrinite reflectance trends

Hacquebard (1984) estimated that up to 3700 m strata were removed by erosion. This observation is consistent with the approximation for the Cumberland Basin. Estimates of the depth of burial of specific horizons throughout the Maritimes Basin are an intricate part of the burial history plots and the thermal modelling discussed later in this chapter. Although the organic maturation data presented here applies to the Maritimes Basin as a whole the burial history plots are specific to the sample locations and the local stratigraphy.

The implications of the data for the whole Maritimes Basin can be summarized as follows: (1) extensive post depositional loading was necessary to produce the organic maturation values measured for the strata; (2) based on observed vitrinite reflectance values at surface and the downhole gradient it is estimated that between 1 and 3 km have been eroded off the basin; and (3) although on a local scale there does not appear to be a correlation between the Ro value and the stratigraphic position, it does appear that a crude trend towards higher reflectance values with increasing age does occur on the basin-wide scale. This information was used to constrain the burial history plots that were constructed for the various study areas within the Maritimes Basin (see section 5.6).

5.3 MINERAL THERMAL INDICATORS (EXCLUDING FISSION TRACKS)

Some information of a general nature can be attained by examining the mineral thermal indicators. The information from the fluid inclusion studies gives some constraint on the maximum temperatures of fluids which resulted in mineralization in the basin. If these fluids are derived from the basin, as suggested by Ravenhurst and Zentilli (1987), they offer some indication of temperatures at the time of the mineralization. Clay mineralogy of several areas within the Maritimes Basin have been investigated, however this method tends to give ambiguous results that are difficult to interpret. Paleomagnetic studies within the study area give some insight as to the timing of the exhumation of the basin. It is assumed that the additional cover suggested by the organic maturation studies must have been eroded prior to or concurrent with the secondary (late diagenetic) reddening of the Pictou Group strata in the basin.

5.3.1 FLUID INCLUSIONS

Lundegard (1989) suggested that fluid inclusion geothermometry is the most direct method of inferring the temperatures associated with cementation in sedimentary rocks. Fluid inclusion studies have been in wide use in the study of ore deposits for many years, however their use in thermal history determinations of sedimentary basins has been limited. The theory behind the method is that two-phase inclusions trapped in the cementing mineral as a single phase at the time of precipitation can yield the homogenization temperature, which may be a measurement of the minimum temperature of formation. The actual temperature of formation can be derived from the homogenization temperature, by correcting for the geochemistry and pressure at the time of precipitation (Roedder, 1984). Tilley et al. (1989) have compared results of fluid inclusion studies with vitrinite reflectance studies in the Deep Basin of Alberta and their work has demonstrated that fluid inclusion studies can be used to interpret organic maturation data and thermal basin history.

Lundegard (1989) lists the three greatest drawbacks of the method as: 1) fluid inclusions in sedimentary cements tend to be very small, and therefore difficult to work with; 2) the most common minerals which contain the fluid inclusions are carbonates and tend to be prone to stretching or necking of the inclusions which yields erroneous results; and 3) pressure corrections are often difficult to estimate. Furthermore, although stretching of inclusions creates a problem for the interpretation of the formation temperature of diagenetic cements or minerals because it gives higher homogenization temperatures, the data can provide a maximum paleotemperature to which the rock has been heated during its burial history (Lundegard,1989; Tilley et al.,1989; Burruss, 1989).

A paucity of two-phase fluid inclusions, large enough to measure in the sedimentary rocks of the Cumberland Basin severely limits the usefulness of this method for the Cumberland Basin study. An effort was made to examine the carbonate units in the basin to see if they have some primary fluid inclusions which could be used for geothermometry, however the there were no primary fluid inclusions observed.

5.3.2 RESULTS AND INTERPRETATION OF THE FLUID INCLUSIONS

Although no additional data were derived from the Cumberland Basin, there have been several fluid inclusion studies undertaken on mineral deposits elsewhere in the Maritimes Basin. Figure 5.9 is a summary of previously published fluid inclusion data from the basin. From these studies, the fluid inclusion homogenization temperatures from within the Maritimes Basin strata range in values from 100 to 350°C. It is unclear whether these values represent the mineralizing temperatures subsequent thermal events. If the Ravenhurst and Zentilli (1987) suggestion that the mineralizing fluids are derived from the basin itself is accepted, the temperatures would reflect the mineralization temperature. The thermal information derived from the fluid inclusions is included in the modelling as another constraint.

Recent work by Kontak (1992) suggested that the primary fluid inclusion homogenization temperatures in sphalerite at Gays River are in the 160 °C range. Homogenization temperatures in calcite from the Gays River Deposit range as high as 250 °C. Similarly, the high temperatures attained from the Jubilee Deposit (> 350°C) have been interpreted to be the result of hydrocarbons within the inclusions, and therefore the homogenization temperatures should be significantly lower (Hein et al.,1988). These recent studies suggest that the maximum temperatures attained were 250 °C or less.

5.3.3 CLAY MINERALOGY

Surdam (1989) and Pytte and Reynolds (1989) have reviewed the significance of clay mineralogy to the development of porosity and thermal maturation of sediments. The transformation of smectite to illite through intermediate mixed-layered clays is probably the most significant mineral reaction in sedimentary rocks (Pytte and Reynolds (1989). In general most workers agree that there is a relationship between the illite/smectite ratios and thermal maturation (cf. Perry and Hower, 1970; Hoffman and Hower, 1979; etc.). Some authors place emphasis on the original composition of the detrital clays (Heling, 1969, 1974) whereas others (Pollastro and Barker, 1986; Velde, 1984) believe that the temperature during burial is the most important factor in determining the final diagenetic products. The degree to which these variables affect the final product is still under investigation, and therefore the method should be used only in conjunction with other maturation methods (McCulloh and Naeser, 1989).

5.3.4 RESULTS AND INTERPRETATION OF THE CLAY MINERALOGY

Approximately fifteen sandstone samples from the Cumberland Basin have been analyzed for their clay content. Additional samples have been processed by Gall and Sangster (1991) and Gall and Hiscott (1986). The results indicate that most of the samples from the Horton and the Upper Windsor groups have remained within the Diagenetic Zone (equivalent to Ro 0.90% or less) although many of the deeper samples from drill cores plot in the Anchizone (equivalent to Ro 0.90 to 1.30%)(Fig. 5.10). These results are consistent with the organic maturation data from this study. It is clear from the literature that, of the methods employed in this study, clay mineralogy is the least reliable and therefore these data served only to corroborate the organic maturation data.

5.3.5 PALEOMAGNETIC STUDY

Turner (1986) has demonstrated the usefulness of paleomagnetic studies in determining the timing of diagenetic events related to the formation of secondary redbeds. The term secondary redbeds is used here to describe grey sandstones that have undergone late diagenetic oxidation of the iron-bearing minerals contained with the sandstones (cf. Turner, 1980). Where the sedimentary rocks have been deposited as grey beds and have subsequently been reddened by diagenetic processes, it is possible to date the reddening event by comparing the paleomagnetic stratigraphy with the actual age of the strata (Turner,1980). This dating is important in so much as the hematization process locks in the age of diagenesis. Most secondary reddening mechanisms are shallow diagenetic phenomena (within 2 km of surface). The timing of the reddening therefore is significant for the burial history plots as it suggests that the strata being reddened is within 2 km of surface. Care must be taken in the interpretation of data because the fine grained overbank rocks of the Pictou Group are primary redbeds as opposed to the secondary (late diagenetic) red coloration of most of the sandstones (see Chapter 7 for discussion).

5.3.6 RESULTS AND INTERPRETATION OF THE PALEOMAGNETIC DATA

In the Cumberland Basin most of the red coloration of the sandstones in the Pictou Group are related to late diagenetic oxidation (Ryan et al., 1989) and paleomagnetic studies were carried out as part of this research by Morris and Associates (Morris, 1987). This work, and the work of Symons (1990) in P.E.I., Roy (1963, 1966) in northern Nova Scotia, southern New Brunswick and P.E.I., and Tanczyk (1988) in the Magdalen Islands, have indicated that the age of magnetization for the Pictou Group strata is Late Carboniferous to Late Permian (Fig. 5.10). The variations in the pole orientation in the studied samples reflect differences between the primary and secondary reddening. Tanczyk (1988) suggested, on the basis of her studies of the Pictou Group strata in the Magdalen Islands, that there may have been a prolonged period of hematite formation. Morris (1987) found similar trends in the Cumberland Basin, which he attributed to late diagenetic alteration. Given the sedimentology of the strata, it is most likely that the variations reflect the primary versus secondary origin of the red coloration in combination with a prolonged diagenetic history.

Tanczyk (1988) has shown that there is a westward migration of the poles with increasing alteration of the hematite present. She divided her data into three groupings according to the diagenetic sequence and the degree of alteration: 1) primary, 2) transitional, and 3) secondary. Morris found primary and secondary trends in the Cumberland Basin data (Fig. 5.11). The late stage pole CU4 was interpreted by Morris (1987) as a dominant magnetization, which he stated was unquestionably associated with movements of mineral-rich fluids. Morris (1987) stated, "At some localities the CU4 magnetization has with minor exception totally overprinted all other magnetizations". The Morris (1987), Tanczyk (1988) and Symons (1990) data were combined to construct Figure 5.11 which depicts the relative shift in the poles with increasing reddening of the strata. Tanczyk (1988) suggested that rotation of the poles may be the result of structural rotation of the Magdalen Islands (cf. pull-apart basin mechanism), similar to the rotation noted by Morris (1987) for the Stellarton Basin. The rotation noted by Morris (1987), however, is a time-restricted event. Whether there was a rotation of the strata or not, there is at least a 50 million year difference between the primary pole (time of deposition) and the secondary pole (reddening of the strata). If the poles were not rotated, then the reddening (or secondary reddening) of the strata appears to have started at about 280 Ma and continued until approximately 230 Ma. Given the burial history plots and forward models for the apatite fission track studies (see section 5.7 of this chapter) it seems most likely that little rotation occurred, and that the 280 - 230 Ma age for the secondary poles should be approximately correct.

Because the age of the reddening is related to diagenetic processes which usually occur within 2 km of surface, the paleomagnetic data can be used to constrain the timing of exhumation experienced by the Pictou Group subsequent to maximum burial. This information can be integrated with the apatite fission track analysis (see section 5.4) and used in the time temperature modelling (see sections 5.6 and 5.7).

5.4 APATITE FISSION TRACK ANALYSIS

5.4.1 INTRODUCTION

Much of the following discussion on the background and the techniques used at the Dalhousie lab was extracted and modified from Hendriks (1991). The reader should also refer to Grist and Ravenhurst (1992) for a concise discussion of the analytical techniques used at the Dalhousie University Fission Tack Lab.

Fission tracks are damage zones created within solids when fission fragments travel through them (Fleischer et al., 1975). Following a fission event, two positively charged fission fragments are mutually repelled, stripping electrons from the surrounding lattice. Repulsion from the trail of secondary positively charged ions embeds these particles into the surrounding lattice, forming a damage zone or fission track. Over the period of geologic interest only ^{238}U has a sufficiently short fission half life to create significant numbers of spontaneous tracks. Trace amounts of uranium occur within several common minerals, and because ^{238}U undergoes spontaneous fission at a known rate, fission tracks can be used to date the sample (Naeser et al., 1990). An age can be calculated by comparing the spontaneous fission tracks on a polished surface of a mineral to the induced track numbers (a measure of the total U content). The tracks themselves are not visible by normal transmitted light microscope methods, unless these zones of weakness are chemically etched.

If a mineral containing fission tracks is heated to high enough temperatures to displace ions along the damage zones, the ions will diffuse back into their normal position and the track completely disappears (anneal). Not all minerals anneal at the same temperatures, the most commonly used minerals are apatite, which anneals between 85-120°C, and zircon which anneals between 160-250°C.

Naeser (1979) was the first to suggest that fission track annealing could be used to study the thermal history of sedimentary basins. Fission track analysis of sedimentary basins is a useful method because annealing temperatures for apatite and zircon coincide with oil generation temperatures (Hood et al., 1975; Waples, 1980; Naeser et al., 1990), and because the timing of these events can also be determined. The method is also useful in establishing the location of thermal anomalies associated with some mineral deposits (Naeser et al., 1990; Beaty et al., 1987; Naeser, 1984; Maksaev and Zentilli, 1989; Arne, 1992, etc.). The usefulness of the apatite fission track technique stems from the low closure temperature of apatite fission tracks (85-120°C, Gleadow et al., 1983). The process of annealing in fission tracks takes place as a progressive shortening of the tracks. The rate of shortening is dependent on the temperature to which the sample is heated and to a lesser extent on the time interval during which the sample has been subjected to this temperature (Naeser et al., 1990). The apatite fission track length distribution yields detailed information on the low temperature (less than 125 °C) thermal history experienced by the host rock (eg. Green et. al., 1989). Age and track length data together have been used to derive quantitative low-temperature thermal histories (Donelick, 1988; Willett, 1992), and demonstrate why the apatite fission track method is so valuable in basin development and maturation studies (Gleadow et al., 1983; Issler et al., 1990) and in regional exhumation investigations (Gleadow and Fitzgerald, 1987).

Perhaps the most important advantage of the fission track analysis over the solid organic thermal indicators is the fact that fission tracks do not appear to be altered by oxidation or chemical alteration, and therefore a comparison of the fission track results with the organic methods can be used to isolate temperature effects from chemical effects. This advantage is of particular interest when the strata being studied are mineralized by basinal brines or by groundwater which often causes erratic organic maturation results (cf. Heroux et al., 1989; Mukhopadhyay, 1991), as in the Cumberland Basin.

5.4.2 APATITE FISSION TRACK ANALYTICAL METHODOLOGY

5.4.2.1 Background

Apatite fission track dating depends on the amount of ^{238}U isotope present and how much has been converted to a daughter product, thus creating a fission track. Measurement of ^{238}U (parent) and the number of spontaneous fission tracks (daughter) is similar to other radiometric dating techniques which measure radiogenic and stable isotopes (ie. U/Pb, Rb/Sr, and $^{40}Ar/^{39}Ar$ methods). The ^{238}U present is determined by irradiating a sample with a thermal-neutron flux which induces fissioning of ^{235}U in the sample. The ratio $^{238}U/^{235}U$ is constant in nature (137.88, Steiger and Jaeger, 1978), and a count of the induced ^{235}U fission tracks is used to indirectly measure the amount of ^{238}U present in a sample. Price and Walker (1963) were the first to propose a fission track dating technique using the equation:

where

$$t=\frac{1}{\lambda_d}\ln(1+I\Phi\sigma g\frac{\rho_s}{\rho_i}\frac{\lambda_d}{\lambda_f}) \quad (1)$$

t = the apparent fission track age of the mineral (Ma)

I = the atomic ratio $^{238}U/^{235}U$ (137 88; Steiger and Jaeger,1977)

Φ = the thermal-neutron fluence during irradiation

σ = the ^{235}U thermal-neutron fluence cross-section (5.802 x 10^{-26} cm^2)

g = the counting geometry factor (0.5 for External Detector Method)

λ_d = the ^{238}U total decay constant (1.55125 x 10^{-10} a^{-1},Steiger and Jaeger,1977)

λ_f = the ^{238}U spontaneous fission decay constant (~ 6-8 x 10^{-17} a^{-1}, Friedlander et al., 1981)

ρ_s = spontaneous fission track density in grain (tracks/unit area)

ρ_i = induced fission track density in detector (tracks/unit area)

Fission tracks cannot be seen by using standard transmitted light microscope methods and must be chemically etched so that they can be observed through a high powered microscope The track density quantities are obtained by counting the number of etched tracks per unit area intersecting an internal surface of an apatite grain (spontaneous track density (ρ_s)) and the number of etched tracks per unit area in a low U detector mica placed over the grain (induced track density (ρ_i)), which records the number of tracks resulting from the one way passage of induced ^{235}U fission tracks from the apatite grain The resulting ratio (ρ_s/ρ_i) is proportional to the age of the sample. The age (t) determined from this ratio is the apparent apatite fission track age A reduction in track length is accompanied by a reduction in age (Willett, 1992 Fig 3) The corrected apparent age (t_{ca}) recalibrates the age based on the full number of fission tracks present by considering the mean etchable track length of a sample (m) shortened by annealing and the original mean etchable track length (m_0 ~15.2) such that t_{ca} = $(m/m_0)t$. The track length original of 15.2 microns is based on the measured length for the Fish Canyon Standard as measured by the author. However, this procedure is controversial, and corrections of the fission track ages should be introduced only with utmost caution (e.g. Wagner 1979, Gleadow et al 1986, Green, 1988). Willett (1992) pointed out that the ratio 1:1 for the reduced track length to reduced track density is not valid for reduced lengths that are less than 65% of the original length. All of the samples from this study are greater than 65% of the original track length and therefore the age correction can be applied. The mean etchable track length of a sample was derived by measuring only etched lengths of tracks confined within the grain and parallel or near parallel to the polished surface. If all tracks formed during time=t_{ca} to time=present are preserved in the sample (ie. no track reduction), then t_{ca} should be the absolute apatite fission track age of the sample (Donelick, 1987).

5.4.2.2 Counting Techniques

A variety of approaches, including the population, subtraction, re-etch, re-polish and external detector methods have been developed to determine fission track ages (Hurford and Green, 1982). All involve indirect evaluation of the apatite uranium concentration by inducing tracks from ^{235}U during thermal neutron irradiation. The external detector method (used in this study) is the only method which avoids the assumption of homogeneous uranium concentration in a sample,by counting corresponding areas in the grain and in a low uranium detector. The basis for the 0.5 geometry factor (g) in the above equation, comes from counting induced tracks resulting from one way passage from the grain into the detector (2π geometry; apatite only on one side), and from two way passage of spontaneous tracks across an internal surface of the grain (4π geometry).

The quantities most difficult to measure in the apparent fission track age equation are: the fission decay constant (λ_f), the rate of ^{238}U decay due to fissioning, and the neutron fluence (Φ), the thermal-neutron dosage experienced during irradiation of the sample. However, the need for explicit determination of these quantities for solving the apparent fission track age equation is circumvented using the zeta calibration method. First proposed by Fleischer (1975); see also Hurford and Green, 1982) the basis for the zeta calibration factor is that for a given thermal-neutron dosimeter (in this study Corning CN-1 glasses), the ratio of thermal-neutron fluence and the number of induced fission tracks (ρ_d) crossing the external surface of the dosimeter is constant

(Faure, 1986). The glass dosimeter is then calibrated to an independently dated apatite age standard by determining the age standard apatite fission track ρ_s/ρ_i ratio. On this basis, we define the zeta calibration factor as a collection of the constants (except λ_d) in the age equation, and it can be evaluated by irradiation of dosimeter glasses with apatite age standards so that:

$$\zeta = \frac{1}{\lambda_d \rho_d}\left(\frac{\rho_i}{\rho_s}\right)_{STD} \exp(\lambda_d t_{STD} - 1) \qquad (2)$$

where

$(\rho_i/\rho_s)_{STD}$ = induced to spontaneous fission track density of apatite age standard

t_{STD} = absolute age of apatite age standard

ρ_d = induced track density of a given dosimeter glass

Zeta values for this study were determined with age standards from Fish Canyon Tuff (t_{STD} = 27.8 +\- 0.2 Ma, $^{40}Ar/^{39}Ar$; Hurford and Hammerschmidt, 1985), and Durango (t_{STD} = 31.1 +\- 1.3 Ma, $^{40}Ar/^{39}Ar$). The Chi^2 test checks for populations in the data. Gaussian statistics determine whether and how well the data can be represented by a single population, or if the variability constitutes another explanation (Galbraith, 1982). All zetas pass the Chi^2 test, and therefore age standard density data may be represented by single Gaussian populations (cut-off $Q < 0.05$). In theory, zeta values are constant for a given dosimeter, neutron energy spectrum during irradiation, and counting technique. Standard practice is to use a running zeta or an overall mean zeta for determining unknown ages in order to cancel out any subjective error from counting in the measurement of zeta values. The running zeta (110 $\pm$ 10, See Appendix I for calculations of Ryan Zeta) used for the ages measured by the author in this study, is given in Table 5.1 along with the ages.

Once a zeta factor has been established, only the spontaneous to induced fission track ratio remains to be measured. The age is determined by substitution of (2) into the age equation (1):

$$t = \frac{1}{\lambda_d} \ln(1 + \zeta \lambda_d \frac{\rho_s}{\rho_i} \rho_d g) \tag{3}$$

which is the apparent age equation used in this study. Ages presented in this study are apparent fission track ages, with errors reported at the σ level and ages corrected to track length (Table 5.1).

5.4.2.3 Mineral Separation

Depending on lithology, 0.5 to 2 kg of each sample was crushed to sand size particles using steel jawcrushers and a pulverizer, and then passed through a 300 µm mesh nylon sieve into a large aluminum tray. The sieved fraction was washed with water to remove clay-sized particles.

Standard heavy liquid density separation techniques were used to obtain heavy mineral fractions from each sample. The sample was poured into large glass funnels containing tetrabromoethane (specific gravity = 2.96) and separated into light and heavy fractions. Both fractions were washed with methanol and allowed to dry in the fumehood. The heavy fraction was passed through methylene-iodide (specific gravity = 3.3), and allowed to separate into light and heavy fractions. Methylene-iodide fractions were repeatedly washed with acetone and allowed to dry.

The light methylene-iodide fraction was hand-picked for apatite grains at 40X magnification using a Zeiss binocular microscope and a moistened 00 brush. Apatite was recognized by its prominent hexagonal crystal shape, resinous luster, and relatively low index of refraction.

5.4.2.4 Grain Mounts and Polishing

The procedures employed in the preparation of apatite grain mounts for fission track analysis were suggested by Dr. Randall R. Parrish (short-course on the fission track method, Dalhousie University, October, 1986).

Evenly spaced circles were traced on a 20 X 25 X 0.5 cm^3 teflon sheet, using a marking pen and a dime. Cardboard strips were placed close enough on either side of the circle so that a slide placed on them would form a bridge over the circle. 50 to 150 apatite grains were distributed evenly into each labelled circle and covered with 5 or 6 drops of a gently stirred epoxy (Araldite) and hardener mix. A glass slide was immediately placed on the epoxy which was allowed to spread radially out beyond the edge of the marked circle, and then left to dry for 24 hours.

Apatite grain mounts were ground and polished using a polishing machine with interchangeable polishing wheels. 600 grit silicon-carbide sandpaper was used for initial grinding on a mounted wheel. The mount was slowly revolved in the opposite direction of the 200 r.p.m. spinning wheel, until the marking pen circles were barely perceptible. The mount was polished using wheels prepared with 15-, 9-, and 1-μm diamond compound. Each wheel was used until scratches of the previous grit were invisible under 400 X magnification reflected light. Before changing each wheel the mount was thoroughly washed with soapy water to rid the sample of any leftover diamond compound. The final polish was obtained by running the mount under light pressure over a 0.03 μm alumina water slurry several turns in each direction. When the polishing was completed, the mount was again thoroughly washed with soapy water and rinsed.

To reveal the fission tracks, mounts were etched for 40 seconds at a constant 21 °C in 7% HNO_3. After they were etched, each grain mount (and glass dosimeter) was removed from the slide and covered with a piece of low-uranium muscovite sheet attached with Scotch-tape. These were placed in an aluminum irradiation capsule in recorded positions, interspersed with 3-4 age standards and capped at the bottom and top by standard dosimeter glasses.

5.4.2.5 Sample Irradiation

Two capsule packages (MM041 and MM043) were irradiated for fission track analysis at site 9D in the McMaster University Nuclear Reactor in Hamilton, Ontario. Capsules were irradiated for 900 seconds. The returned irradiated capsules were stored for up to six weeks under lead, to allow radioactivity levels to diminish to a workable 2 mr/hr at a one cm distance.

After irradiation, sample and age standard detectors were etched for 12 minutes in 48% HF, while glass dosimeter detectors were etched in a similar solution for 40 minutes. Detectors were then rinsed thoroughly with distilled water and dried at very low heat for a few minutes on a hotplate, to drive off any remaining HF.

Irradiated and etched samples and detectors were mounted across a mirror plane on a glass slide. Samples and standards were attached to the slide by a few drops of clear lacquer and the detectors were attached face-side up.

5.4.2.6 Fission Track Age and Length Distribution Measurement Procedures

Fission tracks were counted with dry objectives at 1250 X magnification, using a Leitz Laborlux D microscope equipped with a computerized stage, 100-watt light source, and Olympus 5 X 5 mm grid in the right eyepiece. Throughout the study, tracks intersecting the surface along the top and right margins of the grid were included and along the bottom and left margins of the grid were excluded. Only prismatic sections of apatite (parallel to c-axis) were chosen, and wherever possible, tracks were only counted in the middle area of each grain.

Track lengths were measured using a Leitz drawing tube and a Houston Instruments HIPAD digitizing pad, equipped with a LED cursor and a 9-volt battery. Before each measuring session, a personal calibration was conducted by measuring a known grid distance in the right graticule twenty times, and normalizing the average measured distance by the true distance. Whenever conditions were interrupted or changed (LED focus, graticule focus etc.), the calibration procedure was repeated before track measuring was resumed. Where possible 100 track length measurements were made for each sample to allow for statistical significance. Standard track length calculations (mean, standard deviation, skewness) were made for each sample using a computer program developed by Donelick (1987).

5.4.3 APATITE FISSION TRACK ANALYSIS: SEDIMENTARY BASINS

5.4.3.1 Introduction

Apatite fission track dating has been applied to cooling/exhumation chronology in many areas of the world (Harrison et al., 1979; Naeser, 1979; Parrish, 1983; Gleadow and Fitzgerald, 1987; Maksaev, 1990; Hendriks, 1991, Arne, 1992). Both time of cooling below ~100 °C and, in areas with considerable topographic relief, exhumation rates, are theoretically determinable with apatite fission track methods (Wagner et al., 1977; Harrison, et al.,1979).

Apatite ages have generally been observed to increase with elevation (Dodge and Naeser, 1968; Wagner and Reimer, 1972). This pattern is interpreted to be mainly the result of upward movement of a rock column through the critical isotherm (closure of apatite with respect to fission tracks). Rocks at higher elevation cooled sooner and have had more time to accumulate fission tracks. They give older ages than rocks at lower elevations. The same relationship will hold true for downhole conditions within a well. The age gradient formed over a vertical section of strata is defined as the apparent uplift rate (Parrish, 1983). Interpreting this rate as the true uplift rate (relative to sea level) is not advisable, because the age gradient only represents the rate at which the critical isotherm moves downward with respect to the section (Parrish, 1983). The following conditions must be true in order for the apparent uplift rate to equal the true uplift rate (Parrish, 1983): (1) The geothermal gradient must have remained uniform over the time period represented by the difference in the apatite fission track ages, (2) Steady state tectonic conditions must apply over that same time period (ie. uplift equals erosion).

Investigation of apatite annealing characteristics has revealed that a single closure temperature for fission tracks in apatite is too simplistic. Closure happens over a range of temperatures (75-125 °C; Naeser, 1979; Gleadow and Duddy, 1981; Green et al., 1988; 60-125°C; Gleadow et al., 1983) depending on the cooling rate (Dodson, 1973). The concept of a partial annealing zone has been used to facilitate interpretation of apatite fission track ages by defining a range of temperatures ~70-125 °C) over which apatite fission tracks annealed, and below which tracks were considered stable (Wagner, 1979; Gleadow et al., 1983). Although partial annealing is now known to occur over the temperature range 20-125 °C (Green et al., 1985, 1986; Donelick et al., 1990), the 'partial annealing zone' concept is still useful, and in this study is used to distinguish temperatures of relatively greater annealing (~70-125 °C), from minor annealing temperatures (below ~70 °C). This concept introduces the possibility of slow, induced apparent uplift rates in a vertical suite of rocks, which has resided at partial annealing temperatures for an extended time period. Given the complex interrelationships of all these conditions, an ideal situation is rarely achieved and therefore caution must be exercised when interpreting apparent uplift rates. Ravenhurst and Donelick (1992) pointed out that many reports confuse exhumation or uplift of the rocks with tectonic uplift (the actual upward movement of a mean surface). In areas where there is substantial relief or in areas where deep drilling (2-3 km) has been done, information on the rate of exhumation can be derived (Ravenhurst and Donelick (1992).

5.4.3.2 Apatite Fission Track Annealing

Annealing of tracks occurs at temperatures greater than 20 °C (Green et al., 1985, 1986; Donelick et al., 1990), although the rate of annealing increases with temperature. At low temperatures (less than ~70° C) shortening is very slow, but annealing rates progressively increase with temperature to the base of the partial annealing zone (~125 °C), where it becomes essentially an instantaneous process (Donelick et al., 1990). Given this variability in annealing rate with temperature, and the fact that fission tracks are produced continuously through time, the confined track length distribution (# of confined track lengths vs. track frequency) reflects the temperature variation through time experienced by a sample. Other thermal history indicators, such as vitrinite reflectance (Mukhopadhyay, 1991a; Bustin, 1989) and TAI (Waples, 1980) reflect the maximum temperature experienced by a sample but little about the variability of temperature through time.

Current understanding of apatite annealing characteristics is based on laboratory data which are extended to geological timescales by way of an Arrhenius plot (Naeser and Faul, 1969; Green et al., 1983; Green et al., 1985; Green et al., 1986, Duddy et al , 1988) The annealing kinetics of apatite fission tracks and the resulting nature of the Arrhenius plot distribution have important implications for extracting quantitative information from track length distributions Because debate exists over the exact fission track annealing kinetics of apatite, a variety of Arrhenius plot distributions have been in use (for a review of this see Laslett et al , 1987) Based on best-fit modelling, an annealing kinetics model represented by a set of slightly fanning annealing lines in an Arrhenius plot has been suggested as the preferred kinetic model (Laslett et al., 1987). The fanning is interpreted as being a consequence of different fission track annealing activation energies for the various chemical species of apatite and for different crystallographic orientations in apatite (Laslett et al., 1987). Other kinetic models are represented by parallel annealing lines (constant activation energy) and widely fanning annealing lines in an Arrhenius plot (see Laslett et al., 1987).

5.4.4 APATITE FISSION TRACK SAMPLING

This thesis draws data from several AFTA projects which have been undertaken on the Maritimes Basin including. Ryan, 1992 (this study); Grist et al., 1992, Hendriks et al , 1992, Ryan et al., 1991b; Hendriks, 1991; Ravenhurst et al., 1990; and Arne et al , 1990 The sample locations from these various studies were compiled in Figure 5 13

Samples were taken from surface outcrop, shallow diamond drill holes, as well as from cuttings and cores in offshore petroleum exploration wells (Figs 5 13) As far as possible, samples were selected at horizons for which organic maturation data were also available.

A total of 26 fission track age dates were determined from 55 samples collected as part of this study (Ryan, 1992). The other samples did not contain sufficient numbers of etchable apatite grains to permit dating. These data are combined with 14 samples from Grist et al. (1992), 11 from Arne et al.(1990), 9 from Ravenhurst et al.(1990), 5 from McKillop (1990) and 32 from

Hendriks (1991) to make up a total of 96 fission track age dates from the Maritimes Basin or surrounding highland areas. In addition to the age determinations, 101 apatite fission track length samples were analyzed (see Ryan et al., 1992). Most of these track length samples correspond to the age date samples, however some of the track length samples have no corresponding age determination. The results of the track length spectra and the age date studies are summarized in Table 5.1.

For the sake of regional comparison, all the measured ages were arbitrarily corrected to a mean track length of 15.2 microns (length as measured by the author for the Fish Canyon Standard, similar lengths were measured by other workers in the lab for the same standard). This procedure is controversial, and corrections of FT data should be introduced only with the utmost caution (e.g., Wagner, 1979; Gleadow et al., 1986; Green, 1988). As previously mentioned Willett (1992) suggested that the 1:1 ratio of reduction of fission track length to reduction of fission track age is approximately correct for lengths greater than 65% of the original length. Blind samples from the various Maritimes Basin FT studies were reanalyzed and the results were consistent with those of other workers, therefore such a correction for age was possible. The only samples which can not be reanalyzed were those of Arne et al. (1990) and therefore these data must be compared with caution. The apatite FT procedures for most of the Maritimes Basin data (exception are those of Arne et al.,1990) followed the methods described by Grist and Ravenhurst (1992).

5.4.5 RESULTS OF THE APATITE FISSION TRACK ANALYSIS

All the surface or near-surface results obtained for the strata in the Maritimes Basin have fission track ages which are younger than the depositional age of the rocks and therefore are interpreted as having been reset (Fig.5.14). The results of samples from Prince Edward Island, Scotch Village (SV Fig. 5.13), and from the Sydney Basin are included with the Cumberland Basin histogram (Fig.5.14). This group of samples has a mean corrected age of 198 Ma and a standard deviation of 47 Ma. Although the samples came from both surface and drill holes, there does not appear to be a significant reduction of age with depth. This factor can be explained by the relatively shallow depth (< 1.2 km) of the drill holes sampled (see Table 5.1).

In conjunction with the Cumberland Basin project, a parallel study of a series of offshore drill holes and wells in the Gulf of St. Lawrence was undertaken by the Dalhousie Fission Track Lab (Fig.5.16). Ryan et al.(1991b) and Grist et al. (1992) have summarized the results. The mean corrected age of the samples from surface to a depth of 2 km is 184 Ma with a standard deviation of 35 Ma (Fig.5.16). Significant reduction in the age of the samples from deeper in the wells (> 1 km) was observed, and at a depth of 2925m one sample had an age of 34 Ma (Fig.5.16). This result is not unexpected as at a moderate geothermal gradient of 25° C/km and at depths of 3 km, this sample would be within the partial annealing zone for apatite.

Ravenhurst et al. (1990), McKillop (1990), and Arne et al.(1990) have all done apatite fission track analysis on the Meguma Terrane south of the Cobequid-Chedabucto Fault zone. The samples were from both the Carboniferous strata and from the underlying Meguma Group and the South Mountain Batholith. For the purpose of this study these samples have been divided into those adjacent to the Gays River Deposit and those from other parts of southern Nova Scotia referred to as Meguma samples (Fig. 5.13). The Gays River samples have a mean corrected age of 249 Ma with a standard deviation of 22 Ma. The Meguma samples have a mean corrected age of 221 Ma with a standard deviation of 26 Ma.

Hendriks (1991) carried out another apatite fission track study in the Atlantic region through the Apatite Fission Track Lab at Dalhousie. His primary interest was the exhumation history of the Long Range Mountains in Newfoundland, however his results have a direct bearing on the adjacent Deer Lake Basin which constitutes part of the larger Maritimes Basin. Samples from the Deer Lake Basin and the Long Range Mountains of Newfoundland give corrected ages of approximately 281 Ma with a standard deviation of 44 Ma.(Fig.5.14).

The overall mean for 92 apatite fission track corrected ages from the Maritimes Basin is 232 Ma with a standard deviation of 55 Ma (Fig. 5.15). There were only 92 ages considered in this diagram because of filtering of the data which excluded deep young ages and older ages from higher elevation samples (Top of the Long Range) in the Newfoundland data. Spread in the mean values can be explained by: 1) proximity to onlapped basin margins, 2) stratigraphic position of the sampled horizon, 3) duration of the exhumation event, 4) hot basin fluid expulsion events related to mineralization and faulting, and 5) local paleogeothermal gradient variations within the basin.

5.5 INTRODUCTION TO MODELLING OF THERMAL DATA

Modelling of the thermal data of the Maritimes Basin can be divided into two components: 1) burial history plots and 2) models based on organic maturation and fission tracks. Geohistory analysis or burial history plots have been employed by numerous workers as a means of reconstructing the burial history for rocks within sedimentary basins (Lopatin, 1971; van Hinte, 1978; Waples, 1980; Feinstein et al., 1988). Waples (1980) pointed out that models for sedimentary basin thermal histories must start out with a reconstruction of the depositional and tectonic history of the strata. This is accomplished by plotting depth of burial versus geological age, as shown in Figure 5.17.

Waples (1980) pointed out that burial history diagrams should not be confused with geological cross sections. For example in Figure 5.18, the time of deposition of the lower unit of the Pictou Group was approximately 305 Ma, and given the maximum stratigraphic thickness of the Pictou Group as measured in the Maritimes Basin and the vitrinite reflectance recorded in surface samples of the youngest Pictou Group strata, an estimate of 4.9 km of burial was probable for the lower Pictou Group strata at 280 Ma. Measured vitrinite reflectance values for the lower Pictou Group interval suggest that the period of burial necessary to produce such maturation (at moderate geothermal gradients) could not have exceeded 30 my (Bustin, 1989). After this period of maximum burial, exhumation must have been taken place. The presence of Cretaceous (Albian 95-107 Ma) unconformities on the Carboniferous strata of the Maritimes Basin suggest that most of the exhumation must have occurred prior to 107 Ma. Using this information, a burial history plot for the stratigraphic interval can be constructed. Construction of these plots is more complicated in areas where tectonic movements were occurring and therefore most of the plots used for this study were chosen in areas that have not undergone a complicated tectonic history. In addition to the more traditional constraints used in the construction of the burial history plots, apatite fission track ages were used here. The apatite fission track ages give the approximate time at which the rocks passed through the 100°C isotherm. Based on the downhole vitrinite reflectance curves (see section 5.6 for discussion) it is estimated that the geothermal gradient was approximately 20-25°C/km and therefore the depth of burial at the apatite fission track closure age was approximately 3-4 km. After this interval has been plotted, parallel stratigraphic units may be added to the diagram (see Fig. 5.17).

The burial history plots which are based on geological observations, were constructed first and the thermal models for the organic maturation and apatite fission tracks were used to confirm the time-temperature plots suggested by the burial history of the strata.

5.6 BURIAL HISTORY PLOTS

Burial history plots are the most crucial part of this study. These plots are constrained by the geology and the thermal information for each specific area. Burial history plots are diagrammatic representations of the burial history of the rocks for specific areas within the Maritimes Basin.

5.6.1 INTRODUCTION

Burial history plots have been used extensively in the oil and gas industry as a starting point for the modelling of organic maturation. The method is used to predict the depth of the oil and gas windows. Many predictive models of organic maturation have been proposed over the last several years including: Time Temperature Index (TTI), Lopatin (1971), Waples, 1980; Basinmat, Sweeney, 1990; Easy% Ro, Sweeney and Burnham, 1990. All of these methods rely upon placing temperature constraints on the burial history plots for the strata being studied. Ravenhurst and Zentilli (1987) attempted preliminary modelling of the sedimentation rates for the Maritimes Basin, and Hacquebard (1984) estimated the amount of strata removed from the basin on the basis of coalification curves. This thesis is however, the first attempt to construct comprehensive burial history plots for most of the significant sub-basins which constitute the

Maritimes Basin.

Burial history plots are an approximation of the burial history of any stratum based on geological parameters observed in the surrounding area. The reconstructions are based on the best geological information available. Some reconstructions are easy to make with a high degree of reliability, especially those of the Cumberland Basin because sedimentation was nearly continuous. In complicated or complex areas, such as adjacent to rising syndepositional diapirs, the plots may only represent the best guess. In an effort to limit complications, the areas chosen from the Maritimes Basin are in structurally less complex areas. The basic data used in this study for the construction of the plots and the placement of temperature constraints are:

1) stratigraphy - provides thickness and distribution constraints on rock units;

2) sedimentology - helps to interpret the stratigraphy as a method of predicting facies variations, distribution and thickness of strata, and sedimentation rates;

3) apatite fission track ages - used to define the time at which the rock unit had last experienced temperatures of approximately 100°C;

4) thermal indicators of maximum burial and approximate estimates of the duration of the burial events - these data are used primarily to define the amount of strata which had overlain the present day sampled horizon at some time in the geological history. For the most part, these observations are supported by the stratigraphic information;

5) paleomagnetic studies - whereas some of the sandstones in the study area have undergone secondary reddening, a phenomena which usually occurs within 2 km of surface, the paleomagnetic age reflects when these strata were within 2 km of surface;

6) structural geology - age constraints on the folding and faulting within the basin.

5.6.2 CONSTRAINTS ON THE BURIAL HISTORY PLOTS FOR THE STUDY AREAS

Burial history plots have been compiled in a similar fashion as Figure 5.17 for most of the Maritimes Basin, from the Minas Basin in the south, the Sydney, Cumberland and Gulf of St. Lawrence basins of the central Maritimes Basin, and the Deer Lake Basin to the north (see Figs. 5.18 to 5.20). These plots were constructed using the constraints as listed above.

5.6.2.1 Cumberland Basin and Prince Edward Island

There were four burial history plots constructed in this area. Plots were constructed for the Hillsborough Bay area in P.E.I., and the eastern, western, and central parts of the Cumberland Basin in northern Nova Scotia (Fig. 5.18).

5.6.2.1.1 Hillsborough Bay, Prince Edward Island - Drill Hole CT-1

The CT-1 drill hole at Hillsborough Bay in P.E.I. penetrated the Pictou Group strata to a depth of 1.5 km (Fig. 5.13). The vitrinite at the surface is 0.65% Ro and at a depth of 1.05 km the vitrinite was 0.90% Ro max giving a maturation gradient of approximately 0.25%Ro/km. This maturation gradient corresponds to approximately 22°C/km in paleogeothermal gradient by comparison to the coalification curves, assuming a 25 million year duration of maximum burial. The burial history plot is also constrained by several fission track ages ranging from 168 Ma to 242 Ma with 2 samples at 180 Ma, indicating that the sampled horizons were all subjected to temperatures in excess of 100°C. The fission track ages suggest that the duration of the maximum burial of the strata was significantly less than 40 my given that a fission track age of 242 Ma came from the hole and the age of the ata is approximately 290 Ma. The burial history plot is also constrained by the age of the hematization of the Pictou Group strata in general which suggests that exhumation took place at circa 270-240 Ma. Given the paleogeothermal gradient and the observed maturation of the samples an additional 3600 m of strata must have been deposited on top of the present day surface. All of this information together with the geological parameters were used to construct the burial history plot for the area (Fig. 5.18).

5.6.2.1.2 Eastern Cumberland Basin - Drill Hole NT-47

The drill hole NT-47 penetrated the Pictou Group strata in the Tatamagouche area of the eastern Cumberland Basin (Fig. 5.13). The burial history plot for the location was constrained by several lines of evidence. The vitrinite reflectance for the specific location was 0.98% Ro, although for the area within 1 km from the drill hole has an average reflectance of 0.90% Ro.

The TAI for the drillhole have a value of 3.0 which is approximately equivalent to 0.90 to 1.00 Ro max% and therefore corresponds to the vitrinite reflectance determinations. The clay mineralogy studies indicates that the sandstones from the drill hole are at the boundary of the diagenetic and the anchizone and therefore are roughly equivalent to an Ro max value of 0.90%. The presence of some Cretaceous spores and pollens in the karstic area around Malagash (10 km north of the drill hole) suggest that much of the exhumation must have occurred pre-Cretaceous. The apatite fission track ages for NT-47 range from 156 to 259 Ma with the average of four ages being 207 Ma. This information suggests that the duration of the maximum burial could not exceed 30 million years. If a paleogeothermal gradient of 25°C/km is used (estimate of basin average, see section 5.2.7) and the maximum burial duration was 30 My, it would require an additional 3800 m of cover (ghost stratigraphy) in order to produce the observed maturation in the hole. Figures 5.17 and 5.18 give a diagrammatic representation of this burial history and the parameters used to construct the plot.

5.6.2.1.3 Western Cumberland Basin - Drill Hole SA-1

The drill hole penetrated the upper part of the Cumberland Group in the western part of the Cumberland Basin (Fig. 5.13). The vitrinite reflectance at the top of the hole is 0.88 Ro max% and at a depth of 1.1 km the Ro max is 1.30%. This gives a maturation gradient of 0.40%Ro/km suggesting a paleogeothermal gradient of approximately 25°C/km. The TAI values for the hole are 3 to 3.5 which add credence to the vitrinite reflectance studies from the drill hole. There are three apatite fission track ages from the drill hole ranging from 185 to 210 Ma with an average of 201 Ma. Given the paleogeothermal gradient, apatite fission track ages and the stratigraphy, a minimum of 3 km of additional cover must have been deposited on top of the beds at the top of SA-1. Exhumation of these strata above the 100°C isotherm must have preceded 200 Ma. In the north central Athol Syncline area, approximately 10 km from the SA-1 drill hole, Cretaceous spores have been identified (Dolby, 1988) in poorly consolidated sediments occurring on top of Malagash Formation beds (upper part of the Cumberland Group) suggesting that exhumation of the Malagash Formation to a near surface position must have occurred prior to the Cretaceous (100 Ma). This information was then compiled to construct the burial history plot for the South Athol #1 drill hole (Fig. 5.18).

5.6.2.1.4 Central Cumberland Basin - Drill Hole BP-06

This drill hole penetrated the upper Part of the Cumberland Group in the Oxford area (Fig. 5.13). The vitrinite reflectance varies from 0.90 Ro max% at the top of the hole to 1.20 Ro max% at 760 m depth in the hole. The TAI values for the drill hole range from 3.0 to 3.5 which are roughly equivalent to the observed maturation estimates from the vitrinite reflectance. Several samples of organic rich shales from adjacent drill holes yielded Tmax values of 442°C which also indicate a maturation level equivalent to 0.90 Ro max%. The observed organic maturation levels down the hole indicate a vitrinite reflectance gradient of 0.40 Ro max%/km. Apatite fission track analysis from the drill hole gave some sporadic results. A corrected apatite fission track age of 322 Ma came from one sample but the standard deviation was 120 my and therefore this sample was not used. Another sample gave a corrected age of 114 Ma, however it occurs between two samples that have ages of approximately 180 Ma. The 180 Ma is believed to be the most reliable and was therefore used in the burial history plots. The fission track ages suggest that the duration maximum burial was approximately 40 million years. Given the duration of maximum burial and the organic maturation gradient a paleogeothermal gradient of 25°C/km is probably a close approximation. If this gradient is plausible it would require a minimum of 3600 m of additional strata on top of the present day surface. All of this information is compiled into the burial history plot for BP-06 (see Fig. 5.18).

5.6.2.2 Gulf of St. Lawrence Area

Three wells drilled for petroleum in the Gulf of St. Lawrence were used to construct burial history plots for the area (Fig. 5.13). Figure 5.16 is a cross section of holes from across the Maritimes Basin with emphasis placed on the Gulf of St. Lawrence area. The wells used in the Gulf study were Bradelle L-49 (#4 Fig. 5.16), Cable Head E-95 (#6 Fig. 5.16), and East Point E-49 (#8 Fig. 5.16).

5.6.2.2.1 Central Gulf of St. Lawrence - Cable Head E-95

This well penetrated a thick sequence of Carboniferous strata including the Pictou, Cumberland, and the Mabou groups. The vitrinite reflectance for the well varies from 0.90% Ro max at 1.4 km depth to 2.00 at approximately 3 km. The estimate of the down well organic maturation gradient was estimated from the sample 1.4 km and a value of 1.50 at 2.4 km depth. The deeper vitrinite reflectance values were not used because of the possible influence of heat flux related to Windsor Group evaporite diapirism immediately below the sampled horizon. The gradient from the shallower depths is 0.60% Ro max/km. This value is higher than those observed in the Cumberland Basin examples. If this gradient is compared to shallower samples from the L-49 Bradelle well it is seen that the organic maturation gradient lessens at shallower depths. The problem arises because the deeper samples are at present day temperatures approaching 85°C and have been at these temperatures for approximately 300 million years therefore vitrinite values of 2.00% Ro max are to be expected. Apatite fission track corrected ages for the well range from 157 to 225 Ma. The younger age is from the deepest sample which is at present day temperatures approaching 85°C and therefore yields a young age that does not reflect the exhumation of the strata. The other three samples have an average corrected fission track age of 219 Ma. Because of the problems with deeper holes and the vitrinite reflectance values an estimate of 25°C/km was used for the paleogeothermal gradient. Given that a sample occurring at present day at a depth of 1.5 km has been subjected to temperatures of greater than 100°C prior to 225 Ma, as evidenced by the reset apatite, a minimum of 2 km of additional cover must have been present. All of this information was used to construct the burial history plot for the well (Fig. 5.19).

5.6.2.2.2 Western Gulf of St. Lawrence - Bradelle L-49 Well

The Bradelle L-49 well was drilled in the western part of the Maritimes Basin and penetrated the Pictou, Cumberland, Mabou and the Windsor groups (Fig. 5.16). Vitrinite reflectance values in the well range from 0.79% Ro max at 900 m to 2.00% Ro at 2600 m depth. The same problems as discussed with regard to the Cable Head E-49 well apply to this well. The values of the vitrinite reflectance determinations from deeper in the well reflect the long duration of burial at temperatures approaching 100°C. The apatite fission track corrected ages for samples in the well range from 34 to 208 Ma. There is a dramatic decrease in the age of the sample down hole. The young ages are the result of prolonged burial of the strata at temperatures close to the total annealing temperature of the apatite fission tracks. The age of 208 Ma from the sample at 900 m is the best estimate of the timing of the exhumation for the area. The fact that the apatite from this sample has been completely reset indicates that the horizon at 900 m was subjected to temperatures in excess of 100°C prior to 208 Ma. If the paleogeothermal gradient is assumed to be approximately 25°C/km then a minimum of 2.5 km of additional strata must have overlain the well at some time prior to 208 Ma. This information is compiled into the burial history plot for the well (Fig. 5.19).

5.6.2.2.3 Eastern Gulf of St Lawrence Area - East Point E-49 Well

This well penetrated the Pictou and the Cumberland Groups in the western part of the Gulf of St. Lawrence, off the coasts of P.E.I. and Cape Breton (Fig. 5.16). The only vitrinite reflectance determination for this well is a grab sample of cuttings from near the top of the well which were analyzed for dispersed vitrinite as part of this study. The sample has a vitrinite reflectance of 0.64% Ro max. Whereas the downhole reflectance profiles for the wells in the Gulf of St. Lawrence are consistent it was assumed that the values for the E-95 well were applicable to this well. Apatite fission track corrected ages from 2374 and 2510 m have both been reset (+ 100°C) and have an average age of 190 Ma. The unusual feature is the shallower sample has the younger age (164 Ma) as compared to the deeper sample with a 216 Ma age. Closer examination of seismic profiles from the area suggest that there may be a fault intersecting the well at approximately 2000 m. If there was a heat flux caused by fluid movement along this fault it may explain the younger age at a shallower depth adjacent to the fault.

The burial history plot was constructed without taking the fault into account because the timing and kinetics of the fault are difficult to determine from the geological information available. If this burial history plot follows the trend of the others for the Gulf of St. Lawrence it can be expected that the duration of burial was approximately 30-40 million years. The near surface vitrinite value would require a temperature of between 80-90°C to attain the observed maturation level. Using the regional paleogeothermal gradient of 25°C/km it would require a minimum of 2500 m of additional cover. The fission track ages indicate that the additional strata was eroded off of the area prior to 216 Ma. All of this information was used to construct the burial history plot in Figure 5.19.

5.6.2.3 Minas Basin - Scotch Village Sample FT90-049

One fission track sample was collected from outcrop in the Minas Basin area (SV on Fig. 5.13). The sample was from the Scotch Village Formation (Lower Cumberland Group). The vitrinite reflectance from an adjacent sample had a Ro max of 1.01%. If the paleogeothermal gradient is assumed to be approximately 25°C/km it would require an additional 4000 m of cover for a duration of 40 million years. The corrected fission track age of 171 Ma suggests that exhumation was prior to 170 Ma but in order to exhume the sampled horizon to present day surface the exhumation must have continued post-170 Ma. In the area of the central Nova Scotia there have been examples of Cretaceous sediments overlying Carboniferous strata and therefore it is reasonable to assume that the Carboniferous strata at present day surface must have been near surface prior to the Cretaceous. These assumptions give a burial history plot (Fig. 5.20) similar to those modelled for the Gays River area by Arne et al. (1990). Additional sampling of this stratigraphic horizon in the basin is necessary before a more reliable burial history plot can be constructed.

5.6.2.4 Sydney Basin - Drill Holes P-05 and 82-1

Two drill holes were sampled from the Sydney Basin as part of this study (Fig. 5.13). Drill hole P-05 was drilled offshore in the Sydney Basin and drill hole 82-1 was drilled onland. For the purpose of constructing a burial history plot for the Sydney Basin the geological information from both of the holes were combined. The P-05 hole penetrated redbeds of the Pictou Group that do not occur in the onland portion of the Basin. Both drill holes have a complete section of the Cumberland (Morien) Group and penetrate the underlying beds of the Mabou Group. Surface vitrinite reflectance values from throughout the Sydney Basin usually range from 0.80 to 0.90% Ro max. Down hole vitrinite reflectance values range from 1.25 to 1.30% Ro max at a depth of 1 km. Rock-eval pyrolysis, TAI and clay mineralogy from the 82-1 hole all support the overall trend of maturation down hole. This gives an organic maturation gradient of approximately 0.40% Ro max/km. The fission track ages from the two drill holes give an averages corrected fission track age of 200 Ma. The ages range from 136 to 268 Ma. The youngest age comes from a rock of questionable age from beneath the Mabou Group in drill hole P-05. Because of the uncertainties of the age of the rock it will not be used in the construction of the burial history plot. If the two ages from the 82-1 hole are used the average corrected apatite fission track age is 231 Ma. For the purpose of constructing the burial history plot for the area it was assumed that the Cretaceous unconformity on the Carboniferous strata also occurs in the Sydney area. If this is approximately correct the duration of maximum burial must have been short (<20 my). Given a 20 million year maximum burial duration a paleogeothermal gradient of approximately 25°C/km is suggested. The minimum additional cover necessary to produce the observed maturation is 4000 m. This estimate is very close to the estimate suggested by Hacquebard (1984) based on the vitrinite reflectance from the Sydney Basin. All of this information was used to construct the burial history for the Sydney Basin (Fig. 5.20).

5.6.2.5 Deer Lake Basin Newfoundland - Sample FT90-035

Hendriks (1991) sampled some of the Carboniferous rocks of the Deer Lake Basin in Newfoundland. The surface vitrinite reflectance values in the Deer Lake Basin average approximately 0.75% Ro max. All of the samples from the Deer Lake Basin and the adjacent basement samples have been reset indicating that they have been heated to temperatures in excess of 100°C. If the paleogeothermal gradient of the Deer Lake area is similar to the rest of the Maritimes Basin then it approximately 25°C/km. The corrected apatite fission track age average of 277 Ma for the Deer Lake Basin samples indicates that the maximum burial was probably less than 20 million years. To attain the maturation levels found in the surface samples and given the paleogeothermal gradient, a minimum of 4000 m of additional cover must have been deposited in the area. All of this information was used to construct the burial History plot (Fig. 5.20).

5.6.3 IMPLICATIONS OF THE BURIAL HISTORY PLOTS

An examination of the burial history plots for the Maritimes Basin reveals that they are remarkably similar from one area of the basin to another. These similarities reflect in part the fact that structurally complicated areas have been excluded from the study. Several deductions can be derived from the burial history plots:

1) rapid sedimentation and accumulation occurred from 320 Ma to approx. 290 Ma, although the sedimentation was not continuous in all of the sub-basins it appears as a straight line on the burial history plots because of the scale chosen for the time axis;

2) maximum burial of the strata was at approximately 290 Ma;

3) erosion or exhumation began between 270 and 250 Ma;

4) duration of the maximum burial was between 20 and 40 million years;

5) between 2 and 4 km of strata has been removed from the sedimentary pile post maximum burial; and

6) the rate of exhumation (erosion) decreases through time for most of the areas, for many areas the fastest rate of exhumation is between 270 Ma. and 190 Ma.

As a means of evaluating the burial history plot accuracy, both organic maturation modelling and modelling of the apatite fission track annealing was undertaken.

5.7 LOPATIN (ORGANIC MATURATION) AND FISSION TRACK MODELLING

5.7.1 LOPATIN MODELS

Numerous models for thermal and diagenetic histories of sedimentary basins have been proposed over the past few years. Many of the models have been developed as predictive tools to be used in estimating maturation levels in basins for use by oil and gas exploration companies.

One such model is the Lopatin model (Lopatin, 1971; Waples, 1980; Issler, 1984), an organic maturation model which is the most widely used method in basinal studies. This model is based upon the assumptions that: 1) the reaction rate of kerogen doubles for every 10°C increase; and 2) the total maturation is equal to the sum of the interval maturation (Bustin, 1989). The result of the Lopatin modelling is a Time-Temperature Index (TTI) which can be compared to other maturation indicators (Waples, 1980). The first order kinetic assumption used in the Lopatin method is approximately correct for maturation levels up to an equivalent 1.0 Ro, however at values near Ro 1.0 or greater than Ro 1.0 the TTI to Ro relationships are inconsistent (cf. Sweeney and Burnham, 1990). The Lopatin method was used here because the alternative methods such as the Easy % Ro or Basinmat (Sweeny and Burnham, 1990) depend primarily on reaction rates of specific kerogen types present, a variable that is poorly documented in the strata of the Cumberland and Maritimes Basins.

The success of the Lopatin method relies heavily on having established an accurate burial history for the unit being studied (see section 5.5) and an absence of prolonged post maximum temperature heating. A problem exists with Lopatin model predictions of vitrinite reflectance because the Lopatin calculation continues to add to maturation level (TTI) after maximum temperatures were attained whereas the more reliable models based on the kinetic Arrhenius equation minimize the effects of late prolonged heating at temperatures less than the maximum. As stated earlier, however, the primary obstacle to their use in this study is the poorly documented compositions of the kerogen contained within the rocks of the study area.

One possible solution to the problem with the Lopatin method is to use only the "prograde" thermal history (deposition to maximum burial/temperature) in the calculation. Subsequent erosion and lengthy burial at temperatures significantly lower than the maximum temperature ("retrograde" thermal history) would therefore be excluded from the Lopatin TTI calculation because this part of the thermal history does not affect vitrinite reflectance (Fig.5.17). Another alternative is to define the Lopatin calculation for specific basins, for example Issler (1984) proposed an equation for the relationship of TTI to vitrinite reflectance for the Labrador

Coast which yields consistently lower predicted Ro values than the Waples (1980) equation,would indicate this procedure will allow for the effects of prolonged post-maximum temperature burial to be minimized. Using the Issler (1984) equation on examples from the Maritimes Basin where vitrinite reflectance values are known suggests that the predictions using this equation are approximately correct for the Maritimes Basin samples. Despite the obvious flaws in the Lopatin method, the calculations of predicted Ro using the Issler (1984) equation are a good approximation of the maturation level and are used in the modeliing herein.

Burial history plots are the essential building blocks upon which time-temperature histories can be constructed. The basic approach taken for this study was to combine the stratigraphic information, sedimentology, and thermal indicators to derive a burial history plot see section 5.5) from which a time-temperature (Tt) path could be estimated. This Tt path is constrained by the apatite fission track age date, organic maturation and mineral thermal indicators.

5.7.2 APATITE FISSION TRACK ANNEALING MODEL (TRAC3)

In order to provide supporting evidence for the Tt path estimates derived from the burial history plots, the Tt paths were input into a forward model (Trac3; Willett, 1990) for apatite fission track annealing and Lopatin calculations (based on the Issler (1984) equation). Willett (1992) described in detail a forward model (Trac8) which is an updated version of the model used in this study. The Trac8 program varies from Trac3 in that it provides a statistical measurement of the degree of correlation between the measured and the predicted fission track length distribution, a feature that is useful but not necessary for this study. For a detailed description and discussion of the model the reader is referred to Willett (1992), as only a brief description is included here.

For a given Tt path the trac3 forward model will: 1) calculate the amount of fission track annealing; 2) plot the Tt path; 3) create a predicted apatite fission track length histogram; 4) provide the statistical analysis of the predicted fission track length distribution, mean length, skewness, standard deviation; 5) estimate the measured fission track age of a sample; and 6) using

Lopatin TTI calculations, trac3 estimates the predicted Ro vitrinite reflectance values for the sample.

As a test for the Tt paths estimated from the burial history plots, the measured apatite fission track and vitrinite reflectance results were compared with the predicted results calculated by the Trac3 forward model (Fig. 5.21 to Fig. 5.23). Where there was a good correlation between the measured and the predicted results, particularly the distribution of track lengths, mean track length, and the measured age) it was assumed that the Tt path was approximately correct. In most cases there was a reasonable correlation of the modelled and the measured data in the study area (Fig. 5.21 to 5.23). Statistical analysis of the correlation of the measured versus the modelled data was not undertaken. Values of the modelled Ro max and apatite fission track age which were found to be within one standard deviation of the measured values were assumed to be correct. For the purpose of comparison the modelled distributions were superimposed onto the measured distribution to demonstrate the correlation (Fig. 5.24).

5.8 CONCLUSIONS OF MODELLING

Based on the results of this study and on the data from Hendriks (1991), Arne et al. (1990), and Ravenhurst et al. (1990), the following conclusions emerge:

(1) fission track ages are younger than the rocks from which the samples came, indicating that they have all been reset (subjected to temperature >120°C);

(2) the basin underwent rapid sedimentation from 320 to 290 Ma;

(3) a basin-wide exhumation took place from 280 to 170 Ma, which removed from 2-4 km of strata (presumably of Permian age);

(4) most of the basin underwent a slow erosion (unroofing) taking place from 190 to 100 Ma (Early Jurassic to Early Cretaceous);

(5) over the last 100 Ma there has been slow to moderate erosion (exhumation);

(6) with the possible exception of the E-49 Well in the Gulf of St. Lawrence, there is no evidence of Triassic sedimentation or thermal activity in any of the samples studied, as evidenced by the paucity of bimodal track length distributions. It is logical to conclude

from this that the present distribution limits of the Triassic strata closely approximate the original boundaries; and

(7) the paleogeothermal gradient, as interpreted from the thermal data (eg. vitrinite reflectance, TAI, etc.) and confirmed by the forward modelling of the apatite fission track data, suggests that it was approximately 25°C/km rather than the gradients of up to 67°C/km suggested by Hacquebard (1984).

If the interpretations are correct, one comes to the necessary conclusion that the Maritimes Basin covered most of the Atlantic region of Canada 290 Ma, prior to exhumation. Figure 5.24 is a cartoon of the possible extent of the Maritimes Basin at various times in its history. The extremely important implications from this thermal study are incorporated into basin evolution in chapter 6, and the economic geology, chapter 7 of this thesis. The implications of a sedimentary cover over most of Atlantic Canada are far reaching and may help to explain thermochronology not only of the basin but of the surrounding highland areas as well. The additional confining pressures and the additional sediment load in relation to basin-brine expulsion events significantly alters theories as to the origin of, and distance travelled by, mineralizing basin brines in the Maritimes Basin.

TABLE 5.1 APATITE FISSION TRACK DATA: MARITIMES BASIN

SAMPLE #	DEPTH	GRAINS	SPON.	INDUC.	CHI2	TL MEAN	S.D.	#	FT AGE	AGE CORR.
				RYAN DATA THIS STUDY: CUMBERLAND BASIN, P.E.I., AND SYDNEY BASIN						
FT89-161	305	20	1.84	1.91	PASS	14.74	1.27	46	179±19.1	185
FT89-162	456					14.74	1.11	50		
FT89-163	625					14.04	0.95	35		
FT89-164	665	20	2.77	3.09	FAIL	14.31	1.32	50	196±22.9	208
FT89-165	791					13.83	0.91	15		
FT89-166	961	11	3.10	3.18	PASS	13.09	1.39	61	181±19.5	210
FT89-167	1030					12.87	1.55	32		
FT89-168	1145					11.86	1.65	45		
FT90-001	30	15	1.23	1.43	PASS	13.39	2.01	16	172±32.6	195
FT90-007	560					14.21	1.33	61		
FT90-009	845	16	1.22	1.14	PASS	11.33	1.85	64	200±22.5	268
FT90-010	49	25	8.58	7.94	PASS	13.00	1.76	70	201±22.5	235
FT90-012	210	10	2.19	2.87	PASS	12.23	1.88	111	143±15.7	178
FT90-013	250	13	4.56	3.72	PASS	13.23	1.75	66	225±31.9	259
FT90-014	409	10	2.84	4.52	FAIL	12.71	1.66	85	130±16.2	156
FT90-015	32					12.88	1.89	11		
FT90-017	189	13	1.54	1.64	PASS	14.08	1.56	76	175±26.4	189
FT90-018	308	11	2.09	2.32	FAIL	13.74	1.69	25	164±22.2	181
FT90-019	555	5	7.31	5.49	PASS	12.55	2.03	20	266±120	322
FT90-021	762					12.17	2.61	24		
FT90-022	154	15	1.91	2.75	FAIL	13.02	1.58	101	144±17.3	168
FT90-023	210	10	2.25	2.27	FAIL	12.85	1.75	70	205±35.7	242
FT90-024	259	15	3.00	4.03	PASS	12.69	1.68	67	150±15.8	180
FT90-025	326	15	2.56	3.15	PASS	13.76	1.49	99	164±17.4	181
FT90-026	458	20	4.14	8.79	FAIL	13.02	2.01	100	97 ±10.4	114
FT90-043	S	20	1.94	2.91	FAIL	12.85	1.71	37	149±18.8	176
FT90-044	S	7	2.76	2.90	FAIL	12.65	1.84	100	215±32.1	258
FT90-045	S	15	1.28	1.77	FAIL	13.27	1.88	100	171±24.5	196
FT90-046	S	10	2.80	6.20	FAIL	13.66	1.47	75	94 ±12.2	104
FT90-048	S	10	5.25	1.15	FAIL	12.65	1.26	75	129±41.4	155
FT90-049	S	7	9.51	1.41	PASS	12.13	1.85	25	136±17.5	171
FT90-057	S	15	3.28	3.49	PASS	14.07	1.82	70	188±19.8	203
FT90-058	393					14.48	1.60	20		
				ARNE ET AL. (1990) DATA: GAYS RIVER AREA						
8763-93	S	20	2.09	2.51		13.20	1.64	100	211± 9.2	242
8763-94	S	20	2.08	2.53		13.26	1.58	92	208± 9.2	238
8763-95	S	20	2.10	2.56		13.16	1.28	77	206±12.1	238
8763-97	123	20	1.92	2.01		11.95	2.80	78	205±10.4	261
8763-98	174	20	2.25	2.44		12.87	1.99	100	233±10.3	273
8763-99	90	20	3.21	3.43		13.00	1.90	100	236±11.1	276
8763-100	70.5	20	1.79	2.23		13.34	1.21	85	203±12.9	231
8763-101	57	20	2.91	3.21		13.09	1.23	100	228± 9.4	265
8763-102	69	20	2.50	2.72		12.78	1.98	100	232±11.8	276
8763-103	90	20	3.33	4.14		12.66	1.81	100	203± 8.2	244
8763-104	84	20	3.00	3.36		13.05	1.32	100	226±13.0	263

SAMPLE	DEPTH	GRAINS	SPON.	INDUC.	CHI2	TL MEAN	S.D.	#	FT AGE	AGE CORR.

GRIST, RYAN, AND ZENTILLI DATA: MARITIMES BASIN GULF OF ST LAWRENCE

FT89-117	2374	14	9.98	15.9	PASS	10.75	0.24	55	116±24.0	164
FT89-118	2510	20	96.5	117	FAIL	12.59	0.40	32	179±25.0	216
FT89-121	1260	24	120	104	PASS	12.80	0.19	66	184±14.0	218
FT89-123	2100	17	50.7	51.7	PASS	11.88	0.24	72	176±16.0	225
FT89-124	2520	17	202	230	PASS	11.52	0.17	120	162±21.0	214
FT89-125	2925	28	36.4	55.3	PASS	11.55	0.19	101	119±10.0	157
FT89-131	1400	27	61.6	77.9	PASS	[illegible]	0.26	50	142±22.0	198
FT89-134	966	10	62.8	67.5	PASS	12.49	0.26	62	171±38.0	208
FT89-138	2250	23	72.5	156	PASS	11.10	0.25	49	84± 8.0	115
FT89-139	2945	12	16.1	114	PASS	11.66	0.31	16	26± 4.0	34
FT89-144	1632	17	139	198	FAIL	12.43	0.17	64	111±10.0	136
FT89-147	962	33	157	169	PASS	12.45	0.13	105	149±10.0	182
FT89-148	1005	42	33.9	34.8	PASS	11.79	0.24	47	155±14.0	200
FT89-150	1358	10	35.7	53.0	PASS	10.44	0.67	16	108±15.0	157

MacKILLOP DATA: SOUTH MOUNTAIN BATHOLITH DATA

D60.2	60	20	3.50	1.86	PASS	12.30	2.0	100	197±14.6	243
D249.5	250	20	3.54	1.93	FAIL	12.70	1.10	100	196±15.6	235
D620	620	20	3.32	2.57	PASS	13.00	1.50	100	135± 9.8	158
D848.8	850	17	3.49	2.21	PASS	12.70	1.20	100	165±12.6	197
D1437	1437	20	3.25	1.87	PASS	12.30	1.10	100	182±13.4	225

RAVENHURST ET AL. DATA: GAYS RIVER AND MEGUMA TERRANE

PE-143		15	1.64	1.97	PASS	13.90	1.20	100	173±14	189
PE-150		15	1.73	1.73	PASS	12.60	1.70	100	204±16	246
PE-009		7	2.38	3.26	PASS	12.40	1.10	82	200±18	245
RGR-162		15	1.86	0.95	PASS	13.00	1.30	58	180±20	210
RGR-165		9	1.84	0.99	PASS	13.00	1.20	58	180±20	210
CH-6-7		20	2.18	1.80	PASS	12.90	1.20	21	154±14	181
RSB-106		16	1.78	1.27	PASS	12.70	1.30	81	211±12	253
D1-60		13	2.10	2.19	PASS	13.30	1.10	101	219±12	250
D1-1437		13	1.96	2.59	PASS	12.70	1.30	100	170±9	203

HENDRIKS (1991) DATA: DEER LAKE BASIN AND LONG RANGE NEWFOUNDLAND

FT89-191		19	0.39	0.23	PASS	12.44	2.27	40	253±28	309
FT89-193		21	2.71	1.79	PASS	13.05	1.90	117	253±20	295
FT89-194		23	0.85	0.62	PASS	12.56	1.70	105	241±21	292
FT89-196		18	0.55	0.38	PASS	12.71	1.83	98	255±25	305
FT89-197		20	0.72	0.51	PASS	13.24	1.55	111	248±21	284
FT89-198		9	0.89	O.80	PASS	12.91	1.78	90	194±20	228
FT89-201		18	0.58	0.40	PASS	12.70	1.82	117	257±29	308
FT89-203		22	1.17	0.81	PASS	13.44	1.83	125	256±19	308
FT89-205		18	1.48	1.16	PASS	12.64	1.78	109	245±18	295
FT89-206		23	0.62	0.44	PASS	12.88	2.15	100	248±19	293
FT89-207		27	1.21	0.85	PASS	12.65	1.95	107	251±15	302
FT89-208		21	3.73	3.09	PASS	12.66	2.32	117	213±13	256
FT89-209		18	0.71	0.60	PASS	12.62	1.99	111	209±16	252
FT89-210		17	2.32	1.89	PASS	12.70	2.01	109	225±13	269
FT89-211		21	1.18	0.75	PASS	12.48	2.02	97	276±21	336
FT89-212		21	1.12	0.69	PASS	11.98	2.56	104	283±20	359
FT89-213		15	0.58	0.67	PASS	13.01	1.54	26	169±21	197
FT89-221		18	0.85	0.90	PASS	13.07	1.98	95	187±17	217
FT89-222		23	3.00	2.31	PASS	12.84	1.59	102	256±17	302

SAMPLE	DEPTH	GRAINS	SPON.	INDUC.	CHI2	TL MEAN	S.D.	#	FT AGE	AGE CORR.
FT89-223		23	0.88	0.62	PASS	12.35	2.78	34	279±24	343
FT89-224		21	1.41	1.13	PASS	12.38	2.58	103	246±21	302
FT89-225		25	1.75	1.11	PASS	12.46	1.91	105	309±23	376
FT89-226		19	0.68	0.39	PASS	12.42	1.70	100	343±43	420
FT89-227		24	1.60	1.10	PASS	12.35	1.99	104	285±21	351
FT89-228		18	3.47	3.09	PASS				222±15	
FT89-231		13	0.76	0.63	PASS				235±32	
FT89-232		22	0.11	0.11	PASS	13.34	1.73	110	190±13	216
FT89-233		27	0.71	0.82	PASS	12.70	2.10	100	173±15	207
FT89-235		14	1.79	1.71	PASS	12.80	1.16	31	208±15	247
FT90-034		22	2.17	1.56	PASS	13.14	1.85	110	252±22	292
FT90-035		19	1.03	0.83	PASS	12.99	2.13	110	224±21	262
FT90-036						12.58	2.08	105		
FT90-050		15	1.12	0.77	PASS	13.53	2.40	100	262±31	290

Mean Corrected Age (corrected to 15.2 microns):

(1) Deer Lake Basin 277 ± 21,

(2) All Hendriks Samples 290 ± 51,

(3) Cumberland Basin and Ryan Samples 194 ± 50,

(4) Gulf of St. Lawrence Grist et al. Samples 190 ± 30,

(5) Ravenhurst et al. and MacKillop 218 ± 30,

(6) Arne et al. Gays River Meguma 255 ± 17.

SAMPLE LOCATIONS OF THE APATITE FISSION TRACK STUDIES

FT89-161 TO FT89-168	SOUTH ATHOL DRILL HOLE SA-1&2, SOUTH ATHOL, CUMBERLAND COUNTY, NOVA SCOTIA
FT90-001 TO FT90-009	NSDME DRILL HOLE 82-1, SYDNEY BASIN, NOVA SCOTIA
FT90-010 TO FT90-014	NORANDA TATAMAGOUCHE DRILL HOLE NT-47, TATAMAGOUCHE, CUMBERLAND BASIN, NOVA SCOTIA
FT90-015 TO FT90-21 & FT90-26	BP COAL DRILL HOLE BP-06, NEAR OXFORD, CUMBERLAND BASIN, NOVA SCOTIA
FT90-022 TO FT90-25	DRILL HOLE CT-1, HILLSBOROUGH BAY, PRINCE EDWARD ISLAND
FT90-043	SURFACE SAMPLE, MALAGASH POINT, CUMBERLAND COUNTY,NOVA SCOTIA
FT90-044	SURFACE SAMPLE, MALAGASH FORMATION, ALONG THE SHORE AT PUGWASH, CUMBERLAND COUNTY, NOVA SCOTIA
FT90-045	SURFACE SAMPLE, BACON LEDGE,BOSS POINT, CUMBERLAND COUNTY, NOVA SCOTIA
FT90-046	SURFACE SAMPLE CENTRE WENTWORTH, ALONG THE WALLACE RIVER,CUMBERLAND COUNTY, NOVA SCOTIA
FT90-048	SURFACE SAMPLE NEAR APPLE RIVER ALONG THE JOGGINS SHORE, CUMBERLAND COUNTY, NOVA SCOTIA
FT90-049	SURFACE SAMPLE, SCOTCH VILLAGE FORMATION, SCOTCH VILLAGE, HANTS COUNTY, NOVA SCOTIA
FT90-057	SURFACE SAMPLE, GRAVOIS POINT, ALONG THE NORTHUMBERLAND STRAIT SHORE, CUMBERLAND BASIN, NOVA SCOTIA
FT90-058	NSDME DRILL HOLE TF81-1, THE FALLS, TATAMAGOUCHE SYNCLINE AREA, CUMBERLAND BASIN, NOVA SCOTIA

(FOR MAP LOCATIONS SEE FIGURE 5.13)

GRIST, RYAN AND ZENTILLI DATA

FT89-117 TO FT89-118	WELL E-49, EAST POINT, PRINCE EDWARD ISLAND
FT89-121 TO FT89-125	WELL E-95, CABLEHEAD, GULF OF ST. LAWRENCE, OFF PRINCE EDWARD ISLAND

FT89-134 TO FT89-139	WELL L-49, BRADELLE, NORTHWESTERN GULF OF ST. LAWRENCE
FT89-144	WELL P-05, NORTH SYDNEY, OFFSHORE
FT89-147 TO FT89-150	WELL F-24, NORTH SYDNEY, OFFSHORE

(FOR MAP LOCATIONS SEE FIGURE 5.13)

LONG RANGE AND DEER LAKE BASIN SAMPLES (HENDRIKS DATA)

SOUTHERN TRANSECT 1	FT89-227, FT89-193, FT89-191, FT89-197, FT89-198
SOUTHERN TRANSECT 2	FT89-226, FT89-225, FT89-201, FT89-196, FT89-203, FT89-205, FT89-224, FT89-194
CENTRAL TRANSECT	FT89-212, FT89-211, FT89-210, FT89-207, FT89-209, FT89-208, FT89-206
NORTHERN LONG RANGE	FT89-221, FT89-232, FT89-233
PALEOZOIC ALLOCHTHONS	FT90-050, FT89-213, FT89-235
DEER LAKE BASIN	FT89-034, FT89-035

MacKILLOP SAMPLES ARE ALL FROM THE NSDME DRILL HOLE DIGBY NO. 1 (D1)

ARNE, DUDDY AND SANGSTER STUDY

8763-93	IN THE MEGUMA ROCKS 6 KM SOUTH OF UPPER MUSQUODOBOIT, HALIFAX COUNTY, NOVA SCOTIA (SHEET HARBOUR ROAD)
8763-94	SURFACE MEGUMA SAMPLE, CARROLLS CORNER, NEAR GAYS RIVER, HALIFAX COUNTY, NOVA SCOTIA
8763-95	SURFACE MEGUMA SAMPLE, WITTENBURG, COLCHESTER COUNTY, N.S.
8763-96	SURFACE MEGUMA SAMPLE, NEWTON MILLS-EASTVILLE AREA, COLCHESTER COUNTY, NOVA SCOTIA
8763-97 - 104	SAMPLES FROM CORE AT THE GAYS RIVER DEPOSIT, HALIFAX COUNTY, NOVA SCOTIA

RAVENHURST, DONELICK, ZENTILLI AND REYNOLDS SAMPLE LOCATIONS

PE-143	HUBBARDS, LUNENBURG COUNTY, N.S. (SURFACE)
PE-150	AVON RIVER AREA, HANTS COUNTY, N.S. (SURFACE)
PE-009	PUBNICO AREA, YARMOUTH COUNTY, N.S. (SURFACE)
RGR-162	GAYS RIVER DEPOSIT, HALIFAX COUNTY, NOVA SCOTIA
RGR-165	GAYS RIVER DEPOSIT, HALIFAX COUNTY, NOVA SCOTIA
CH-6-7	CLARKSVILLE # 1 NSDME DRILL HOLE, HANTS COUNTY, N.S. 67m
RSB-106	TRURO AREA, COLCHESTER COUNTY, N.S., (SURFACE)
D1-60	NSDME DRILL HOLE D-1, 60 METRES, DIGBY, NOVA SCOTIA
D1-1437	NSDME DRILL HOLE D-1, 1437 METRES, DIGBY, NOVA SCOTIA THE D-1 SAMPLES ARE REPEATS OF THE MacKILLOP SAMPLES

FOR MAP LOCATIONS SEE FIGURE 5.13

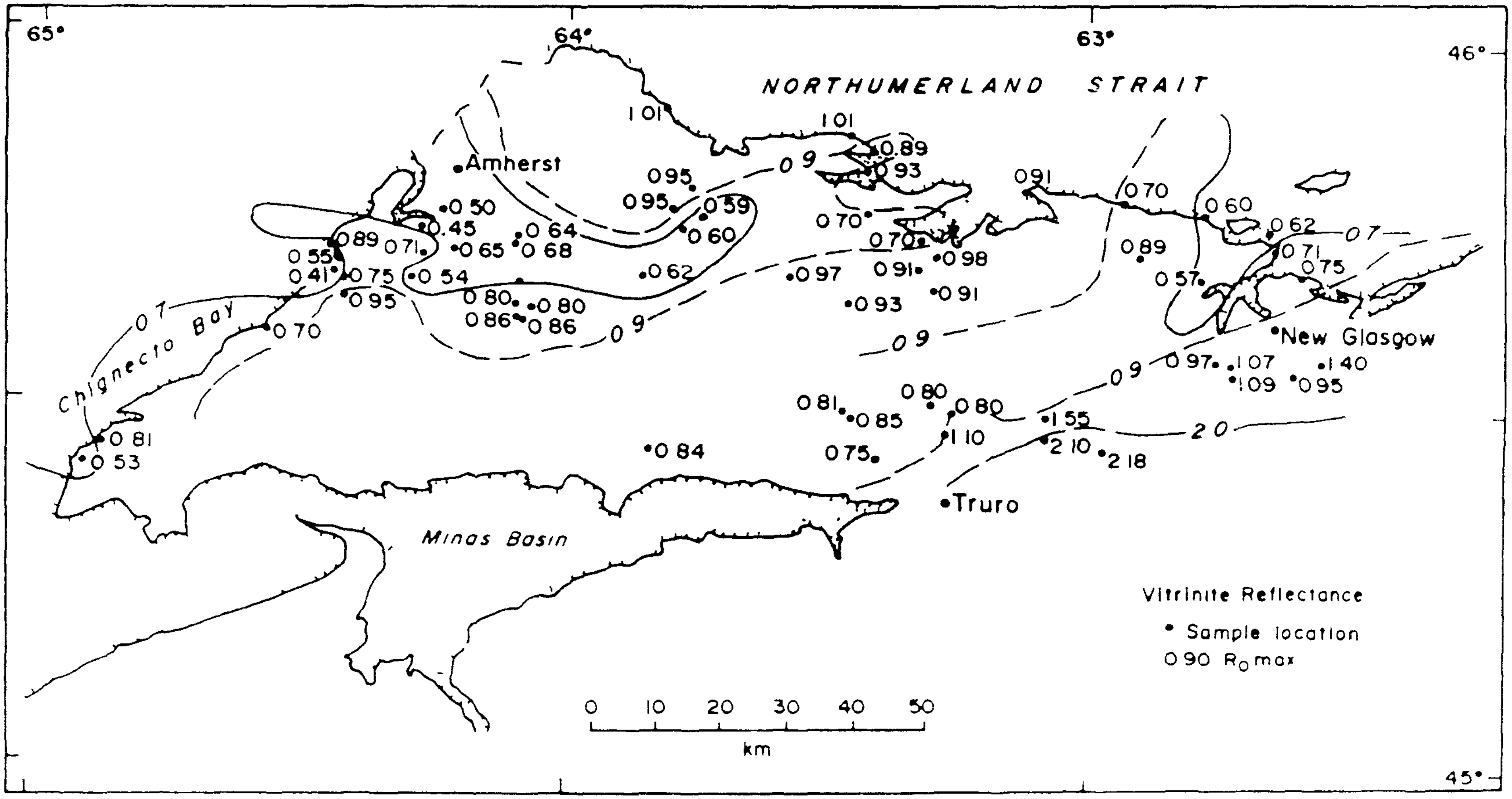


Figure 5 1 Compilation of vitrinite reflectance for northern Nova Scotia, data from this study and Mukhopadhyay (1991b) The lower values in the Amherst area reflect the variance between the Ro% of sandstones versus organic-rich shales

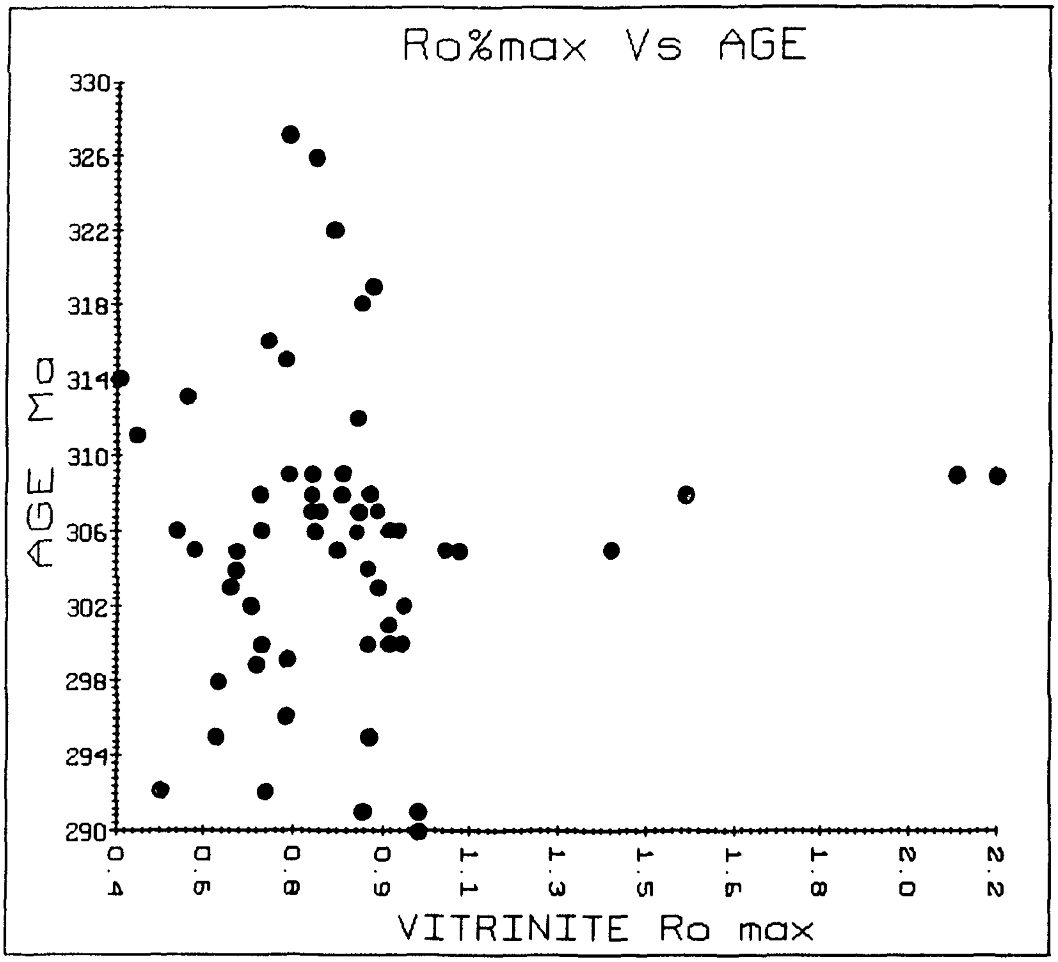


Figure 5.2: Plot of vitrinite reflectance Ro %max versus the age of the strata. There does not appear to be any correlation of age and vitrinite Ro %max.

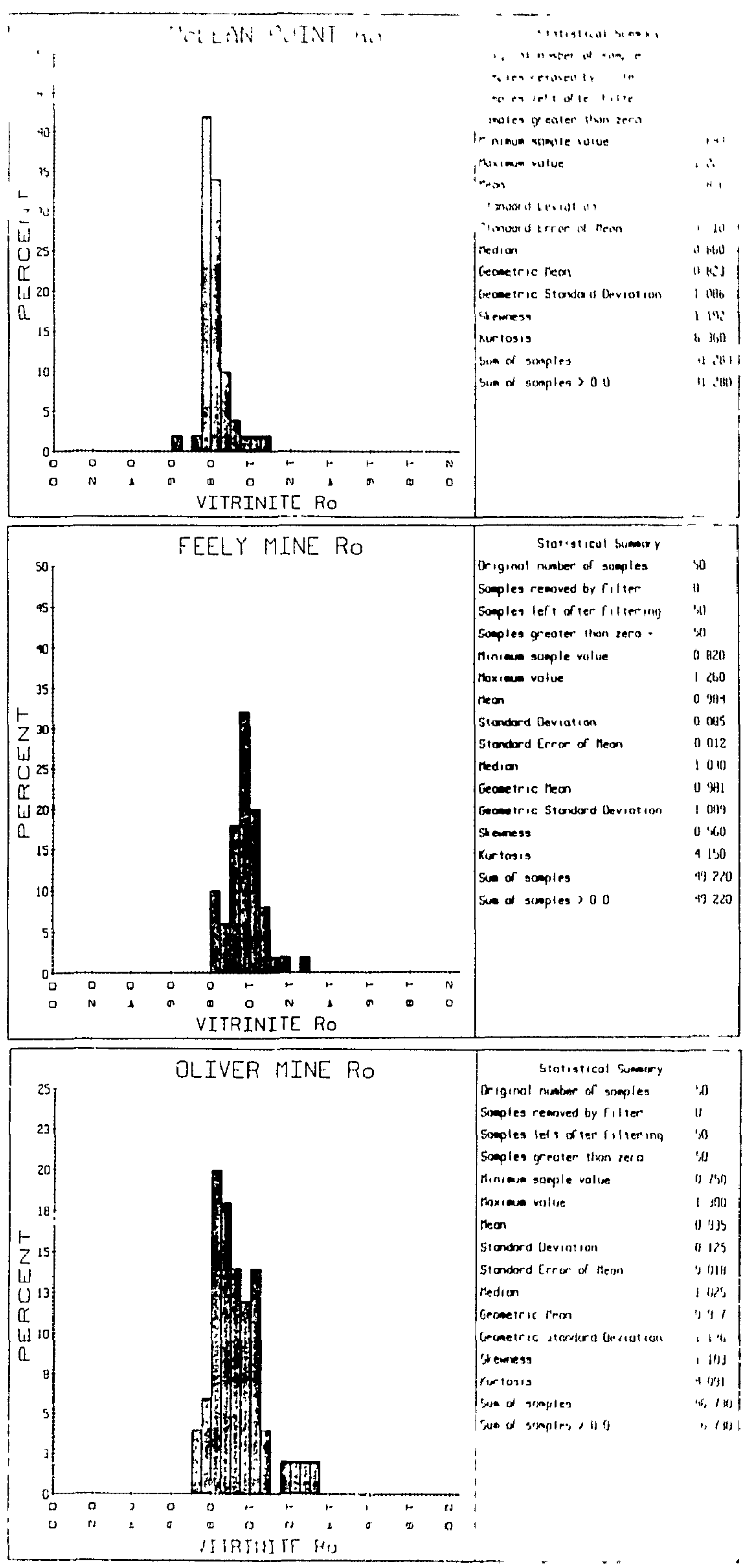


Figure 5.3: Histograms of vitrinite reflectance measurements for three mineralized areas in the Cumberland Basin, note the positive reflectance skewness of the histograms. The secondary low amplitute peaks at higher values are most likely the result of oxidation.

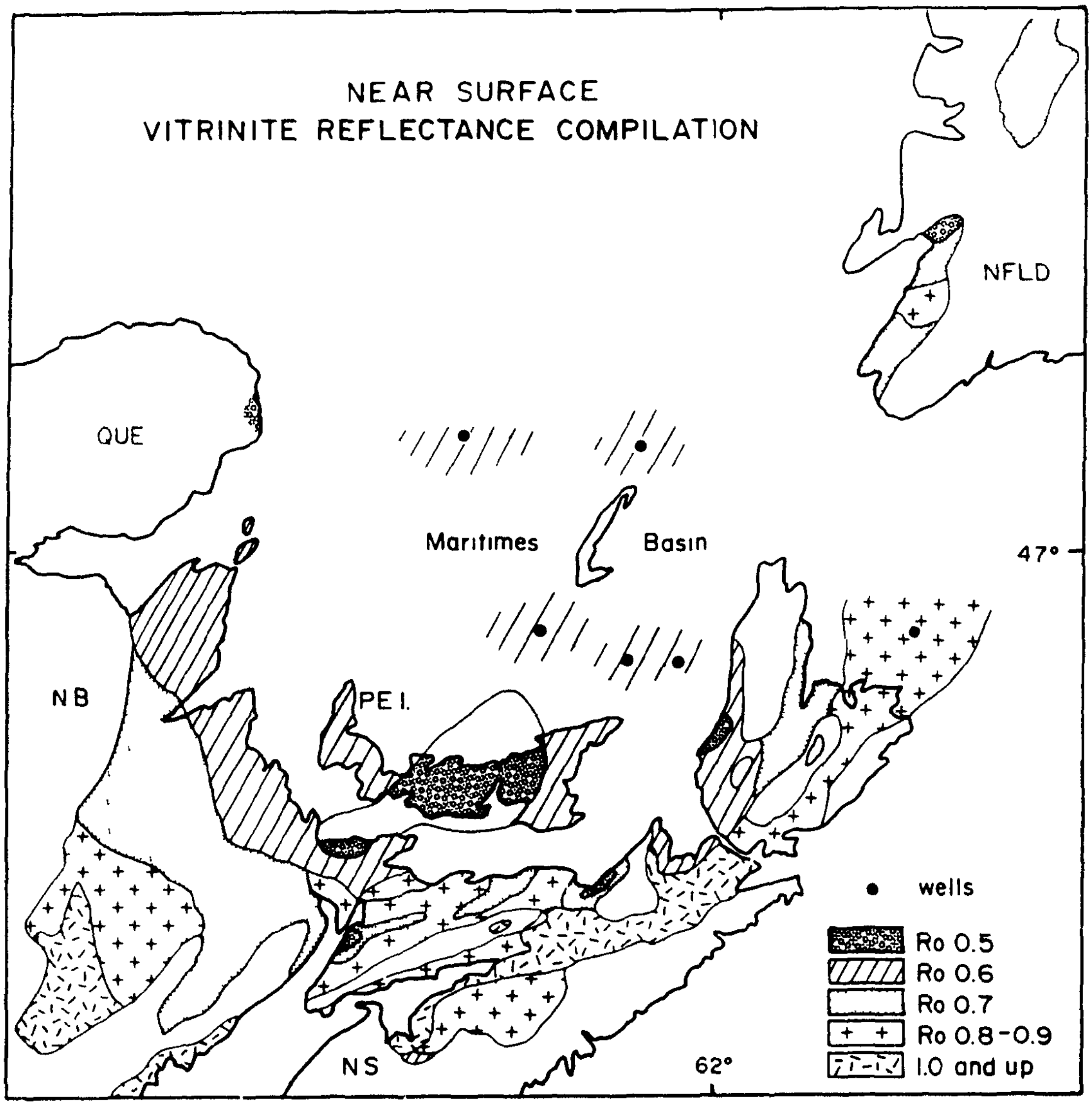


Figure 5.4: Compilation of near surface vitrinite reflectance values (Ro%max) from throughout the Maritimes Basin. Data from Hacquebard and Donaldson (1970), Hacquebard and Cameron (1989), Mukhopadhyay (1991b), Hyde et al. (1991) and this study.

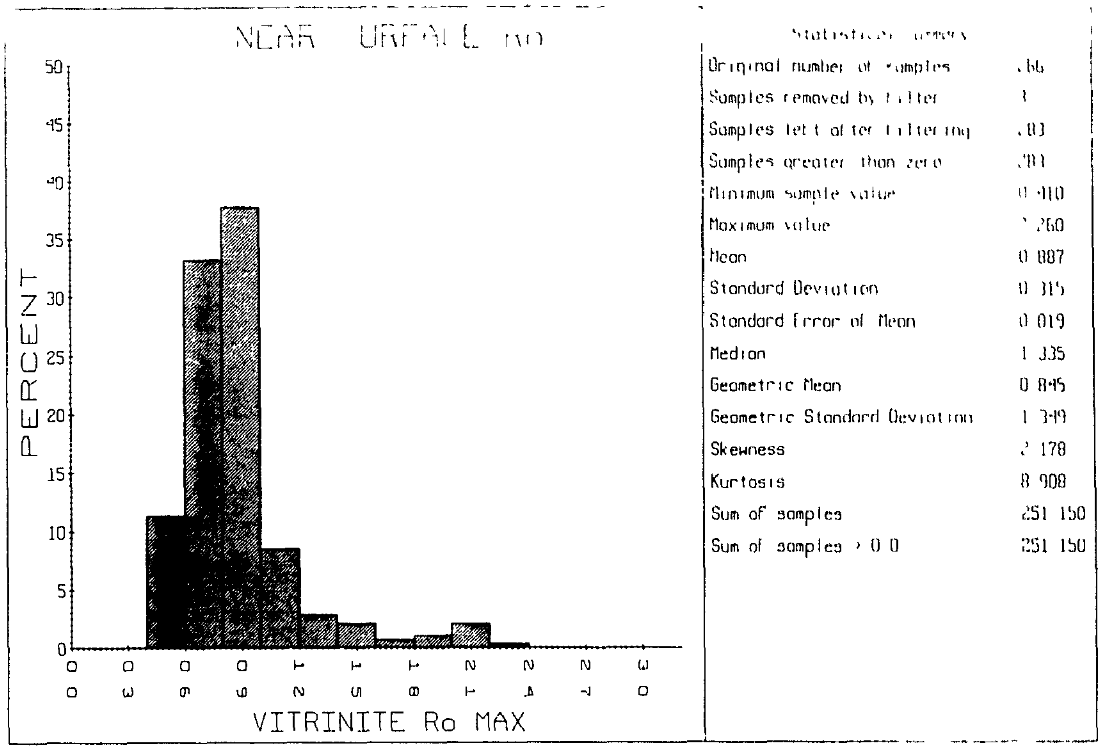


Figure 5.5: Histogram of vitrinite reflectance Ro %max values for 286 near surface localities from the Maritimes Basin. The mean value is approximately Ro = 0.90%. The higher values are associated with faulting or mineralization where hot fluids have raised the value of the Ro max.

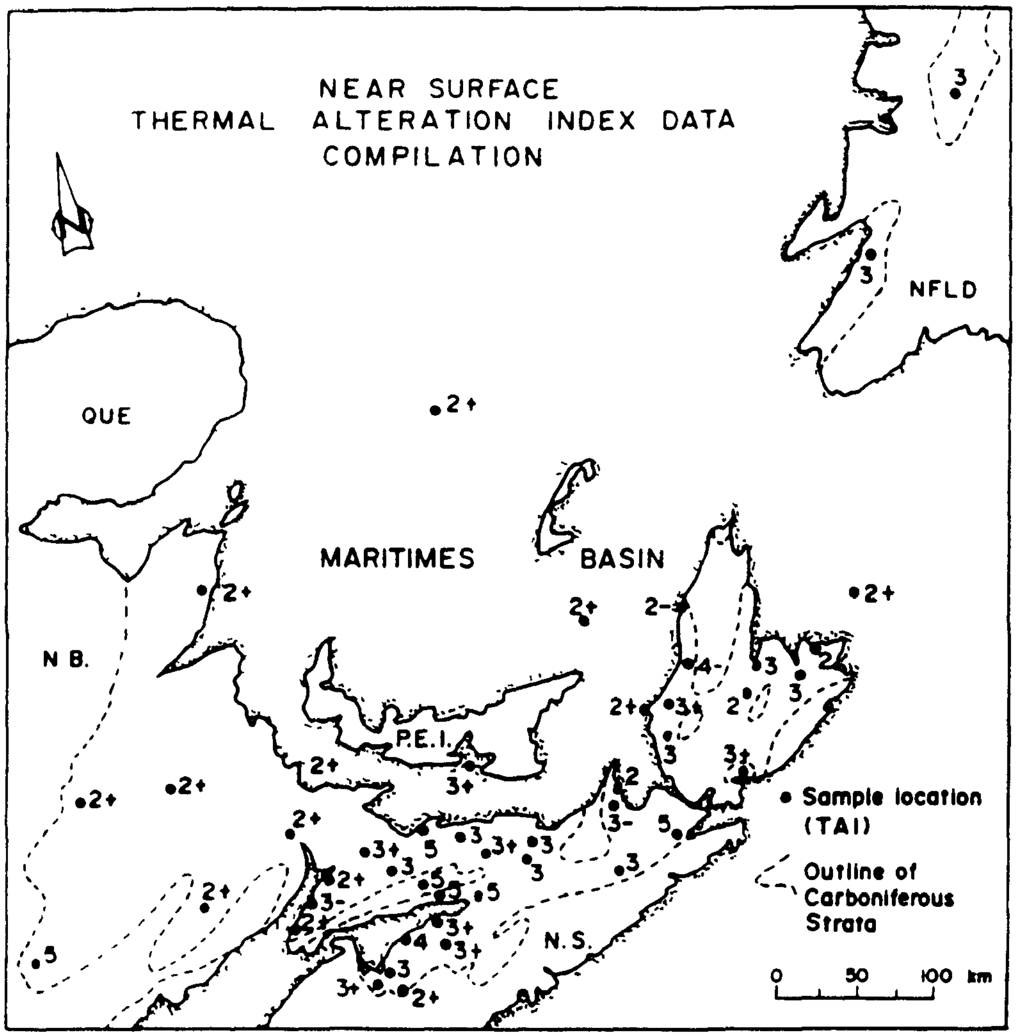


Figure 5.6: Compilation of TAI (Thermal Alteration Index) data for the Maritimes Basin. Data from Mukhopadhyay (1991b), Dolby (1987, 1988, 1989), Barss (various unpublished reports) and from company oil well reports. The overall plot compares well to the vitrinite reflectance compilation (see Fig. 5.4).

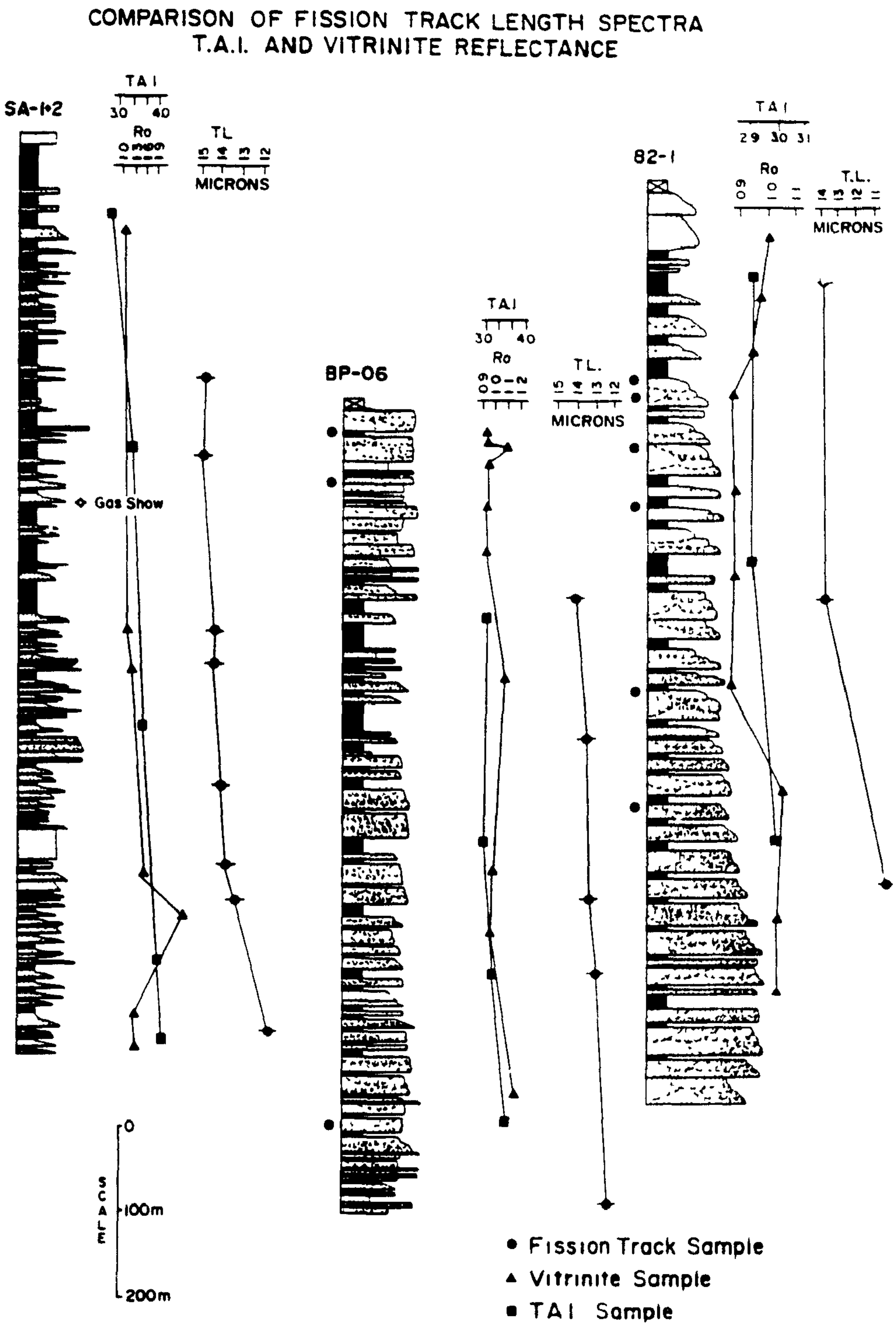
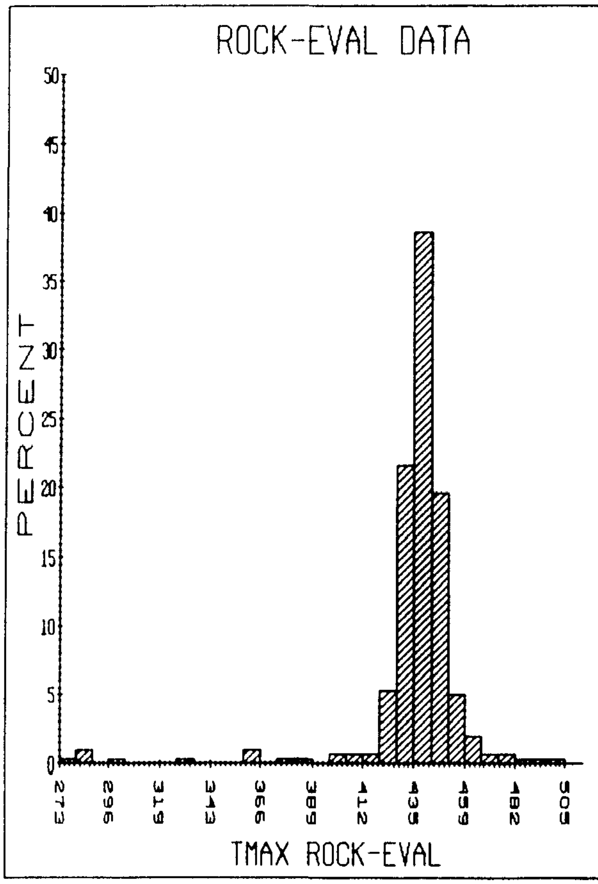


Figure 5.7: Comparison of various thermal indicators on downhole profiles, SA-1&2 - NSDME South Athol drill hole, BP-06 - British Petroleum drill hole 6 from the area north of Oxford, and 82-1 -NSDME drill hole form the Sydney Basin. The plot demonstrates the variability of the various methods, the uniform response of the apatite fission track length spectra is misleading because all of the apatites have been reset.



Statistical Summary	
Original number of samples	301
Samples removed by filter	0
Samples left after filtering	301
Samples greater than zero	301
Minimum sample value	273 000
Maximum value	505 000
Mean	435 844
Standard Deviation	25 278
Standard Error of Mean	1 457
Median	389 000
Geometric Mean	434 960
Geometric Standard Deviation	1 069
Skewness	-3 977
Kurtosis	24 433
Sum of samples	131189 000
Sum of samples > 0 0	131189 000

Figure 5.8: Compilation of Rock-Eval Tmax values from throughout the Maritimes Basin, data primarily from company logs and Mukhopadhyay (1991b). The mean value of 436°C is equivalent of an Ro% max value of 0.6% and 85% of the data have values equivalent to Ro = 1.0% or less.

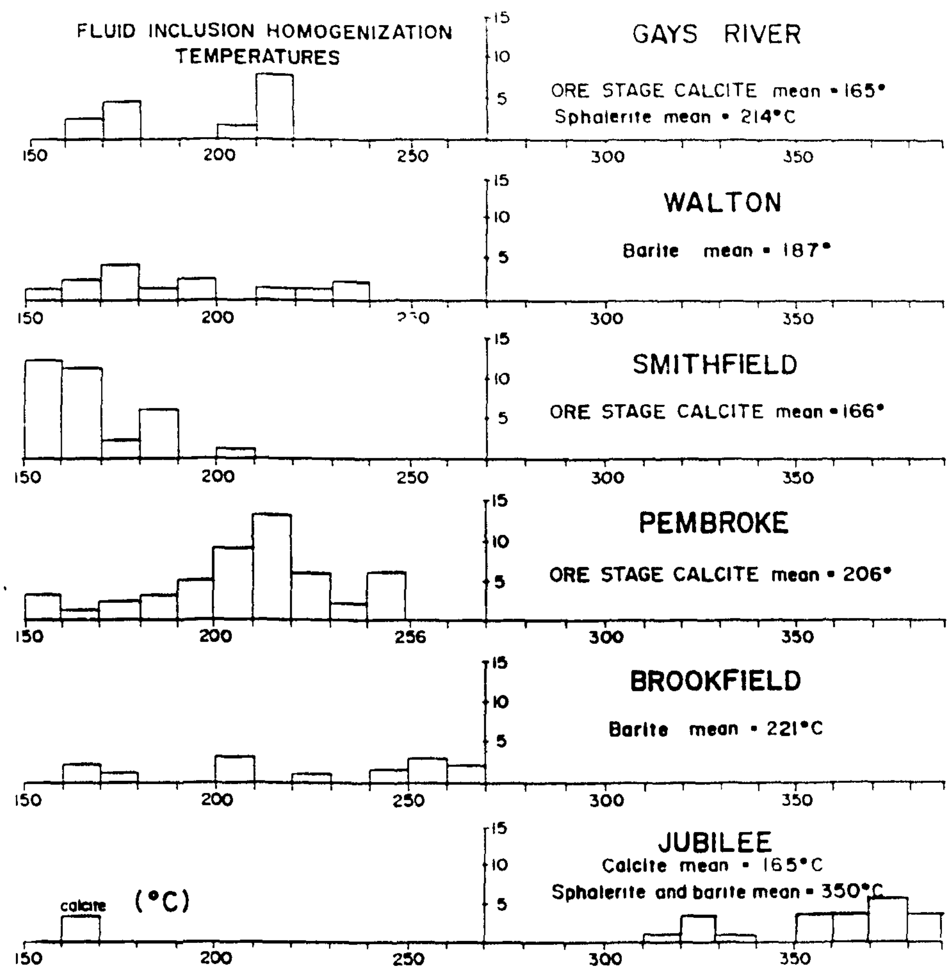


Figure 5.9: Compilation of fluid inclusion study results from throughout the Maritimes Basin, modified after Ravenhurst et al.(1989). The values constrain the maximum temperature of the mineralizing fluids in the basin.

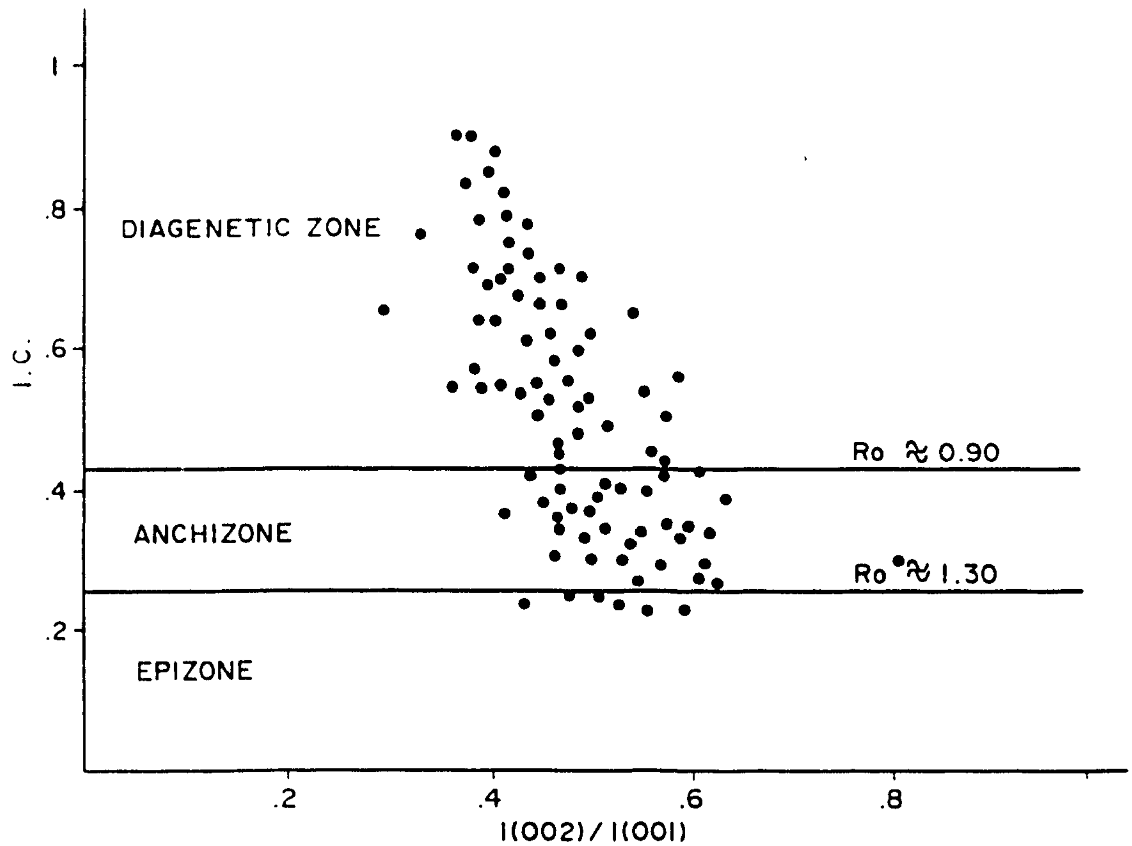


Figure 5.10: Plot of clay mineralogy form the Maritimes Basin, primarily from this study and Gall and Sangster (1991) and Gall and Hiscott (1986). Plot is Illite Crystallinity Index versus the Illite peak 002 divided by Illite peak 001 (see Gall and Sangster, 1991, for explanation). Equivalent Ro% max values were added to the plot for comparison of maturation data (Bustin et al., 1985).

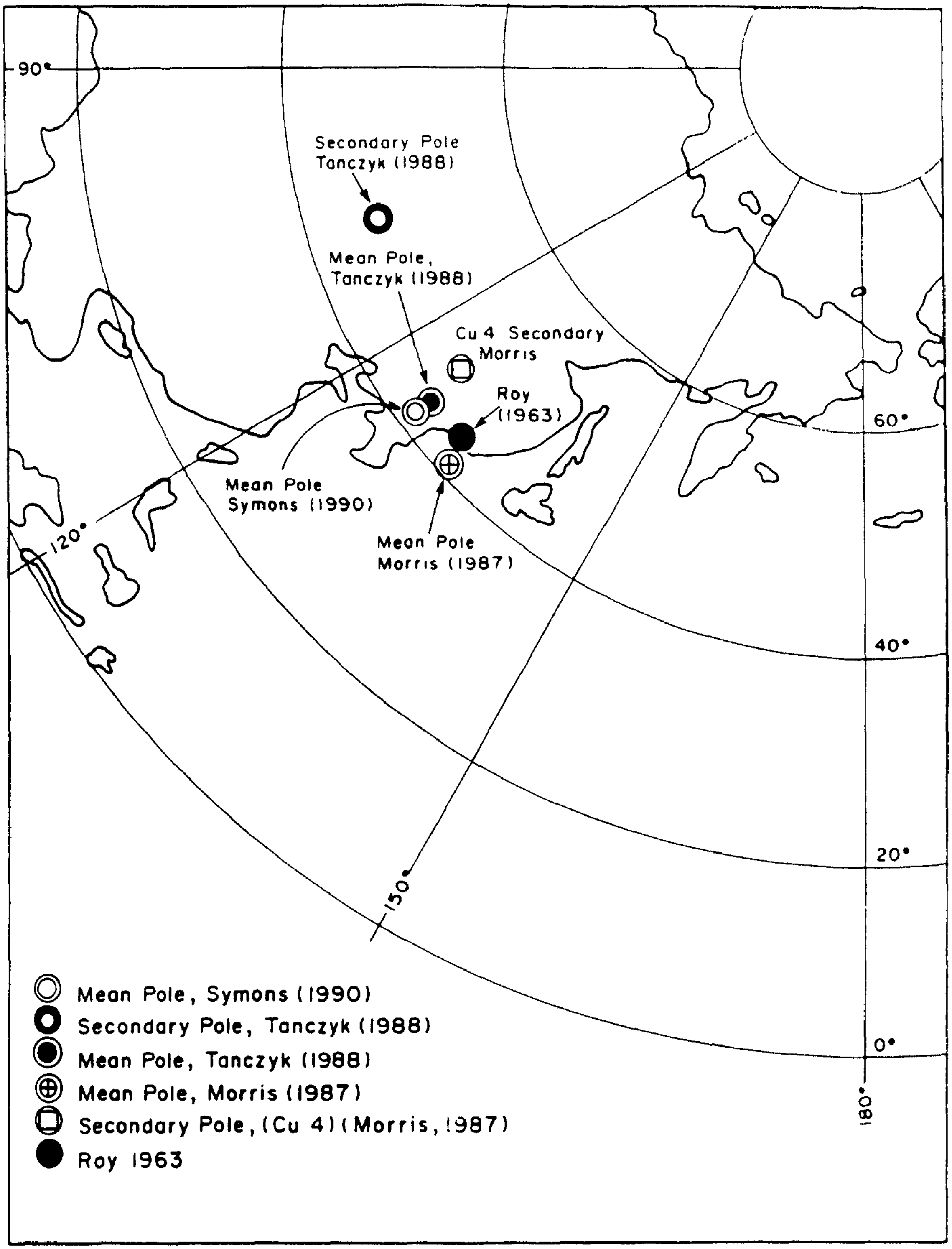


Figure 5.11: Paleomagnetic poles of Upper Carboniferous to Permian redbeds determined by various workers for the strata of the Maritimes Basin.

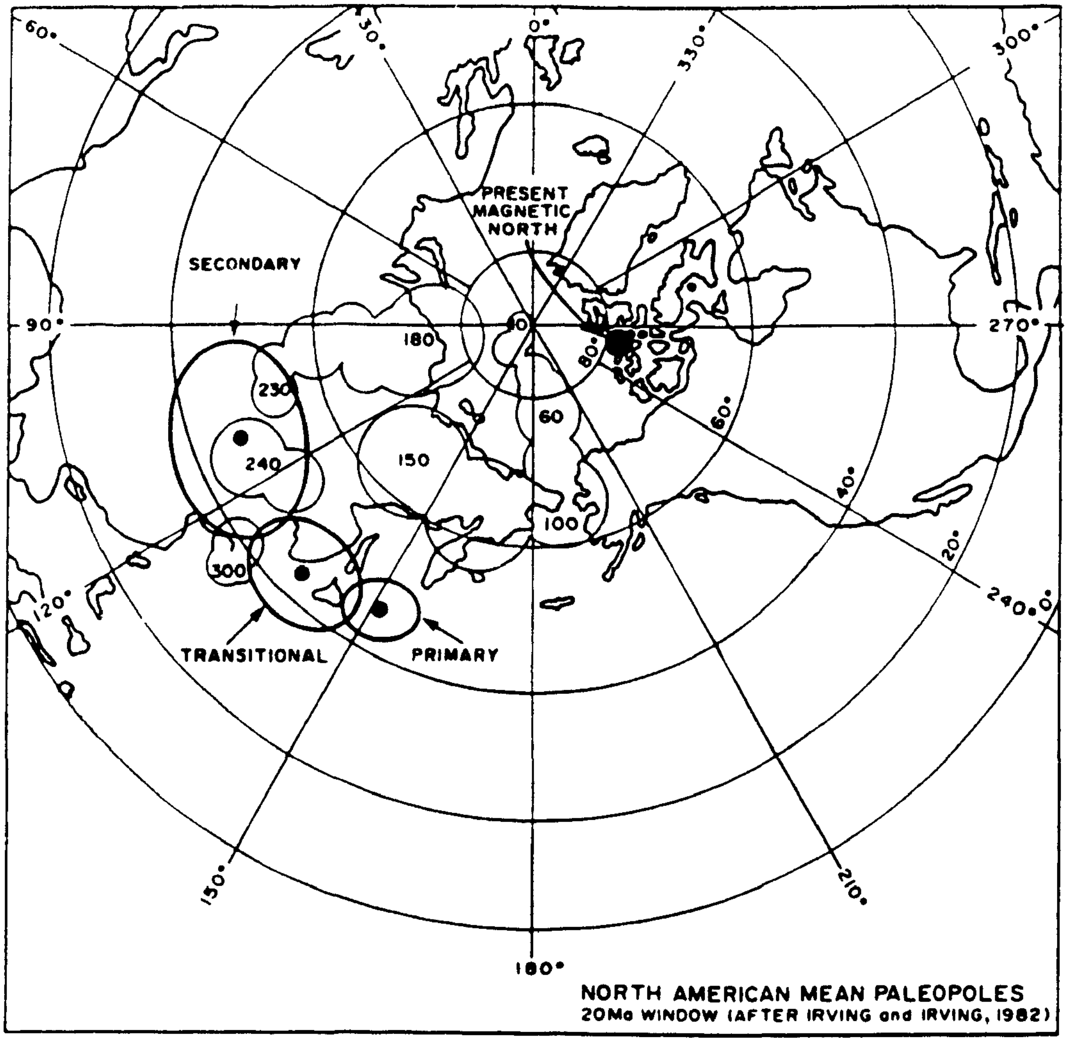


Figure 5.12: Plot of the polar wandering through time (after Irving and Irving, 1982) with plots of the pole field shifts from primary to secondary poles in the Maritimes Basin (after Tanczyk, 1988; Symmons, 1990; and Morris, 1987).

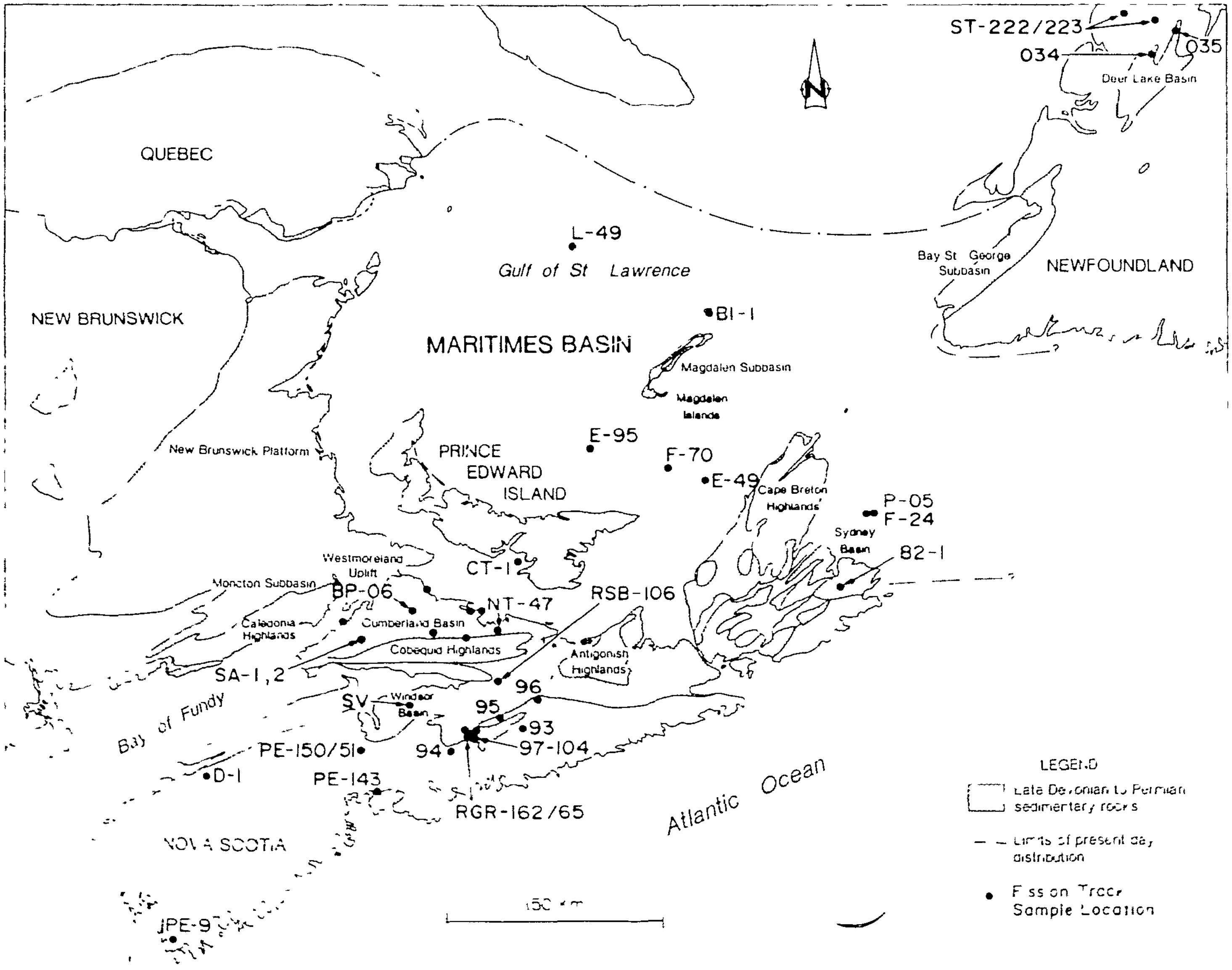


Figure 5.13: Sample location map of Maritimes Basin apatite fission track studies.

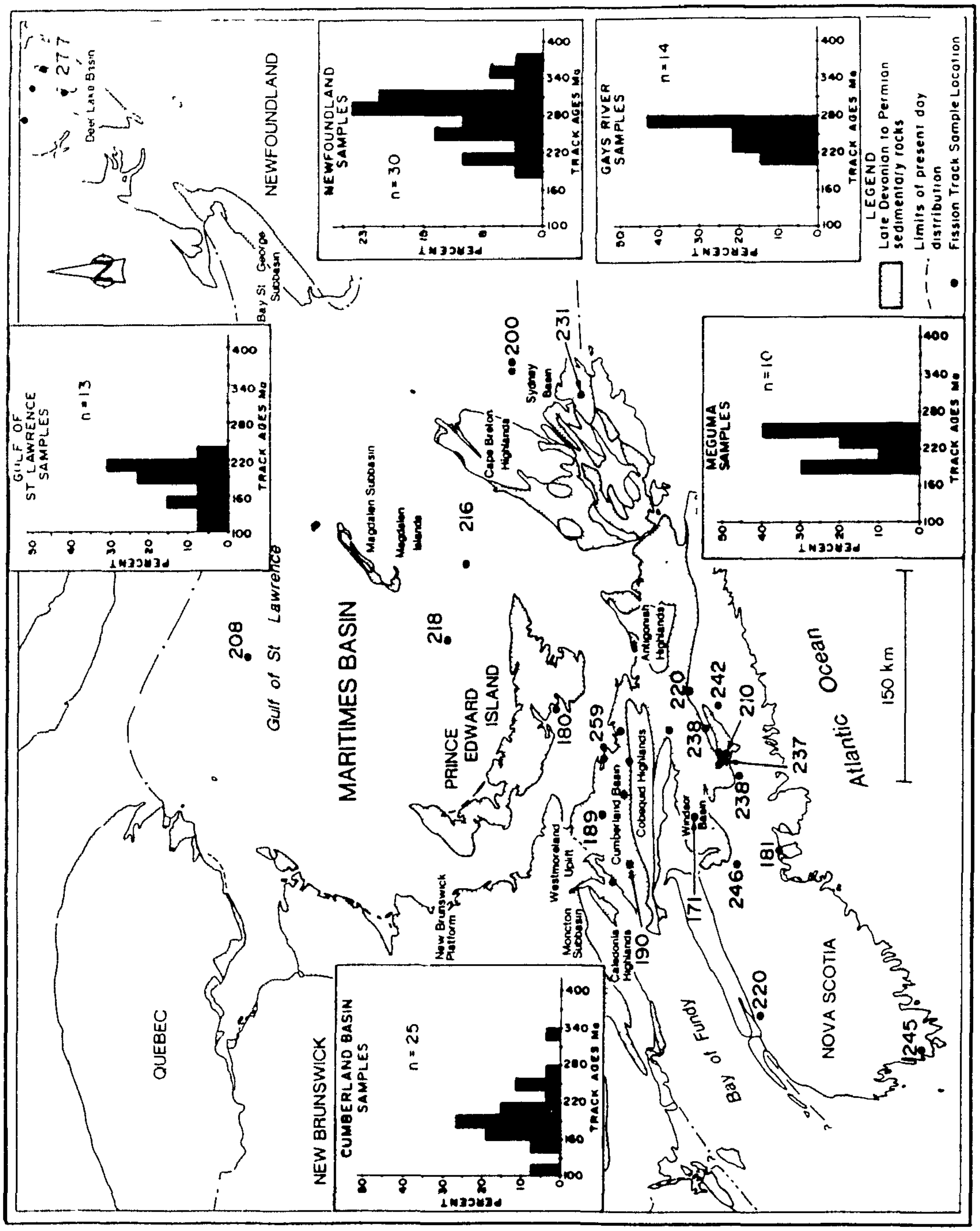
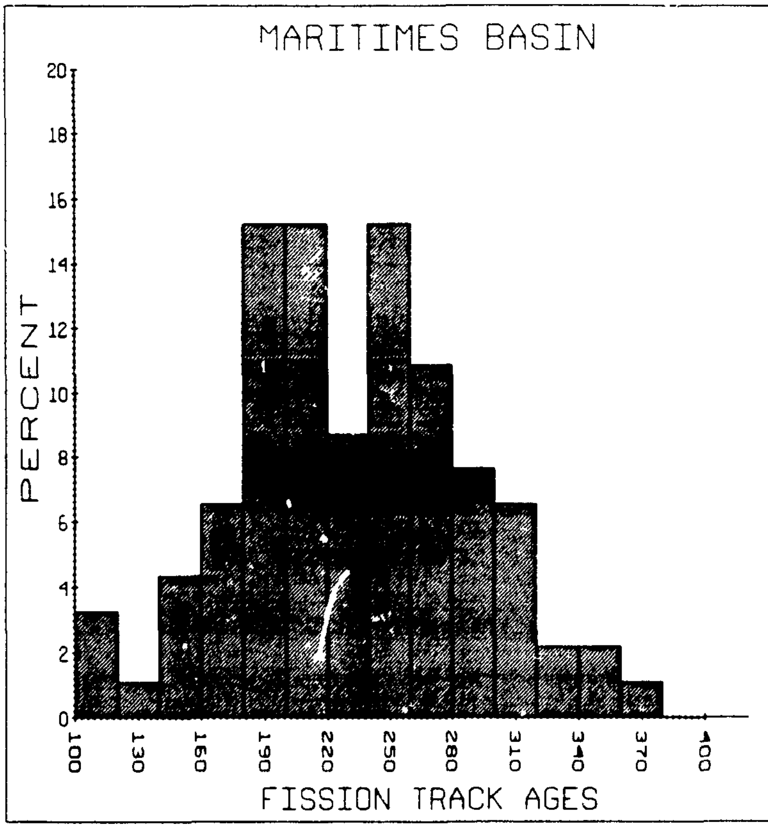


Figure 5.14: Results of the apatite fission track studies in the Maritimes Basin. The ages are given as ages corrected to a track length of 15.2 microns. (see section 5.4.5 for clarification of what data was included in each of the histograms)



Statistical Summary	
Original number of samples	94
Samples removed by filter	2
Samples left after filtering	92
Samples greater than zero	92
Minimum sample value	104 000
Maximum value	376 000
Mean	232 370
Standard Deviation	51 781
Standard Error of Mean	5 711
Median	240 000
Geometric Mean	225 651
Geometric Standard Deviation	1 283
Skewness	0 128
Kurtosis	2 813
Sum of samples	21378 000
Sum of samples > 0 0	21378 000

Figure 5.15: Histogram of the corrected apatite fission track ages form the Maritimes Basin The range in values is the result of the fact that the samples came from varying depths and elevations both within and adjacent to the Maritimes Basin. The overall mean of 232 Ma corresponds well to most of the samples from near surface sampled throughout the basin.

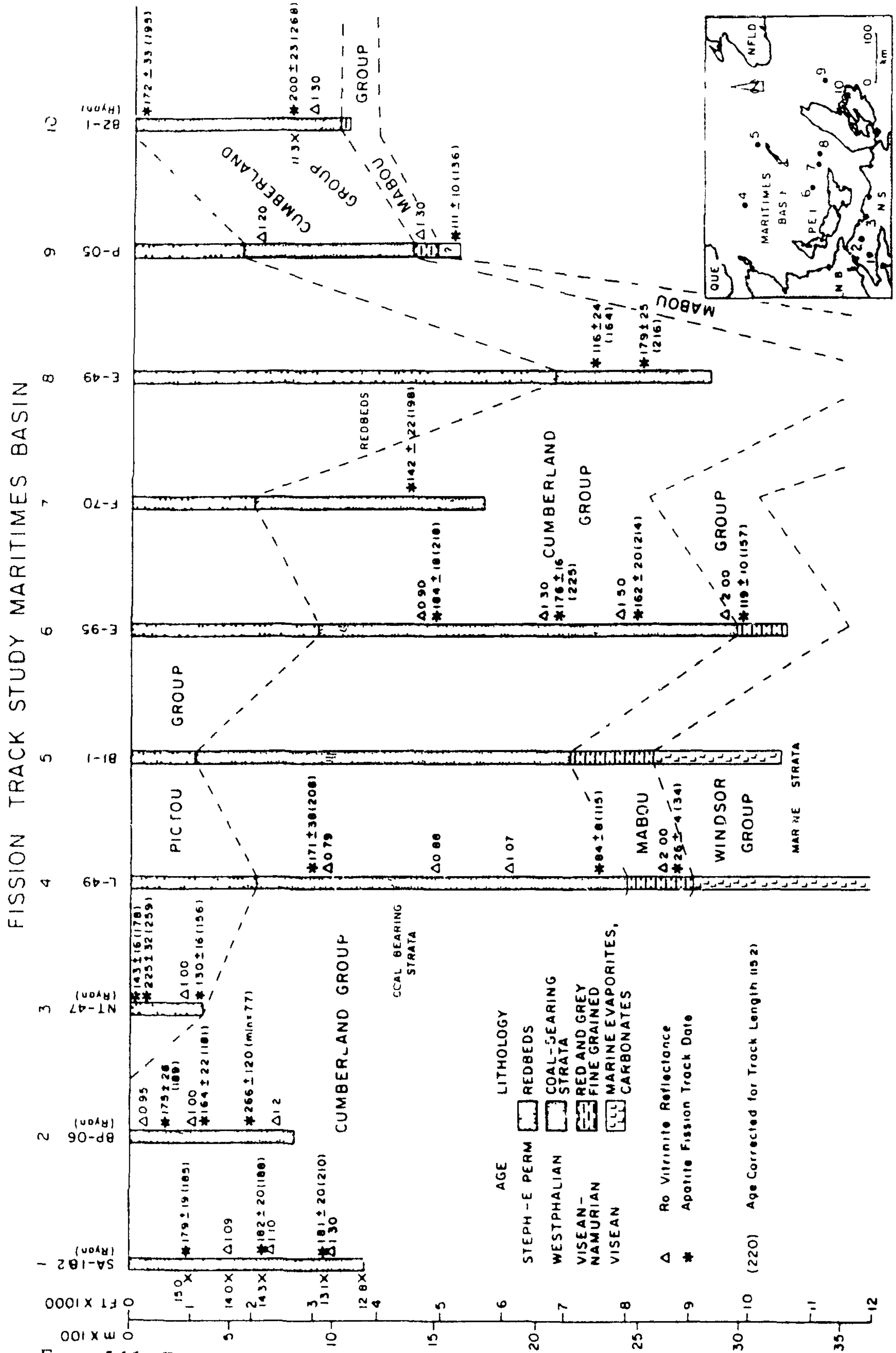


Figure 5 16 Cross section of drill holes and wells from the Maritimes Basin and the apatite fission track results from the sampled horizons Note the overall decrease in apatite fission track age with depth (After Ryan et al , 1991)

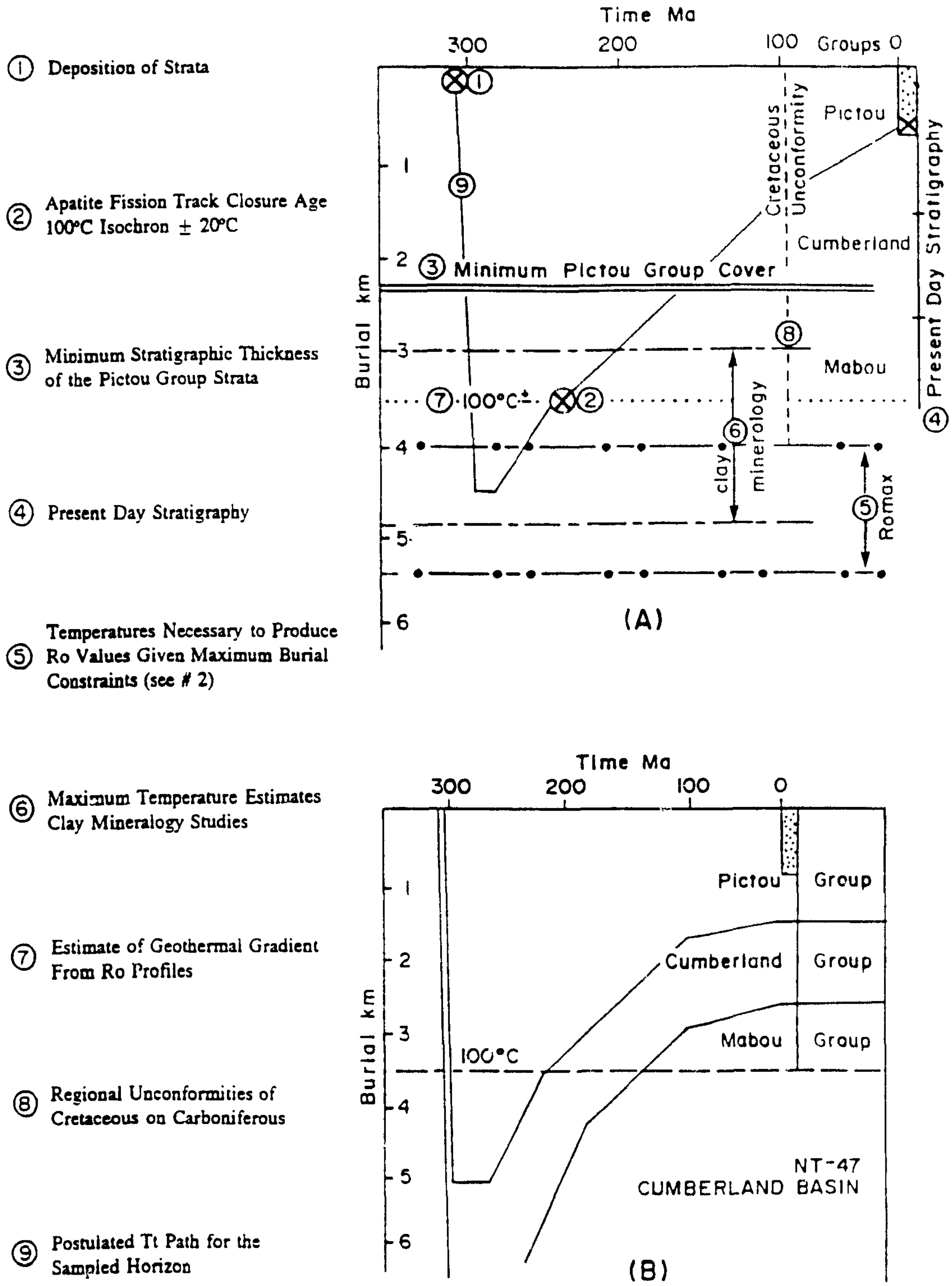


Figure 5.17: (A) Example of the geological constraints used in the construction of burial history plots. The plot construction shown is for the Pictou Group strata in Drill Hole NT-47 from the Tatamagouche area of the Cumberland Basin. (B) After the construction of the time-burial path for the sampled horizon the stratigraphic intervals are added to complete the burial history plot.

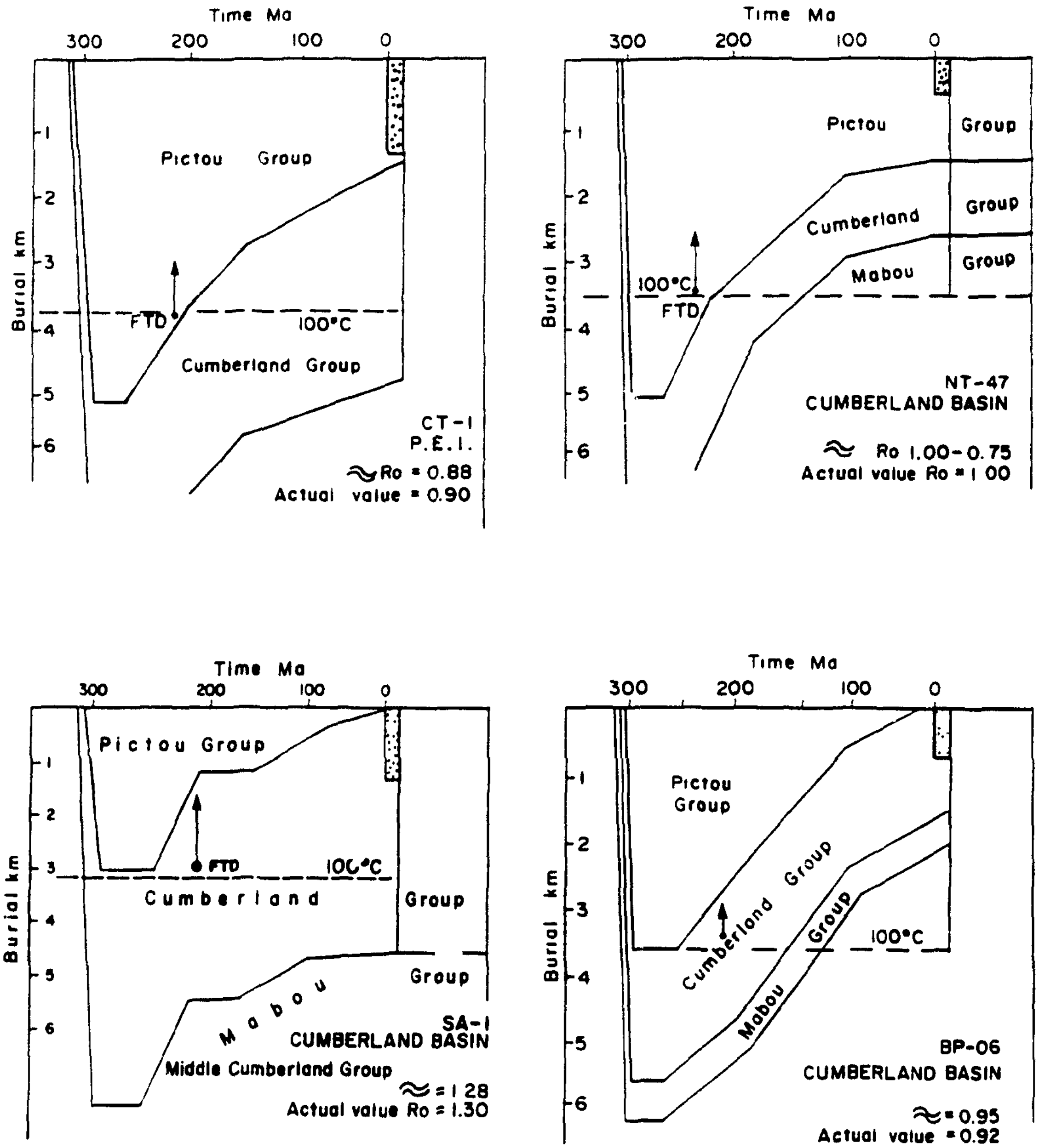


Figure 5.18: Burial History Plots for selected drill holes in the Cumberland Basin and Prince Edward Island. CT-1 is from Hillsbourough Bay, southeast PEI; NT-47 is from the Tatamagouche area in the eastern part of the Cumberland Basin; SA-1 (1&2) is from Athol in the western Part of the Cumberland Basin; and BP-06 is in the Oxford area in the central part of the Cumberland Basin (see Fig. 5.13 for locations and Section 5.6.2.1 for constraints).

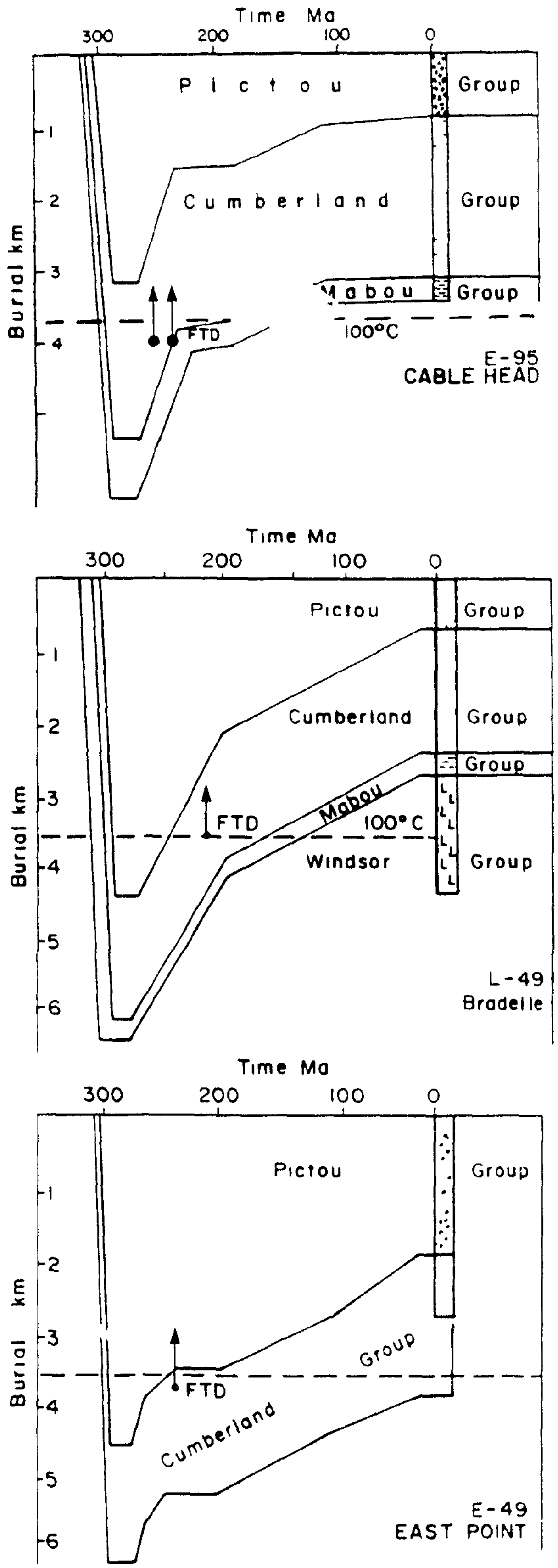


Figure 5.19: Burial History Plots for selected wells in the Gulf of St. Lawrence area, central Maritimes Basin (see Fig. 5.13 for locations and Section 5.6.2.2 for constraints)

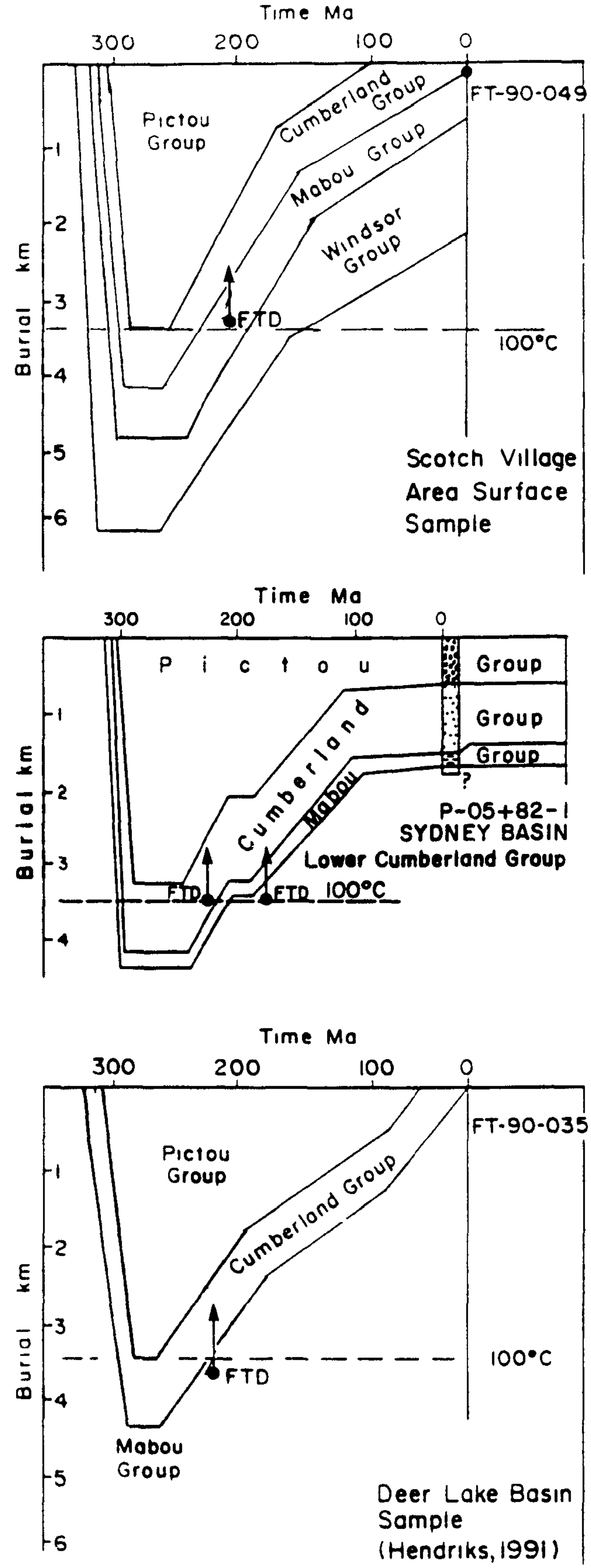


Figure 5.20: Burial History Plots for the south (Scotch Village area, Minas Sub-basin); east central (82-1 Sydney Basin), and northern (Deer Lake Basin, Newfoundland) parts of the Maritimes Basin (see Fig. 5.13 for locations and Section 5.6.2.3 for constraints).

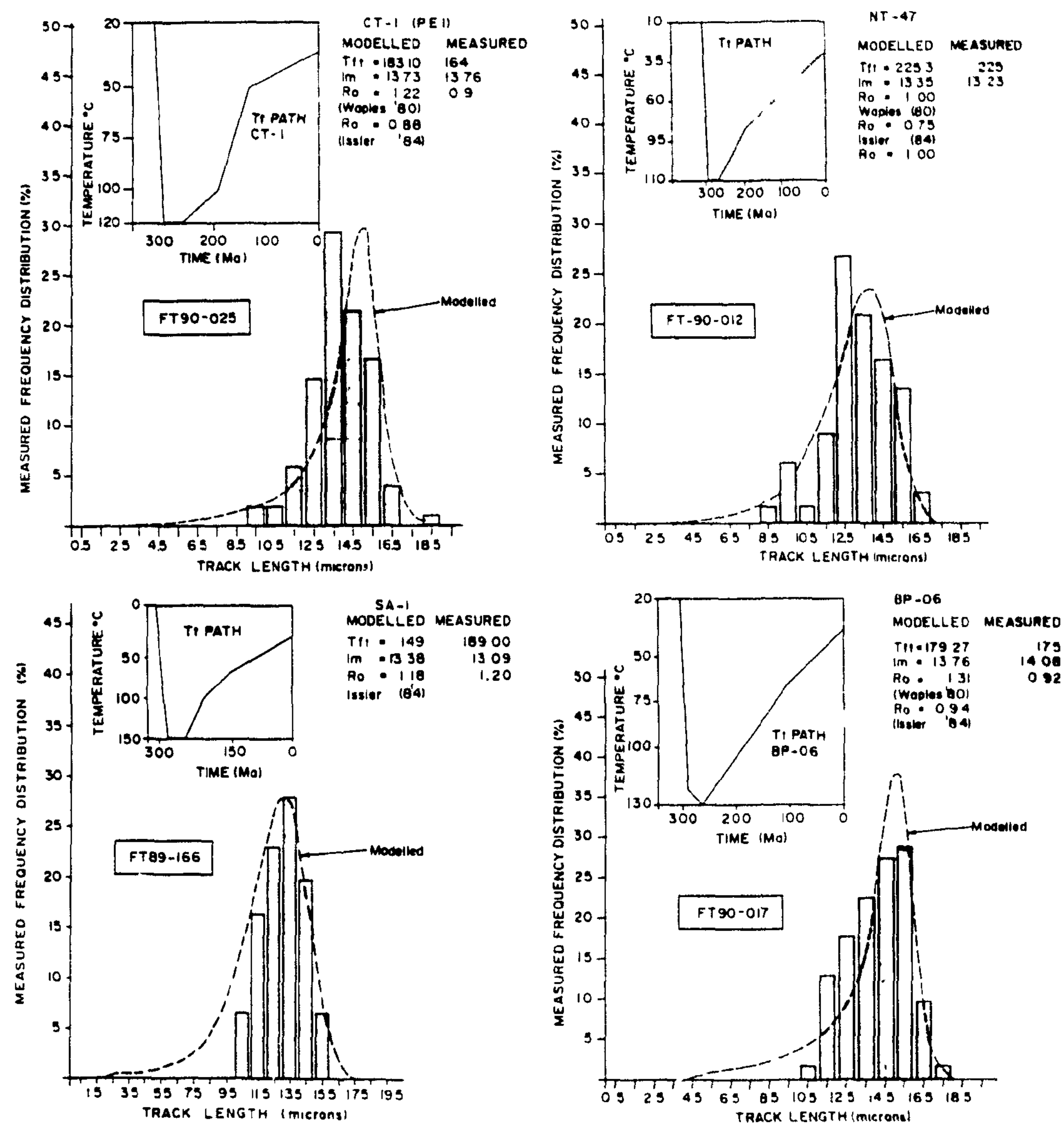


Figure 5.21: Comparisons of Trac3 modelled distributions for track lengths and apatite fission track ages and measured values for the Cumberland Basin samples and the sample from PEI.

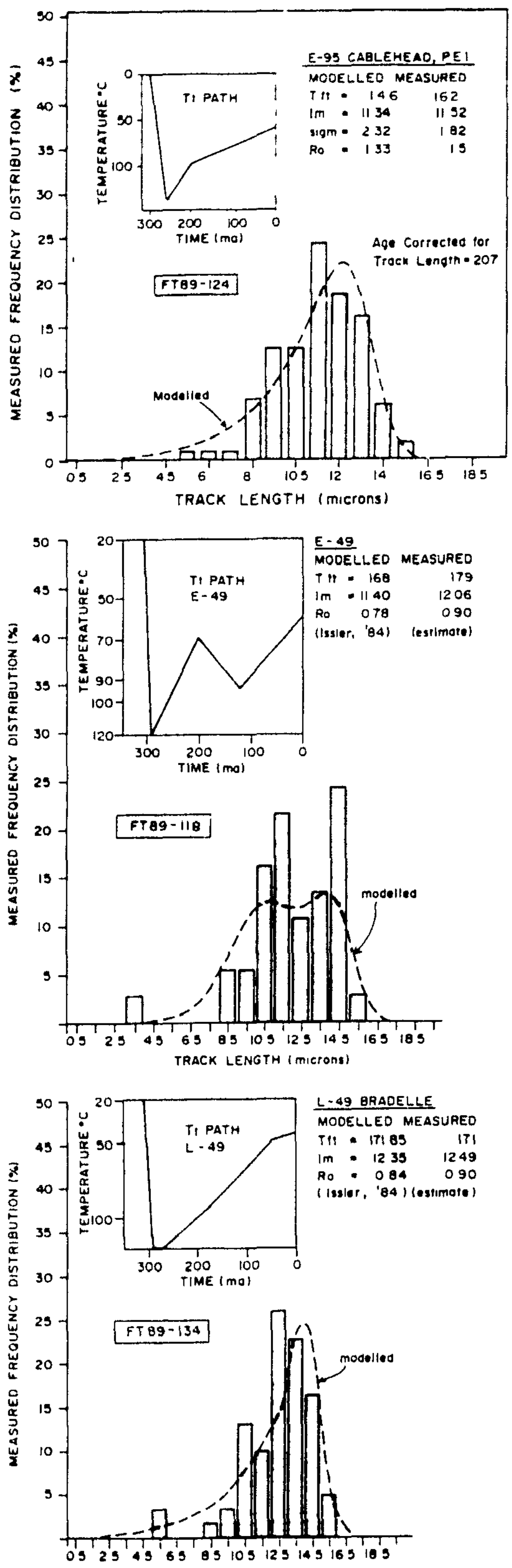


Figure 5.22: Comparisons of Trac3 modelled distributions for track lengths and apatite fission track ages and measured values for the Gulf of St. Lawrence samples. Note that the track length distribution of E-49 reflects a secondary heating event probably related to the fault which occurs near the sampled horizon.

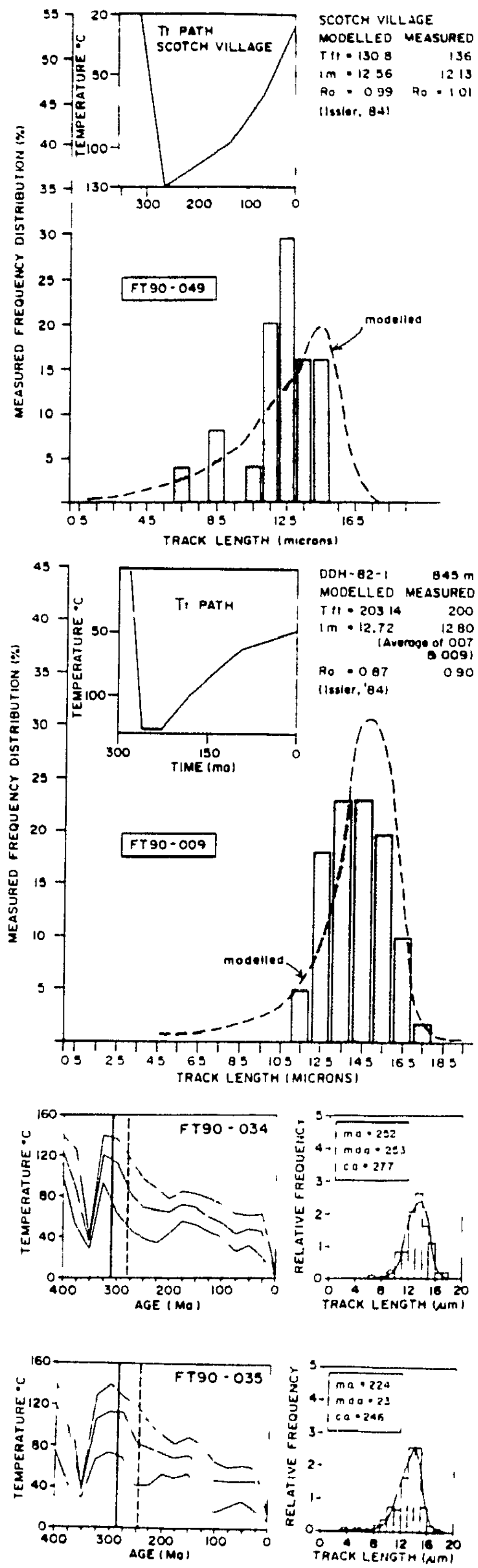


Figure 5.23: Comparisons of Trac3 modelled distributions for track lengths and apatite fission track ages and measured values for the south (Minas Basin) and east central (Sydney Basin). The lower two models are inverse models on the samples from the Deer Lake Basin (temperature scale reversed relative to other models presented here) (after Hendriks, 1991).

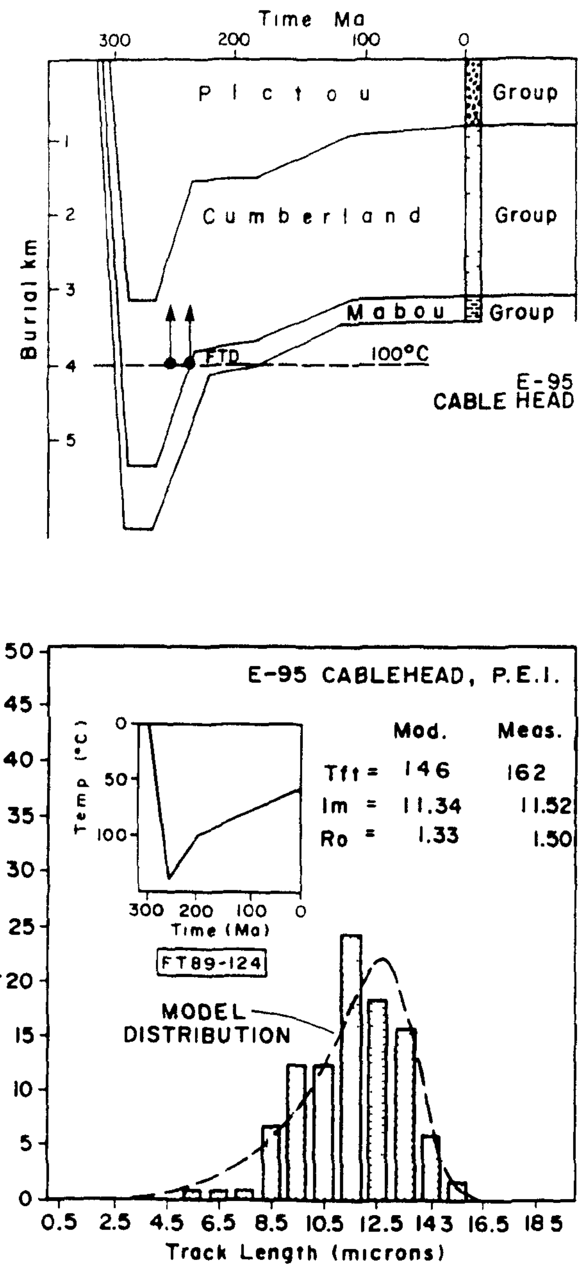


Figure 5.24: An example of the comparison of the burial history plots generated by other thermal and stratigraphic information and the forward model for the apatite fission tracks (Trac3). Note the close correlation of the time-temperature paths.

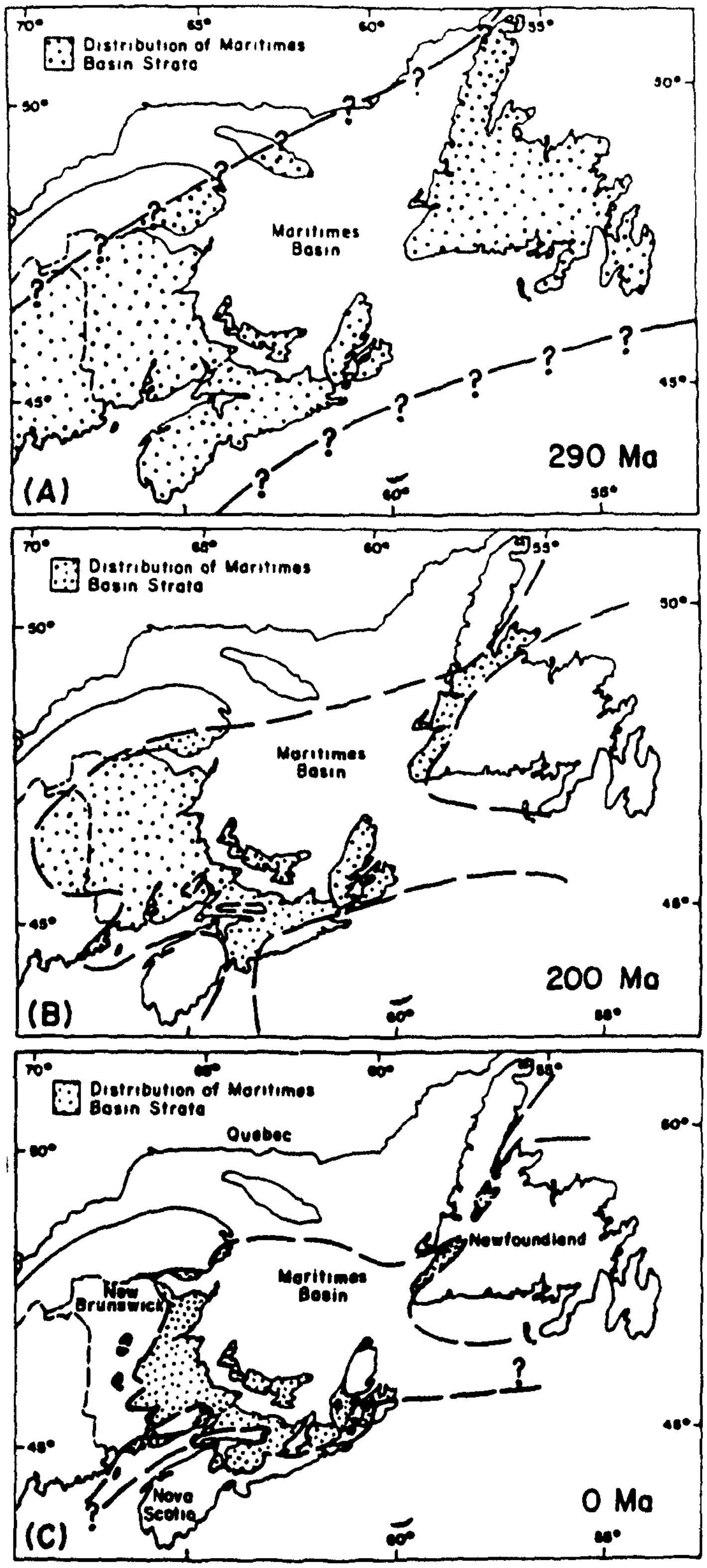


Figure 5.25: Diagrammatic representation of the possible extent of Permo-Carboniferous sedimentary cover through time.

CHAPTER 6

BASIN DEVELOPMENT AND HISTORY

6.1 INTRODUCTION AND TECTONIC SETTING

The previous chapters have outlined the stratigraphy, sedimentology, structure, and thermal history of the Cumberland Basin in particular, and the Maritimes Basin in general, and led to the important conclusion that 2-4 km of sedimentary strata was stripped off the Atlantic region between the Permian and the Cretaceous. This chapter examines the relationship of sedimentation to tectonics, in order to better understand the tectonic development of the basin. In particular, this chapter attempts to explain how and why there has been a basin-wide erosion or exhumation event that has so uniformally stripped off 2-4 km of strata throughout the basin between 280 and 170 Ma. In chapter 7 this tectonic history is applied to the metallogenesis of the basin.

The late Paleozoic to Mesozoic rocks in Atlantic Canada record a complex history of sedimentation, tectonics, and volcanism in the northeastern Appalachians. Strata contained within these successor basins reach a maximum thickness of twelve kilometres (Howie, 1988) in the central Gulf of St. Lawrence (Magdalen Basin). These are represented by a complex molassic succession dominated by continental deposition. Sediments were derived both locally (especially in the Late Devonian and Early Carboniferous) and regionally (Late Carboniferous) from the Appalachian Orogen. Figure 6.1 is a northern hemisphere reconstruction for the Stephanian. This figure, along with Figure 6.2, clearly indicates that the Maritimes Basin is a deposition centre within a mobile large-scale fault zone adjacent to mountain-forming chains of the Appalachians and northern Africa to the south. This depocenter represents the waning stages of the Devonian Acadian Orogeny and the subsequent uplift of the orogen, following the mid-Devonian juxtaposition of the Avalon Composite Terrane and the Meguma Terrane (Fralick and Schenk, 1981). Superimposed on this are the early Mesozoic strata which record the initial rifting phase of the Atlantic Ocean, and the subsequent late Mesozoic to Cenozoic opening (Wade and MacLean, DNAG in press).

6.2 TECTONO-STRATIGRAPHIC HISTORY

The tectono-sedimentary features of the Cumberland Basin and Maritimes Basin are examined in order to evaluate the basin development theories within the context of the geological constraints.

The Cumberland Basin is the structural remains of a relatively deep (7000 m+) sedimentary basin which developed just north of, and apparently parallel with, the east-west trending strike-slip zone of the Cobequid-Chedabucto Fault System This complex tectonically disrupted zone, marks the suture between the Avalon Terrane and the Meguma Composite Terrane (Fig. 6.3). The western margin of the Cumberland Basin is a structurally complex area where it converges with the dominant northeast regional structural trend in southeastern New Brunswick South of the juncture of the Caledonia Highlands Massif and the Harvey-Hopewell Fault in New Brunswick is a significant reorientation of the structural features in the basin from east-west to northeast-southwest (Gussow, 1953; Ruitenberg and McCutcheon, 1982, Nance and Warner, 1986). This adjustment in trend coincides with the change from the strike-slip movements of the eastern basin to the Mid-Westphalian thrusting and high angle reverse faulting in southern New Brunswick (Gussow, 1953, Nance and Warner, 1986).

Stratigraphic sections for various areas located adjacent to the Cobequid Highlands Massif were compiled by Ryan et al.(1987) (Fig. 6 4) These sections were used to evaluate onlap relationships and sedimentary facies adjacent to the highlands. These data were supplemented by the sedimentological data, particularly the sediment dispersal trends and facies variations, in order to create, by backstripping, a series of paleogeographic reconstructions for various times in the basin development (Fig 6.5). Ryan et al (1987) suggested that the Carboniferous strata can be considered to comprise at least three megasequence packages These individual packages reflect major tectonic events, and perhaps related or coincident paleoclimatic changes, which have affected the basin-fill history. The three sedimentary megasequences are: (1) the Fountain Lake Group to the Mabou Group of Upper Devonian to Namurian age (365-325 Ma), (2) lower part of the Cumberland Group of Upper Namurian to mid-Westphalian A age (325-310 Ma), and (3) the upper part of the Cumberland Group and the Pictou Group of Late Westphalian A to Lower Permian age (310-280 Ma)(Ryan et al.,1987)(Fig. 6.6).

Each megasequence (allocycle) records a deceleration of the subsidence rate or a shift from local uplift and subsidence to more regional subsidence. Initial rapid subsidence (and/or uplift) resulted in local deposition of fanglomerates at the basin margins, which interfingered basinward into lacustrine sequences. These marginal coarse deposits were succeeded by a transition to fluvial, lacustrine, and in one case marine basin-fill. The later episodes of basin infilling were regionally extensive and overlapped older basin strata in some areas, reflecting a slower subsidence rate or more regional extent. These allocyclic packages are useful simplifications of the large-scale depositional trends, and aid in understanding the relationships of local and regional tectonic activity (Ryan et al., 1987).

6.2.1 LATE DEVONIAN - EARLY NAMURIAN (365-325 Ma)

The late Devonian to early Visean in the Maritimes Basin was characterized by crustal instability, with initial molassic deposition of coarse- to fine-grained alluvial, fluvial, lacustrine, and locally rift-related volcanic deposition in intermontane basins (Fountain Lake Group and Horton Group). Deposition occurred initially under dry conditions (late Devonian), followed by humid lateritic conditions. Extensive lacustrine deposition in the early Tournaisian evolved, with the advent of semiarid dry conditions, with local evaporitic lacustrine deposition and redbeds in the late Tournaisian to early Visean (Howie, 1988).

The Late Devonian to Namurian stage of basin development has been interpreted as rifting pull-apart tectonics related to major regional and subsidiary wrench faults. Sedimentation patterns within the basin-horst terrane typically reflect local provenance from internal and adjacent basement highland areas, with subordinate (but increasing with time) extrabasinal input. Many basin margins are onlap unconformities, and thus the basins cannot be interpreted simply as being entirely fault bound. The Fountain Lake Group and the Horton Group strata exceed 4000 m in thickness. They record the earliest sedimentation following the deformational phase of the middle

Devonian Acadian Orogeny, and represent initial basin development Continental deposition occurred in intermontane rift basins, and indicate that alluvial fan, fluvial, and lacustrine environments predominated in the intermontane basins (Donohoe and Wallace, 1985, Carter and Pickerill, 1985) Locally these strata are interbedded with basalts and rhyolites The large volumes of detritus derived from the local highlands resulted in rapid sedimentation and facies variation Alluvial fanglomerate facies thin basinward and up-section into laterally equivalent fluvial to lacustrine facies (Ryan et al , 1987) The relationships between these facies during the Late Devonian to Early Namurian are not well documented, and contacts are poorly exposed in the study area because they have been overstepped by younger strata

The Horton Group sedimentation ended when a marine invasion occurred during the Visean (Boehner et al , 1986). An arid climate and the restricted inflow of normal marine waters resulted in the deposition (up to 1000 m) of a multi-cycled sequence of saline marine evaporites, fine to coarse redbeds, and thin but areally extensive marine carbonates that comprise the Windsor Group (Giles, 1981). Lower Windsor Group deposition was laterally widespread throughout the Maritimes Basin (Moore and Ryan, 1976)

The restricted marine evaporitic sedimentation of the Windsor Group was succeeded by up to 1500 m of the continental deposits of the Mabou (Canso) Group These fine grained, red to grey fluvial-lacustrine facies (Belt, 1965 and Bell, 1944) were deposited throughout much of the Cumberland Basin and the larger Maritimes Basin from the Late Visean to Early Namurian The Upper Devonian to Lower Namurian megasequence records (1) rapid initial basin subsidence, continental alluvial, fluvial-lacustrine deposition with associated early volcanism, succeeded by (2) mixed marine carbonates and evaporites with redbeds, and subsequent (3) fluvial-lacustrine clastics, deposited during a period of slower regional subsidence (Ryan et al , 1987)

6 2.2 LATE NAMURIAN - WESTPHALIAN A (325-310 Ma)

The lower part of the Cumberland Group diachronously overlies the Mabou Group and contains thick, widespread extraformational conglomerates of the Claremont Formation

Basinward, the Claremont conglomerates interfinger with immature red sandstones and siltstones. The Claremont Formation is succeeded by more than 1000 m of grey sandstones and fine-grained redbeds of the Boss Point Formation The Boss Point Formation strata represent widespread deposition of sand over a large portion of the Cumberland Basin (Fig. 6.5).

In areas near the Cobequid Highlands Massif, the Boss Point Formation oversteps older Carboniferous strata and onlaps the basement rocks. Boehner et al. (1986) confirmed Van de Poll's (1966) suggestion that the mature nature of the sandstones of the Boss Point Formation reflected the initiation of a distal source for detritus. The Claremont Formation fanglomerates were deposited adjacent to the Highlands Massifs in response to uplift and rapid subsidence. Deposition of the conglomerates was followed by a period of slower? or more regional subsidence, represented by the sandstones and mudrocks of the Boss Point Formation. The deposition of the Westphalian A Boss Point Formation is generally dominated by regional scale fluvial, braidplain, and alluvial floodplain environments.

6.2.3 WESTPHALIAN A - EARLY PERMIAN (310-280 Ma)

The middle to late Westphalian tectonic episode in the Maritimes Basin produced variably intense folding, faulting, uplift, and evaporite tectonism, as well as unconformities and erosion-recycling of older basin fill. It was an extended episode that peaked in intensity in the Westphalian B, and waned through the late Westphalian to early Permian. It has been referred to as the Maritimes Disturbance and related to the Hercynian, Variscan and Alleghenian orogenic events in Europe, the United Kingdom, and the United States, respectively.

Major lateral (dextral transform) motion along the Cobequid-Chedabucto Fault System culminated in the mid-Westphalian, with complex and locally intense deformation. Thrusting, especially in southern New Brunswick (Nance, 1987) as well as other areas adjacent to the fault zone (Fig. 6.7). The deformation locally produced rapid uplift and subsidence with accompanying thick alluvial fan and lacustrine deposition in extensional (local pull apart) areas. Broad areas of uplift and unconformity, especially in the relatively stable platform areas accompanied this event. The late Carboniferous to early Permian generally records regional subsidence and deposition in a large alluvial floodplain setting, which fines upward and ultimately is dominated by redbeds. This phase has been characterized as foreland basin deposition (Keppie, 1982a) and overlap-burial of former basement highland and platform areas (Ryan et al., 1987). Sedimentation was dominated by regional extra-basinal provenance and large fluvial systems, with sediment dispersal patterns parallel to the regional basin and basement structural trends (easterly to northeasterly) (Calder et al., 1988; van de Poll, 1973; and Gibling et al., 1992).

Episodes of marginal alluvial fan deposition are recorded in the Cumberland Group strata. These conglomerates reflect uplift of the massifs, and the coincident subsidence of the basin, as well as the development of extensive drainage systems out of the highlands (Fig. 6.5). A range of fluvial channel configurations, including braided (Calder and Naylor, 1985; Salas and Rust, 1985), internally braided-meandering (Calder, 1985b), meandering (Ryan, 1985), anastomosing (Rust et al., 1984), and composite (Ryan, ibid), evolved contemporaneously within the basin. Lacustrine deposits comprise only a minor component of the basin-fill. The dextral transpression and related thrusting which was occurring in the Westphalian B in the northwestern part of the basin (Nance and Warner, 1986), must also have affected the evolution of fluvial systems (Fig. 6.7).

Deposition of the second part of this allocycle is represented by the predominantly fluvial redbeds of the Pictou Group (up to 2500 m thick), which exhibit regional overlap onto the adjacent platforms (Fig. 6.5). Pictou Group strata rest disconformably, or with angular unconformity, on older Carboniferous strata and Pre-Carboniferous basement rocks. Within the Pictou Group, the decelerating subsidence rate may have resulted in the overall fining upward trend in the basin infilling (Ryan, 1985). Many of the basement and diapir-related faults within the Cumberland Basin are sealed by the Pictou Group. Although this indicates that their greatest degree of movement was pre-Westphalian D, faulting and deformation of the Pictou Group of Stephanian or younger age with local evaporite intrusion (eg. in the Gulf of St. Lawrence), also occurred.

The late Carboniferous to early Permian records an evolution to a drier climate with extensive redbeds and locally reported eolian deposits in the Permian. These conditions are generally similar to the pre-Zechstein evaporite basin conditions in northern Europe and Great Britain There is no rock record of the late Permian to early Triassic in the Maritimes Basin. The late Permian apparently was a major hiatus, and was accompanied by an important reddening episode of late Carboniferous strata especially, in the Cumberland Basin.

All the Devono-Carboniferous strata of the Maritimes Basin were subsequently probably affected in some manner by the Mesozoic and Cenozoic tectonism and sedimentation in the Atlantic region of Canada The following section describes the tectonic and sedimentological settings in the Atlantic region post Devonian to Permian sedimentation.

6 2.4 MESOZOIC - CENOZOIC (245-0 Ma)

During the late Triassic to early Jurassic, continental rift sedimentation occurred in the area of the Cobequid-Chedabucto Fault System. Alluvial, fluvial and lacustrine redbeds and tholeiitic basalt were deposited and preserved in narrow graben to half graben basins in the Bay of Fundy (Fundy Rift), which is located to the south and southwest of the Cumberland Basin as well as in Chedabucto Bay (Orpheus Graben) A rock record representing this age is not preserved or recognized in the Cumberland Basin, although strata of this age have been documented under Chignecto Bay. Fault and fracture systems affecting portions of the basin fill may, however, be related to Mesozoic tectonics. The Mesozoic basins represent an early stage of rifting related to sinistral motion on Cobequid-Chedabucto Fault System during opening of the Atlantic, and the strata rest with strong angular unconformity on the eroded late Paleozoic landscape. The distribution beyond the rift areas is unknown Apatite fission track studies suggest that only a thin cover of Triassic-Jurassic sediments could have existed beyond the present day outcrop limits of the Mesozoic basins (See Chapter 5)

The only preserved late Mesozoic sedimentation onshore, is recorded by the presence of unconsolidated interstratified silica sands, kaolinitic clay, and mud with minor lignite coal of early

Cretaceous age. These rest unconformably on a deeply eroded late Paleozoic landscape, especially in central mainland Nova Scotia. The preserved distribution is minor in comparison to the pre-erosional extent, however the apatite fission track studies indicate that the thickness of these strata were not sufficient to affect the time temperature path of the area. Brightly coloured, grey to variegated grey-green and red muds are locally associated with Windsor Group karsted outcrop areas, including those at Minudie, Oxford and Lazy Bay-Malagash. This material may be Cretaceous in age. The Mesozoic sediments represent terrestrial fluvial-alluvial plain to (?) coastal plain equivalents of the extensive prograding deltaic-marine facies in the Scotian Basin to the east. They may represent deposition as an accretionary prism along the subsiding shelf and continental margin of the opening Atlantic Ocean No preserved sedimentary record occurs onshore for the late Cretaceous to Tertiary.

The tectono-stratigraphic framework for the strata of the Maritimes Basin provides the necessary background to start to assess what type of basin or basin-forming mechanism is responsible for the sedimentation during the Carboniferous. In the following sections the various basin models proposed are evaluated and an attempt is made to classify the Maritimes Basin.

6.3 TECTONO-STRATIGRAPHIC MODELS FOR THE EVOLUTION OF THE MARITIMES BASIN

Numerous conflicting interpretations have been proposed for the tectonic history of the Late Paleozoic basins in the northern Appalachians of Atlantic Canada (e g. Bell, 1944, Gussow, 1953; Belt, 1968; Webb, 1969; Poole, 1976; Keppie, 1977, 1982a, 1982b; Williams, 1974; Fralick and Schenk, 1981; Bradley, 1982; McCutcheon and Robinson, 1987; Durling and Marillier, 1990) Bell (1944, 1958), and Gussow (1953), emphasized the composite nature of the Carboniferous "basins", and described them as intermontane troughs or miniature geosynclines Normal faulting was thought to have taken place at or near the basin margins.

Subsequent workers (Belt, 1965b; Webb, 1969; Fralick and Schenk, 1981; Bradley, 1982) emphasized the importance of strike-slip movement along the basin-margin faults. Despite the conflicting views on the history of faulting, uplift and subsidence, most interpretations state or imply a two-part character to the history of sedimentation-tectonism (Boehner et al, 1986; Ryan et al, 1987). The first stage involved an Upper Devonian to mid-Westphalian continental and marine deposition within elongate basins bordered by highland areas. The second stage of the basin history is characterized by widespread fluvial deposition during the late Westphalian into the Early Permian. The younger strata widely overstepped earlier basin margins, and onlapped the basement rocks of the adjacent platforms and uplands as well as the internal highland massifs.

Bradley (1982) proposed a two-phase deposition of the Carboniferous strata; the first caused by initial rifting in a dextral strike-slip tectonic framework or "pull-apart basin", followed by the second, a regional thermal subsidence phase. Keppie (1982) applied the term transpression in reference to the early pull-apart phase described by Bradley (1982), and suggested that the second phase was deposited in a "foreland basin" setting. This two-phase subdivision, although generally applicable, oversimplifies the basin fill. Similarly, all late phase basin limits are not low relief unconformities, as locally there are major faults. McCutcheon and Robinson (1987) concluded that the strike-slip faulting and the pull-apart basin model of Bradley (1982) was an unlikely mechanism for the formation of the Maritimes Basin. They proposed that overthrusting and crustal thinning related to the Acadian Orogeny produced isostatic adjustment, rapid subsidence, and block faulting in the late Devonian to early Carboniferous. This was succeeded by slower thermal subsidence through the late Carboniferous to early Permian.

The author believes that the multi-phase megasequence stratigraphy and obvious cycles of regional versus local subsidence, suggests that the basin-forming mechanism was not a pull-apart. The scale of pull-apart necessary to form the Maritimes Basin would have to have been enormous and bounding major faults oriented southwest - northeast have not been documented. Pull-apart basins on a smaller scale, such as the Stellarton Basin, occur within the Maritimes Basin but do not explain the basin as a whole. The Maritimes Basin developed along terrane suture zones nearly perpendicular to the Appalachians. This would not be the right orientation nor a likely tectonic setting for the development of foreland basins. The following section (Section 6.4) examines the probable classification of the Maritimes Basin in light of these geological constraints.

6.4 MARITIMES BASIN TECTONIC CLASSIFICATION

This section of the chapter is an attempt to classify the Maritimes Basin based on the geological parameters and tectonic setting. Kingston et al. (1983) proposed a global basin classification scheme based on plate tectonic settings and mechanisms causing basin subsidence. It is generally accepted that the Maritimes Basin was formed on the continental crust in an area of convergent plate movements (emplacement of the Meguma Terrane) near the plate margin but away from a subduction zone (Keppie, 1988). Using the criteria of Kingston et al.(1983), the Maritimes Basin can be classified as a Continental Wrench or Lateral Basin (Fig.6.8).

The Maritimes Basin in cross section resembles the Malay Basin (Fig.6.9), in that it is situated away from the volcanic arc area at the interior of the plate, and is dominated by wrench or shear structures (Fig.6.7). Figure 6.10 is a generalized cross section of the Maritimes Basin in a three stage sequence similar to that proposed by Kingston et al. (1983) for an idealized LL Basin; episodic shear/wrench events or oblique compression has modified the basin features (Fig. 6.11). It is to be expected that different parts of the Maritimes Basin were affected, to varying degrees, by one or both of these mechanisms. Furthermore, all events may not be equally represented in terms of style or intensity. For example, a wrench fold belt event (FBf) may closely resemble the configuration of the thrusted Carboniferous strata in the St. John area of New Brunswick (Nance and Warner, 1986), whereas the Cumberland Basin may be weakly to moderately affected by episodic wrench events.

Although the two-part tectonic development of the Maritimes Basin proposed by Bradley (1982) generally explains the local (proximal) versus the external (distal) source for the derived basin-fill material within the Maritimes Basin, it does not adequately explain local basin variations, particularly the allocycles of Carboniferous sedimentation within the Cumberland Basin.

Within the Tatamagouche area of the Cumberland Basin, three episodes of rapid subsidence (or uplift) are recorded by thick fanglomerates in the Devonian, the Namurian, and the early Westphalian A. Each fanglomerate facies is succeeded by onlapping fluvial and (or) marine facies, which may represent sedimentation during deceleration of subsidence within the basin (Ryan et al., 1987).

The structure of the southwestern part of the Maritimes Basin is dominated by northeast-southwest trending faults. This pattern is disrupted by the east-west trending Cobequid - Chedabucto Fault system and in southern New Brunswick where this complex fault zone merges with the northeast trending structures (Caledonia Highlands Massif and related faults), a highly complex faulted (thrusting) and folded belt has been formed (Gussow, 1953; Ruitenberg and McCutcheon, 1982; Nance and Warner, 1986).

The east-west trending Cobequid Highlands Massif appeared to have behaved as a fault-bound wedge which was tilted in response to the strike-slip movement (cf. Fralick and Schenk, 1981) and flexure. This in turn may have been due to resistance to thrusting in southern New Brunswick. The result was allocyclic sedimentation within the Upper Devonian to Lower Permian strata of the Cumberland Basin. (Ryan et al., 1987).

If this pattern is the result of westward transform movement along the Cobequid and en echelon faults, as implied by Keppie (1982b), then the episodes of rapid basin subsidence or source area uplift, and the subsequent slower, regional subsidence, may be the result of the same tectonic mechanism. Alternating periods of transpressional flexure and rapid subsidence by downward block faulting and tilting due to strike-slip movement along the faults, resulted in the allocyclic sedimentation within the Cumberland Basin. Motion on the northeast trending faults through southern New Brunswick and extending into the Gulf of St. Lawrence (Magdalen Basin) can be interpreted in several ways. The most recent work by McCutcheon and Robinson (1987) and Durling and Marillier (1990) indicate minor strike-slip (post-Horton and pre-Windsor) on the Belleisle Fault. It is unlikely that there was a master fault pattern for the pull apart to develop as proposed by Bradley (1982). Morris (pers. comm) suggests that there are significant rotations of the strata at the base of smaller pull-apart basins such as the Stellarton Graben, however rotations of the paleomagnetic signatures are minor in the main part of the basin. This would suggests that although small scale (tens of km) pull-apart basins occur within the Maritimes Basin, the larger Basin itself is not a pull-apart. The Maritimes Basin can be better classified in general terms as a continental wrench basin caused by the flexural subsidence and fault block tilting, that occurred in response to strike-slip movements along the suture zone between two geological terranes. The burning question left to be answered about the basin, however, is where has the 1-3 km of Permian strata gone and what kind of mechanism caused this exhumation event.

6.5 WHERE HAS ALL THE PERMIAN GONE ?

Perhaps the most important inference that can be made from the thermal study of the Maritimes Basin (Chapter 5), is that there was removal of 1-3 km of strata from the Maritimes Basin, starting in the Late Permian and continuing through until at least the late Jurassic. The problem arises in the interpretation of such a process. What was the driving mechanism for such a uniform exhumation throughout an entire basin? In examining the burial history plots (Figs. 5.18-5.20) and the time-temperature plots (Figs. 5.21-5.23), it is clear that this mechanism caused a remarkably consistent exhumation throughout the basin. In the early stages of this study, it was postulated that the erosion (exhumation) may have been related to a pre-rift bulge stage related to the opening of the Atlantic. However, as evidenced by the apatite fission ages, exhumation continued to occur after this rifting was initiated. This is therefore not a reasonable explanation for all the exhumation.

The Maritimes Basin has been classified herein as a continental wrench or lateral basin, similar to the Malay Basin. Paleoflow studies (Gibling et al.,1992) indicate that the Maritimes Basin represents a now flattened topography (caused by erosion of a mobile fault zone) which occurred at the end of a lengthy zone of transport parallel to the Appalachian and North African mountain belts. The rapid sedimentation rates for the basin-fill units in the Maritimes Basin had been discussed earlier in this thesis. The rates of basin fill indicate that the basin was receiving an enormous volume of material throughout the Permo-Carboniferous. If the Maritimes Basin does indeed represent the first break in the steep gradient between the two mountain ranges, the result would be an overfilled basin, thus raising the baselevel above sealevel. This overfilling of the basin would continue at a steady state as long as there was a constant contribution of detrital material entering the basin. As the transport of the material waned, the basin surface must have been peneplaned during isostatic rebound to a level of approximately sealevel. Given the paleogeographic reconstructions for the time period (see Fig. 6.1), this appears to be a reasonable explanation for the exhumation of the basin, and would explain the relatively uniform exhumation exhibited throughout the Maritime Basin. The above sealevel deposition and subsequent erosion to base level may not be the only possible explanation for the exhumation event experienced by the Maritimes Basin, however it is the most plausible theory proposed to date.

6.6 CONCLUSIONS

The following are the implications for the basin evolution of this study:

(1) there are several tectonically-driven allocycles present in the stratigraphic record of the Maritimes Basin;

(2) pulses of rapid sedimentation were interspersed with periods of regional subsidence;

(3) the same mechanism drives both the local and regional subsidence (the westward movement of the various terranes, and their associated sutures);

(4) the Maritimes Basin can best be described as a lateral wrench (continental wrench) basin formed on a mobile zone of multiple mega-faults,

(5) paleoflow studies and basin development studies indicate that the Maritimes Basin formed near the end of a zone of longitudinal sediment transport between the mountains of the Southern Appalachians and the mountains of Northwest Africa, where the mountainous topography subsequently flattened, due to a wide zone of crosscutting faults;

(6) this basin may have filled and continued to build up so that sedimentation occurred above sea level. Subsequent erosion to baselevel resulted in a basin-

wide erosion (exhumation) in the late Permian to early Mesozoic

All of these observations are taken into account in chapter 7 of this thesis, in an attempt so as to constrain the possible models for the metallic mineral resources of the Maritimes Basin

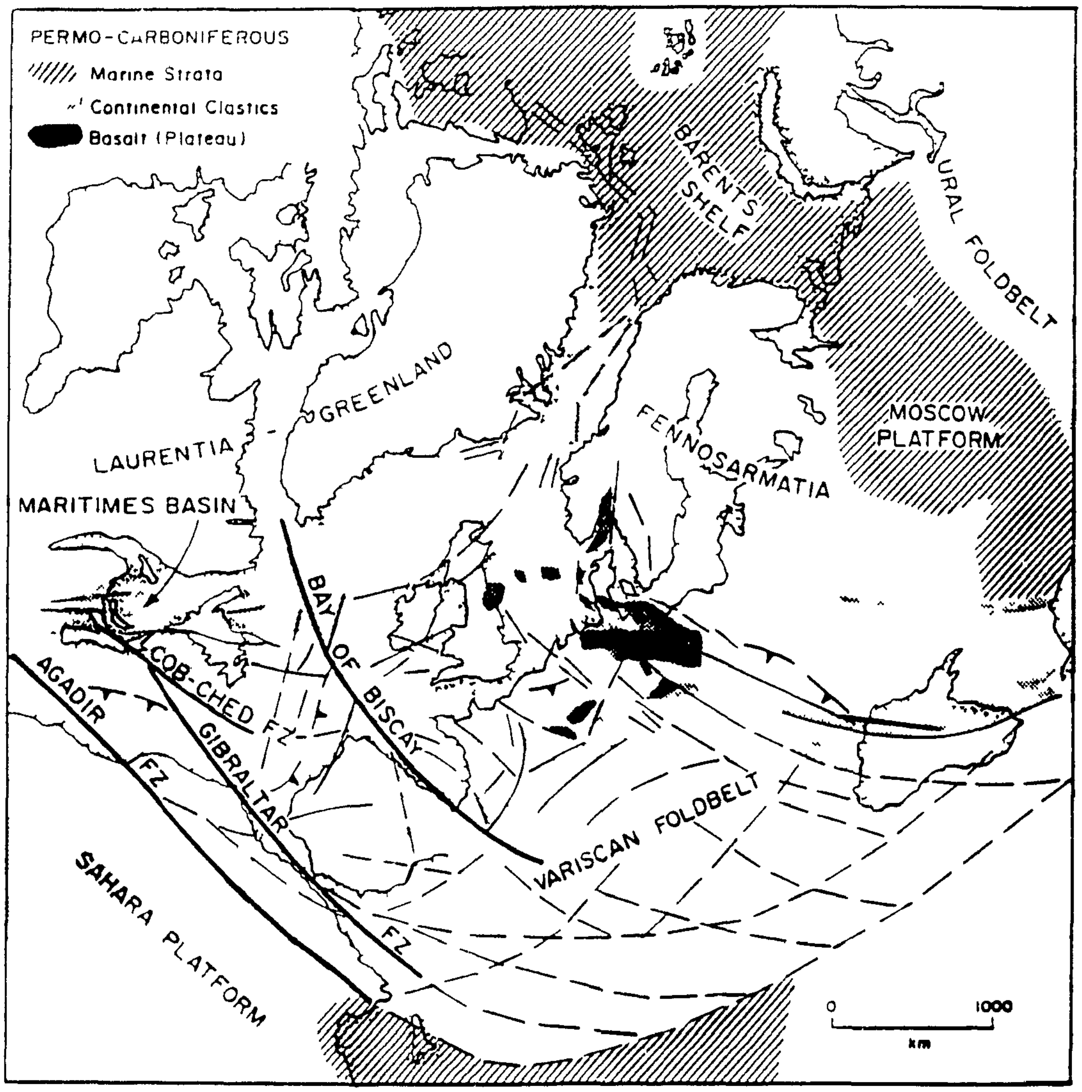


Figure 6.1. Reconstruction of the northern Hemisphere for the Stephanian (after Ziegler, 1988). Note the relative position of the Maritimes Basin in relation to the other basins.

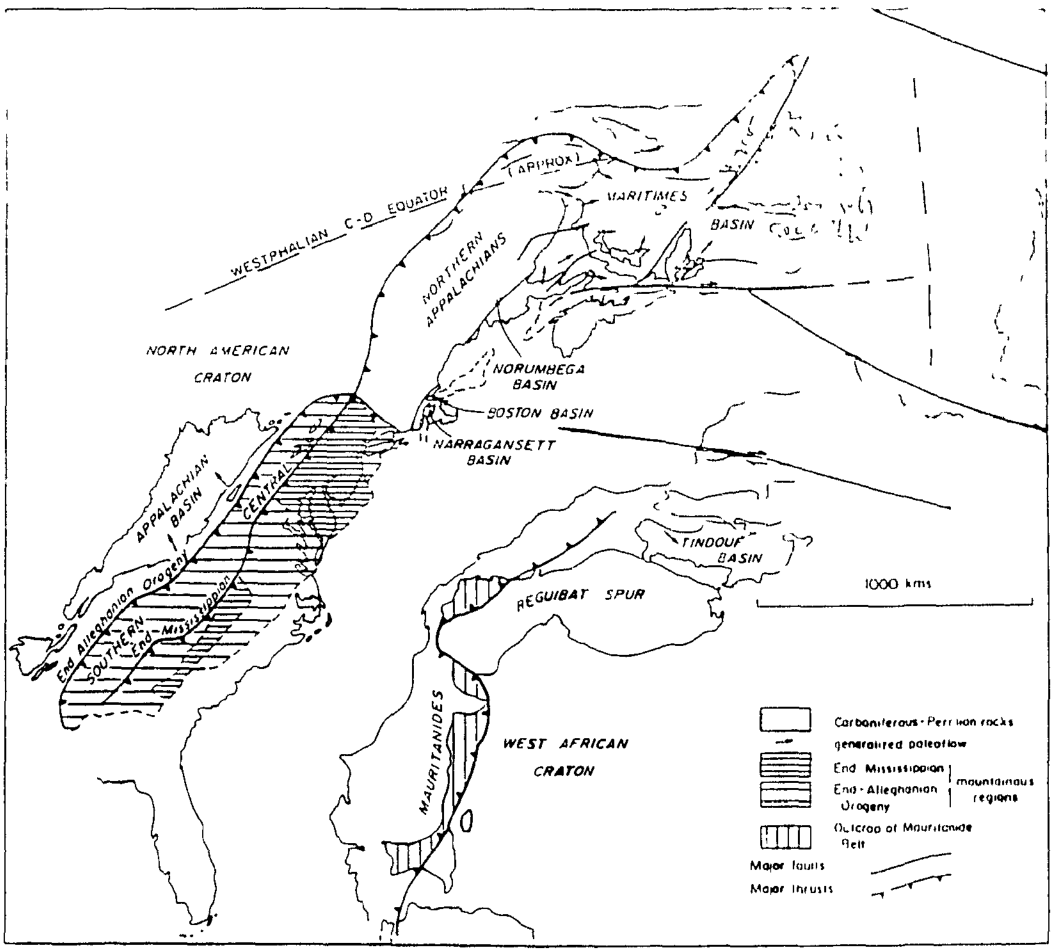


Figure 6.2: Paleogeographic reconstruction of the late Pennsylvanian along the Appalachian Orogen (After Gibling et al., 1991). This reconstruction is consistent with the paleoflow studies which have been carried out on the basin.

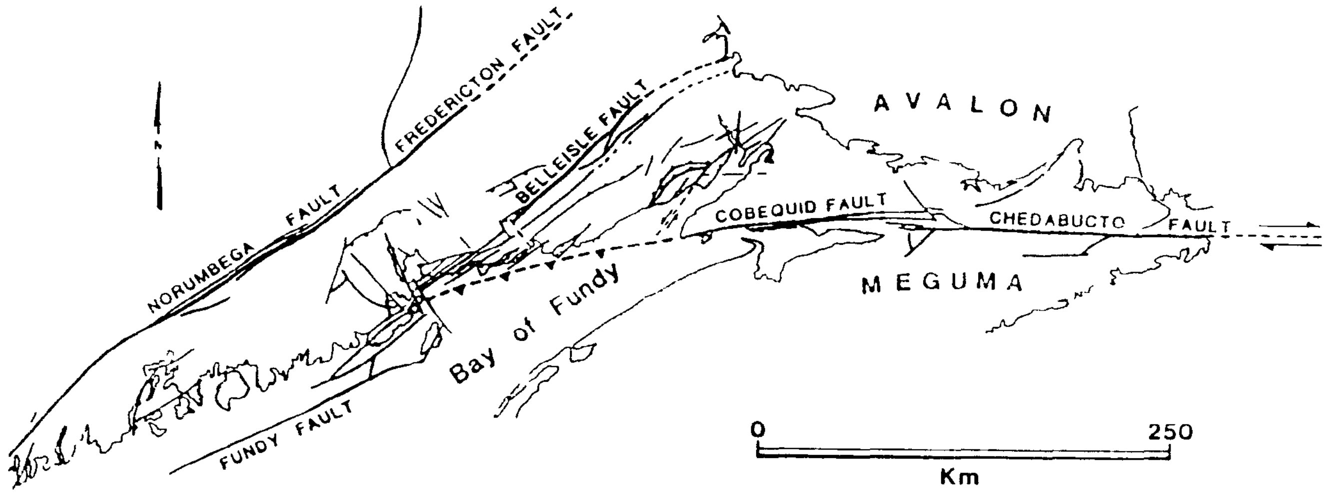


Figure 6 3: Relationship of the Avalon and the Meguma Terrane in the Late Paleozoic (After Nance, 1987)

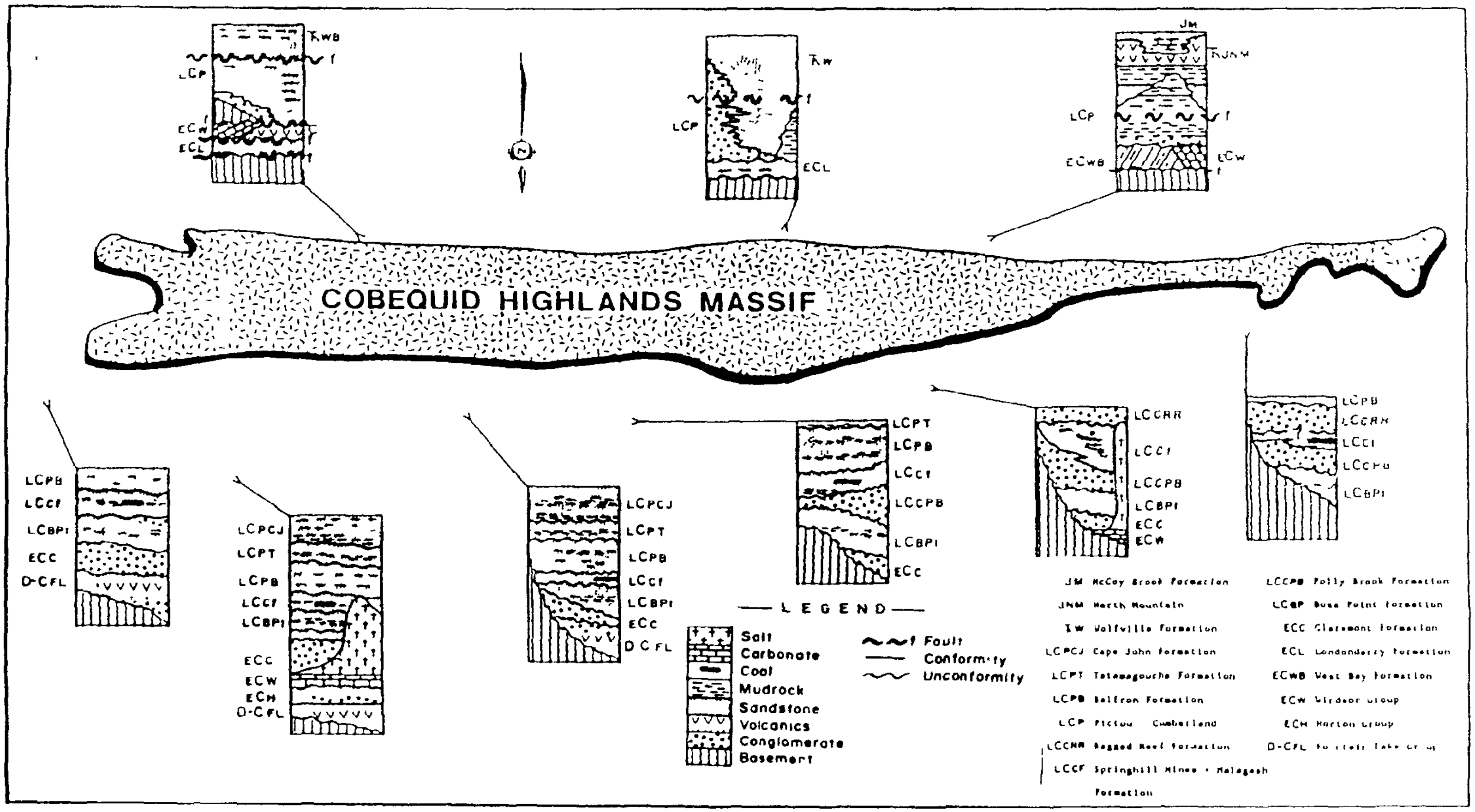


Figure 6.4: Stratigraphic columns in areas adjacent to the Cobequid Highlands Massif

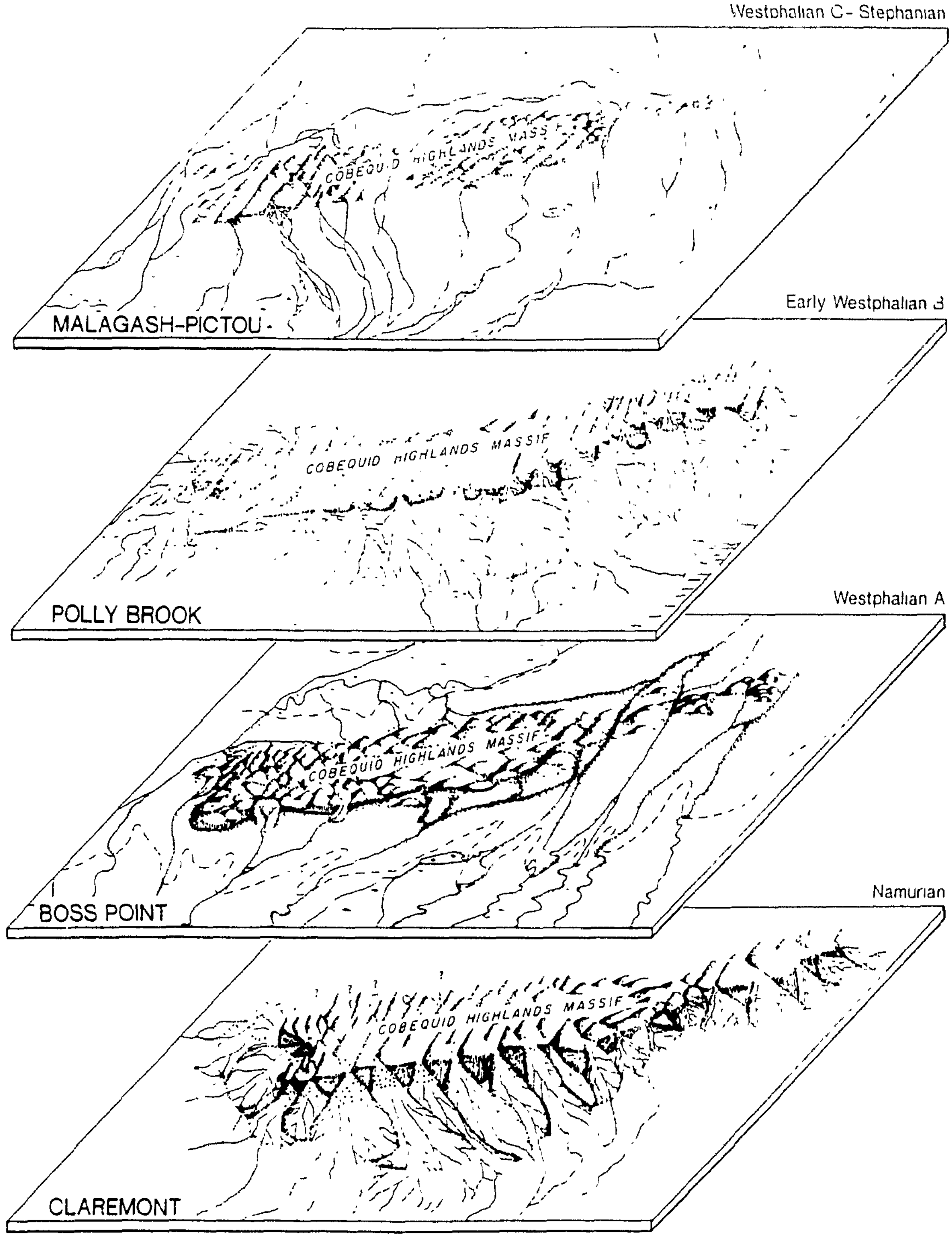


Figure 6.5: Reconstructions of the Cobequid Highlands Massif and the adjacent basin through time (modified after Ryan et al., 1987).

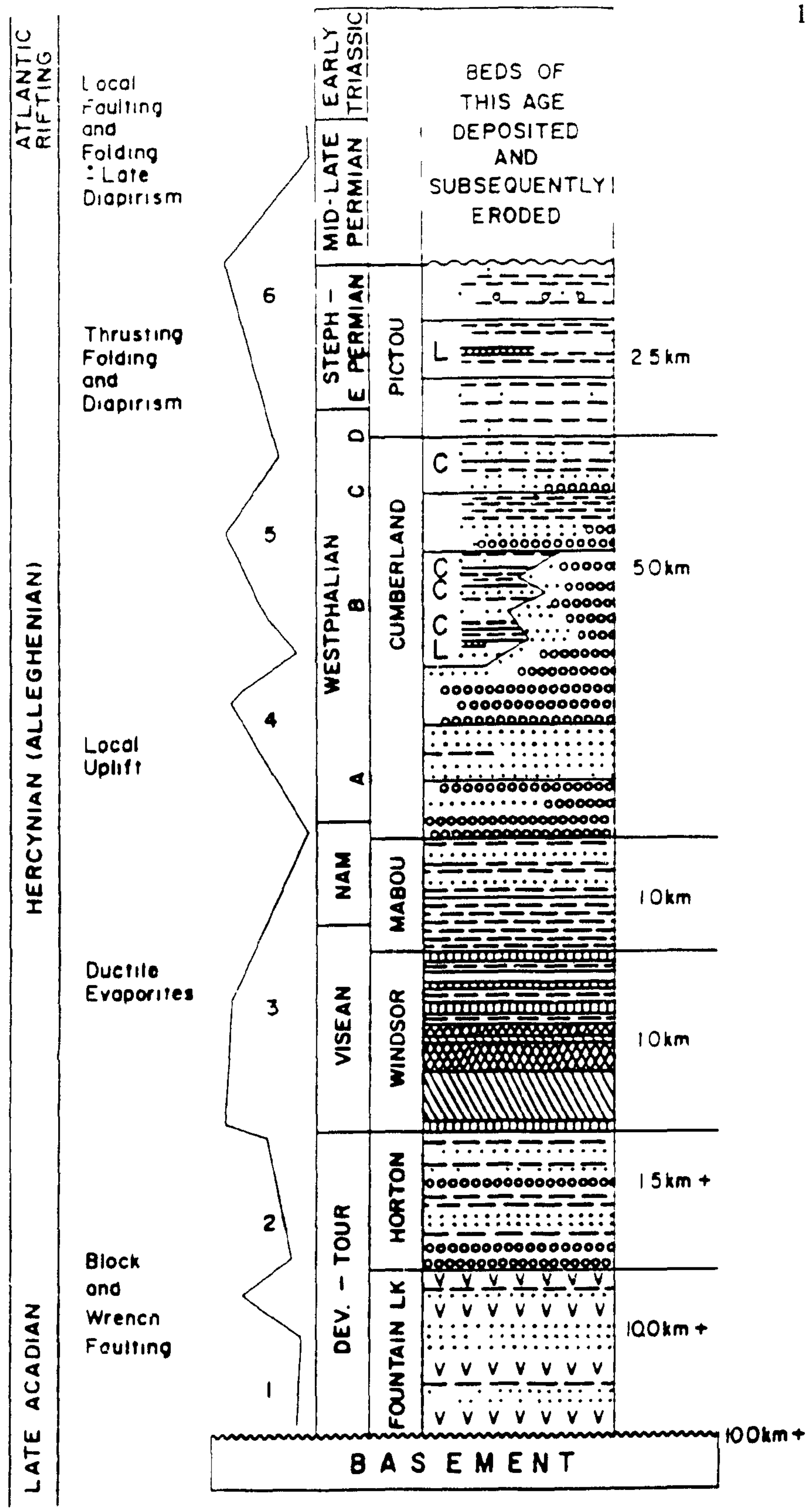


Figure 6 6 Stratigraphic column and the related allocyclic megasequences in the Carboniferous of the Cumberland Basin (modified after Ryan et al., 1987)

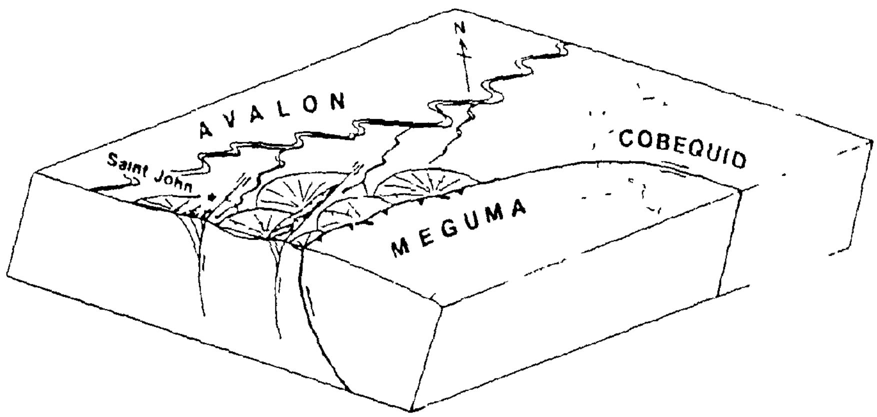


Figure 6.7. Structural alignment of the Avalon and the Meguma Terrane in the late Carboniferous (after Nance, 1986).

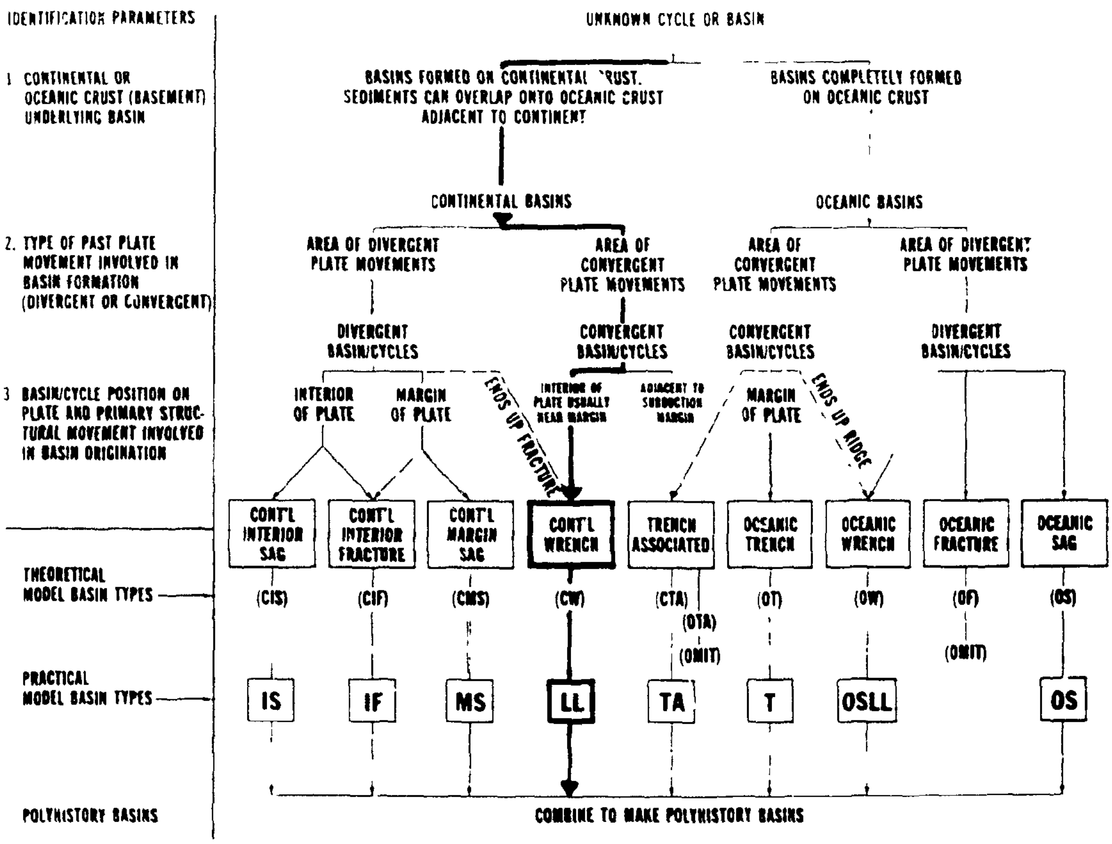
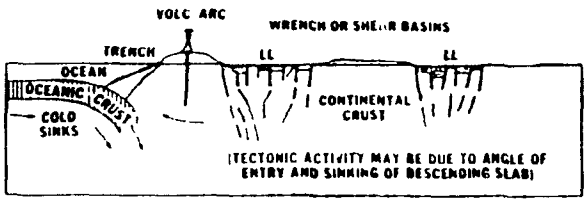
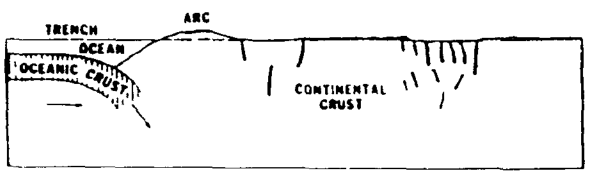


Figure 6.8: Classification of sedimentary basins (Kingston et al., 1982).



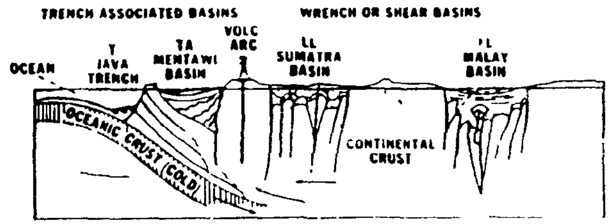
2. MIOCENE TIME

- A Arching of upper slab Basin formation
- B Trough collects deep water sediments (some volcanic)
- C Volcanoes on inside arc
- D Wrench or shear basins initiated by block faulting and differential plate movement



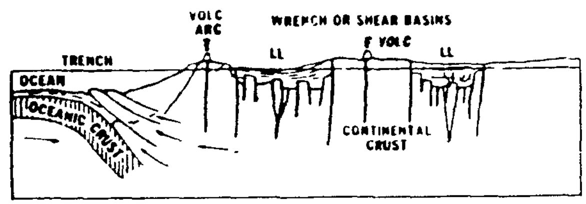
1 MIDDLE TERTIARY

- A Convergence of 2 plates (oceanic + continental) subduction begins
- B Trench and arc are formed (downbending of oceanic plate causes tension in overriding plate, or cold oceanic plate simply sinks under upper plate, and no compression results)



4. PRESENT DAY

- A Trench sediments deformed Thrusting produces new non volcanic arc and associated basin
- B Volcanoes inside arc
- C Strike slip basins continue to fill and deform by wrench fault couplet



3. PLIOCENE TIME

- A Trough continues to collect sediments which are continuously folded and thrust faulted This is only area of compression
- B Volcanoes inside arc
- C Strike-slip tension basins fill first with nonmarine clastics later with marine sediments Basins sporadically wrenched (structured) as they fill

Figure 6.9. The evolution of the Malay Basin, comparison to the Maritimes Basin (after Kingston et al , 1982)

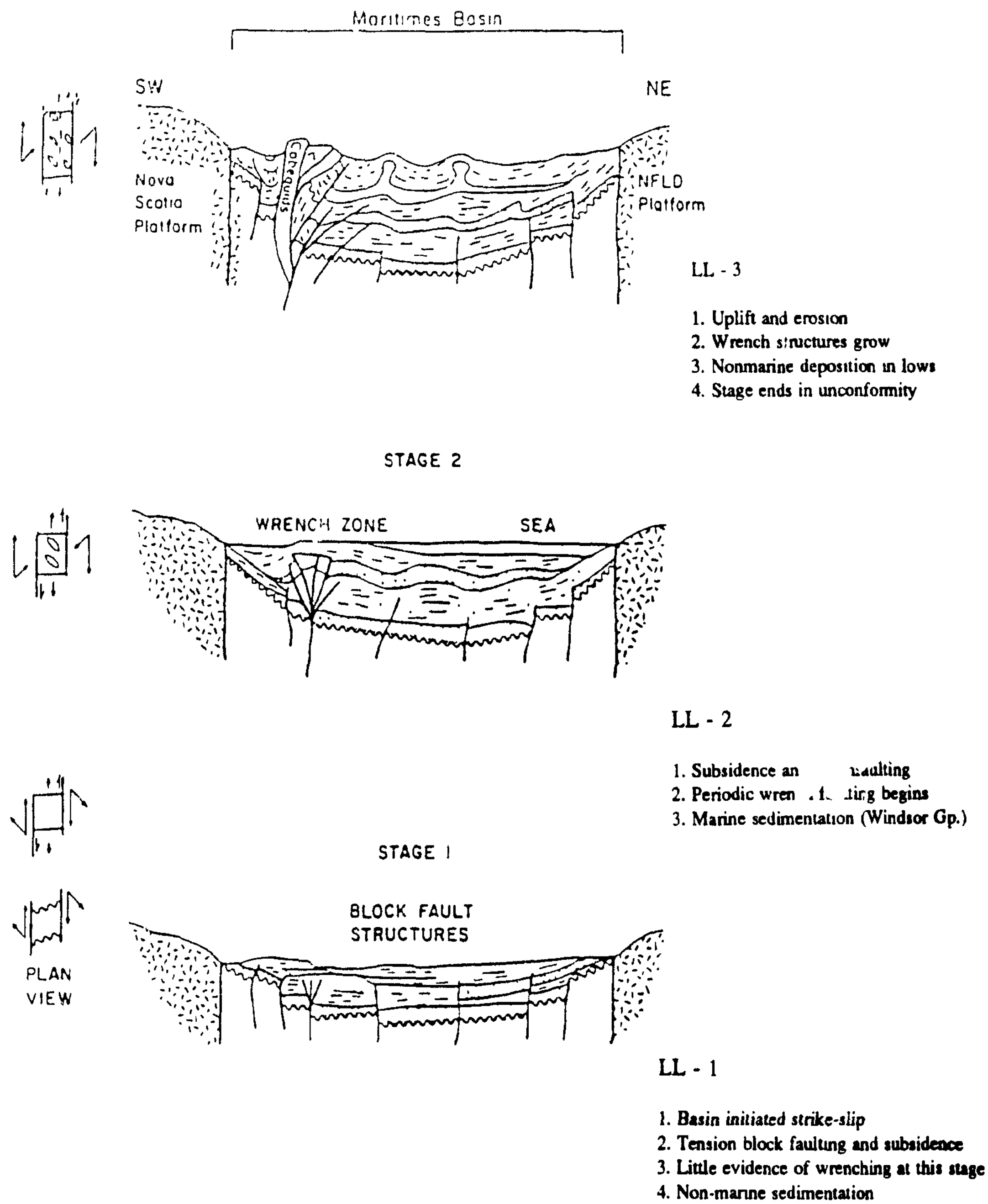


Figure 6.10: Cross section of the Maitimes Basin through time.

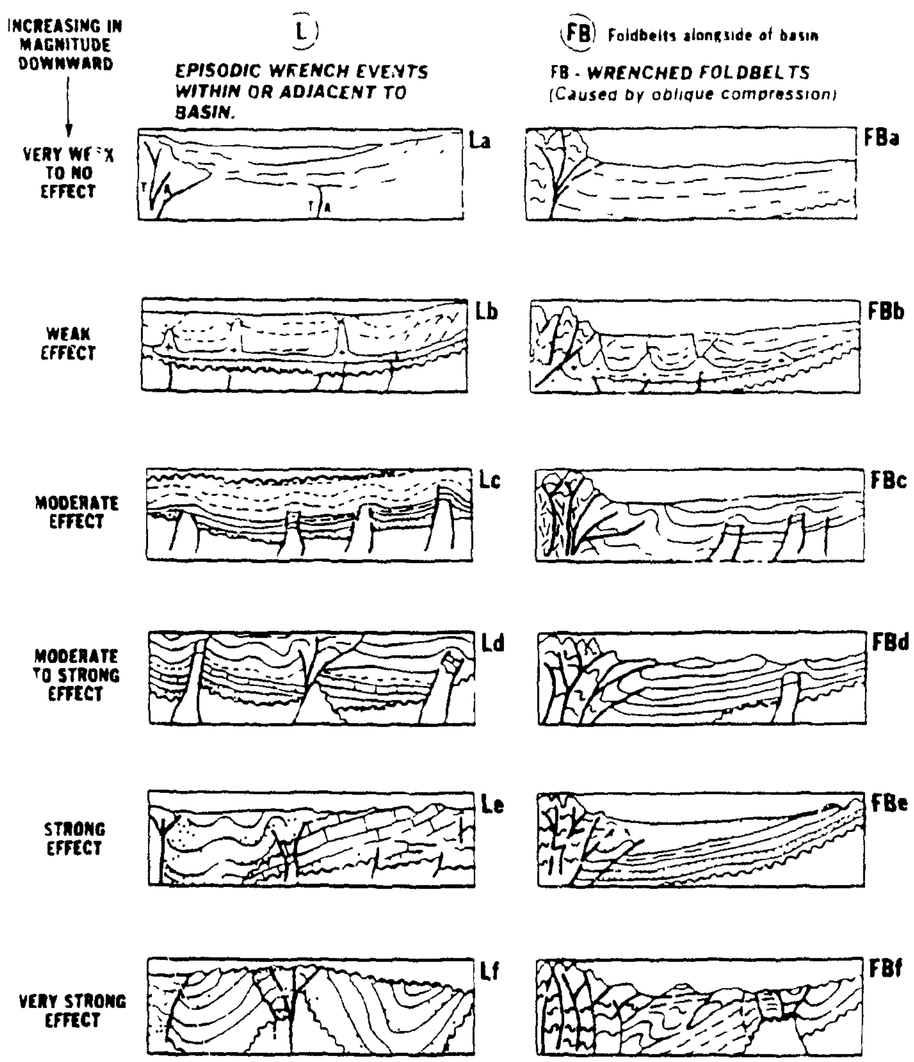


Figure 6.11: Modification of sedimentary basins by subsequent tectonism (after Kingston et al., 1982).

CHAPTER 7

METALLIC MINERAL RESOURCES OF THE CUMBERLAND BASIN AND IMPLICATIONS FOR THE MARITIMES BASIN

7.1 INTRODUCTION

The mineral occurrences of the Maritimes Basin can divided or classified into numerous types based on the host-rocks and the style of mineralization. In section 7.2 types of mineralization occurring in the Cumberland Basin study area are considered. For the purpose of discussion, the various the types or styles of metallic mineralization can be grouped together, on the basis of their inferred genesis, into a three genetic affinities. In chapter 1 of this thesis the concept of genetic affinities (groups) for metallic mineral deposits in the Maritimes Basin was introduced. Models or affinities are examined here and evaluated in light of the thermal and geological constraints established in chapters 2-6 (Fig. 7.1). This chapter synthesizes the essential character of the resources within a milieu of evolving genetic models of mineralization, regional tectonics and sedimentation (Figs. 7.1, 7.2). Every effort has been made to balance the treatment of these complex and often controversial subjects by incorporating and integrating previously published data within the context of the thermal and basin development theories generated through this study.

7.2 METALLIC MINERAL OCCURRENCES OF THE CUMBERLAND BASIN

The mineral occurrences in the Cumberland Basin area (Fig. 7.3) can be classified into several types: (1) sandstone-hosted (redbed) Cu, Ag, Zn, Pb, Co, Ba stratiform; (2) sandstone and shale-hosted uranium occurrences; (3) carbonaceous shale/limestone-hosted unconformity related Cu-Ag; and (4) fault-related Cu, Pb, Zn, Ba mineral occurrences. Also, potential exploration environments, as yet undocumented, may include: (i) carbonate-hosted Pb-Zn; (ii) carbonate-hosted Pb-Zn-Ag-Ba mineralization related to faulting; (iii) paleoplacers of Au and Sn; (iv) unconformity related sandstone-hosted Pb-Zn-Ag mineralization where grey carbon-rich sandstone onlaps basement; and (v) sulphate-hosted Ba, Sr deposits (Fig.7.4).

Whereas most of the metallic mineral occurrences in the Cumberland Basin thesis area are sandstone- and shale-hosted redbed Cu-Ag deposits, the focus of this economic geology section deals mostly with these deposits. The approach taken here is to examine the occurrences of the Cumberland Basin in some detail and then to make inferences based on this information as it relates to the Maritimes Basin as a whole.

7.3 GEOLOGICAL SETTING OF THE MINERALIZATION

7.3.1 Cu-Ag SANDSTONE-HOSTED OCCURRENCES

The Cu-Ag occurrences (chalcocite, bornite) most commonly occur at, or near, the base of fining-upward fluvial sequences (Dunsmore, 1977a), where most of the coalified plant material is concentrated in channel lags. This is an important consideration, because it means that the best mineral concentrations occur within the channels; and therefore, the channels must be traced in order to attain the best results. Brummer (1958) suggested that the chalcocite formed as a result of supergene enrichment, and that its vertical extent is limited to the local depth of the groundwater table. If true, this would seriously limit the size of the potential deposits. However, more recently Ryan and Boehner(1986) observed chalcocite in drill core to a depth of 440 m, thus challenging a simple supergene (shallow) enrichment interpretation. These copper occurrences have varying amounts of associated minerals present. At some localities high grade grab samples have up to 10 ounces per ton Ag, up to several hundred ppm Co, and up to 0.5 ounces per ton Au has been reported although values of 100 ppb are the norm.

7 3 1 1 Canfield Creek Cu Deposit

The best example of redbed sandstone-hosted Cu-Ag mineralization occurs at the Canfield Creek prospect (Fig 7 5) The Canfield Creek deposit is situated in the central portion of the Cumberland Basin in northern Nova Scotia, approximately 5 km south of the town of Pugwash (Figs 7 6 & 7 7) There is little visible mineralization at this locality, and most of the information on the deposit is derived from the drill cores. The continental clastics of the Mabou, Cumberland, and Pictou groups overlie the marine Windsor Group strata. In the central portion of the Cumberland Basin the Upper Carboniferous clastic strata are pierced by a series of diapiric evaporite domes The Canfield Creek prospect flanks one of these domes (Fig 7 6).

The Canfield Creek deposit has 300,000 tons of 1 2% Cu with minor zinc and silver showings (O'Sullivan, 1981). The deposit has not been tested at depths greater 120 m, and is open enued in at least two directions. There are two surface occurrences of copper in the Canfield Creek area, one 1.8 km west of the drilling, and the other in a geochemical sample trench 1.1 km south of the ore body (Fig.7 6) The drilling at Canfield was initiated because of the occurrence of copper in chip samples from the potash drill hole SR-29-1 which was drilled in 1966 by Scurry Rainbow Exploration. Esso Minerals DDH P1 was drilled close to the old drill hole (SR-29-1) and intersected 8.1 m of 0 53 % Cu at a depth of 74 m in grey sandstone of the Malagash Formation. A follow-up grid drilling program comprising 27 holes, outlined 300,000 tons at 1 2% Cu, with traces of Ag (O'Sullivan, 1981)(Fig. 7.7).

The ore is hosted primarily by a grey medium- to coarse-grained sandstone. The sandstone is cross bedded, variably arkosic, and contains abundant plant debris along bedding planes. The sandstone is part of a multistoried-multilateral channel sandstone sequence, and varies in thickness from 2 to 25 metres (Fig.7 8) The channel sequence sandstones are inter-cross bedded with thin grey mudstones (>30 cm) and calcareous mud chip conglomerates (>70 cm). The mud chip conglomerates represent the basal lags of the channel sequences. These grey channel sandstone bodies occur within a primarily red mudstone overbank sequence of strata. Chandler (1992, pers. comm) has suggested that thin grey mudrocks interbedded within and overlying the mineralized channel sandstone bodies are lacustrine (Fig. 7.8). If his suggestion is correct it may help to explain why the sandstone bodies retained their grey coloration, were pyrite-bearing, and acted as redox boundaries (See also Chandler and Ryan, in prep.).

The ore grade mineralization occurs to a depth of at least 110 m, is up to 5.2 m thick(1.2% Cu), and the mineralized zone appears to be open-ended. The drill hole profile (Fig. 7.8) indicates that the drill holes on the eastern part of the grid may not have been drilled deep enough to intersect the main ore zone. The occurrence of malachite in a geochemical sample trench (see MacDonald et al.,1992) at a higher stratigraphic horizon indicates that there may be stacked horizons of mineralization rather than the single horizon as interpreted by Esso during the original exploration on the property.

The mineralization occurs as disseminated chalcocite (Fig.7.9), chalcocite nodules up to 3 cm in diameter (Fig.7.10), and wispy infillings along parting planes (O'Sullivan, 1981). The mineralogy and paragenesis of the ore minerals is discussed in section 7.3 of this chapter.

7.3.2 UNCONFORMITY SHALE-HOSTED CU-AG OCCURRENCES

In the Cumberland Basin greybeds of continental origin which are part of the Boss Point Formation are usually the first grey horizon overlying a thick succession of redbeds of Early Carboniferous age. Mineralization is common at this boundary (Stea et al.,1986). The Windsor Group marine strata may also have a similar relationship to red clastic rocks of the Horton Group however, this part of the stratigraphic section is not exposed at surface within the basin and therefore discussion will be limited to the better exposed Boss Point Formation shale hosted occurrences. The mineralogy of the ore minerals is almost exactly the same as the sandstone-hosted deposits of the area. The Cu minerals are chalcocite and bornite with minor associated digenite, and covellite. They occur as nodules or as replacement of coalified plant material within the grey siltstones and shales. The Cu minerals are usually closely associated with pyrite, and some traces of sphalerite are also present. A detailed description of the ore mineralogy is presented in section 7.4 of this chapter.

7.3.2.1 Scotsburn Brook Prospect

One of the best examples of this type of mineralization is located at Scotsburn Brook, near Scotsburn, Pictou County (Fig. 7.11). The original shaft sunk in the area prior to 1887 can no longer be seen, it may be represented by a water-filled hole now used for watering cattle. On the small stream near the original shaft approximately 2 m of mineralized mudstone and siltstone are exposed (Fig. 7.11). The mineralized horizon is confined to grey siltstone and mudstone which occurs between two channel sandstones (Fig. 7.12).

Recent mapping in the area has missed both the Fitzpatricks Mountain Fault (shown on earlier series of geological maps) and also has incorrectly assigned the strata at the mineral occurrence to the Claremont Formation (Fig. 7.11), whereas the host rocks of the occurrence should be assigned to the Middleborough Formation. The relationship of the fault to the mineralization is unclear, however there are numerous stream sediment geochemical trends that appear to be related to this fault (Fig. 7.13).

The mineralization occurs primarily as malachite stains in the grey mudstone, although minor amounts of chalcocite-bornite were observed associated with the coalified plant material in the mudrock. Copper values are as high as 3.95% over 50 cm with a grade of 1.66% Cu over a 1.5 m interval. The property is currently under exploration license to Cominco and is being assessed by diamond drilling for its economic potential.

7.3.2.2 Donaldson's Mill Brook Prospect

Another example of this type of mineralization in the study area is the occurrence at Donaldson's Mill Brook (Fig.7.14). This occurrence is hosted in a 3 m thick grey silty-shale, of the Boss Point Formation, which overlies red siltstones and sandstones. The mineralized horizon is approximately 50 to 100 m stratigraphically above an unconformity with red conglomerates of Early Carboniferous age. The mineralization occurs as a 1-3 m thick horizon that contains chalcocite and bornite nodules up to 2 cm in diameter, and as coalified plant stems that have been permineralized by pyrite, chalcocite and bornite. The occurrence has an outcrop strike length of 45 m (Fig.7.15).

The host rock of this occurrence is greenish-grey mudstone and fine siltstone. The mudrocks are finely laminated and contain thin wisps of organic debris along the parting planes. Minor cross laminations are found within the silty beds. The unit is variably calcareous and contains a few rhizoconcretions (calcium carbonate concretions surrounding plant roots), which occur is distinct bands in the mudrocks.

As part of this study, samples from three assay channels were analyzed, and they delineated a 110 cm zone of 1% Cu with 0.25 ounces per ton Ag. High grade grab samples from the occurrence contain up to 17 ounces per ton Ag. This property is currently under exploration license to Cominco as is being assessed for economic potential.

7.4 MINERALOGY OF THE COPPER OCCURRENCES

The mineralogy of the two types of redbed Cu mineralization in the study area (See section 7.2) are extremely similar. Examination of polished thin sections suggests that separate discussions of the mineralogy of the various deposit types is therefore unwarranted, and the following section applies equally to all of the Cu occurrences studied.

Papenfus (1931) demonstrated that the Cu-Ag-U ore in the Cumberland Basin occurs as three different forms: (1) nodules and concretions of chalcocite, bornite and pyrite; (2) chalcocite replacing pre-existing cementing material in the sandstone; and (3) chalcocite and pyrite associated with coalified plant material. In each case, much of the chalcocite occurs as replacement of pyrite and/or rose coloured bornite. Digenite and covellite are also present in minor amounts. Papenfus (1931) demonstrated that many of the chalcocite nodules are pseudomorphs after pyrite nodules, and Shumway (1951) found that many of these chalcocite nodules have pyrite cores.

Where chalcocite, bornite, and pyrite are found in association with coalified plant material, the pyrite occurs originally as: (i) coatings on the coalified plant material, (ii) botryoidal nodules, or (iii) replacement of the plant material. Some well preserved examples of mineralized fossil-wood fragments exhibit replacement of original cell structure by some combination of pyrite, bornite, chalcocite, and digenite (Fig.7.16).

Barite commonly occurs adjacent to or associated with the redbed Cu mineralization as cement or as replacement of coalified plant material, e.g. Treen Bluff. The concentration of barite is generally less than 1% and therefore not of economic importance by itself.

Pyrite occurs as replacement of original coalified plant material, cement, and as small nodules and is replaced or cut by all of the other ore minerals (Fig. 7.17). The polished sections studied do not have pyrite replacing or cutting any of the other ore minerals. Pyrite can rarely occur with sphalerite intergrowths, but only in the absence of the copper minerals. This relationship suggests that at times the pyrite and sphalerite are cogenetic.

Bornite from the Cumberland Basin occurrences always exhibits exsolution or replacement textures (Fig.7.18). Host phase rose-colour bornite can occasionally exhibit basket weave texture with chalcopyrite as the exsolved phase. More commonly rose-bornite is intricately intergrown with chalcocite-dige. as a cogenetic suite or occurs as a roughly cubic network of chalcocite replacing bornite. Bornite often replaces pyrite forming a micro-brecciated sub-cubic network of veinlets emanating from star-shaped blebs (Fig. 7.19).

Chalcocite and digenite occur primarily as replacements of pyrite and bornite, or more rarely as mono-minerallic nodules. The chalcocite can also form in apparent equilibrium with the bornite where mutual replacement occurs. Digenite and covellite are minor constituents of the ore and occur as replacements of pyrite or chalcocite.

The mineralogy of the uranium occurrences associated with the redbed copper is unclear (Chatterjee, 1977), however radioluxographs of the mineralization indicate that the radioactivity occurs as crustified layers enclosing the primary pyrite or Cu-Ag ore minerals. Similar observations were made by MacKay and Zentilli (1976) on samples from one of the occurrences at Black Brook. MacKay and Zentilli found traces of pitchblende surrounding the Cu-sulphides and concluded that the uranium mineralization was later than the Cu. These observations indicate that the uranium mineralization postdates the Cu ores and pyrite and could possibly represent a much later mineralizing event or phase.

Textural relationships of the ore minerals, as observed in polished sections, indicates the following order of mineralization from oldest to youngest : (1) pyrite; (2) sphalerite and pyrite; (3) bornite with traces of chalcopyrite; (4) chalcocite, digenite, barite, and silver (native and within the chalcocite lattice); and later, (5) uranium. There is a possibility that this mineral assemblage could represent a metamorphic post-mineralization overprint. If the timing of heating extrapolated from the burial plots is correct then the mineralization postdates maximum burial and therefore the mineral assemblage should closely resemble the original.

7.4.1 ZONATION

The poor exposure and lack of drilling information for most of the occurrences in the study area makes speculation as to mineral zonation within the occurrences difficult. At the Canfield Creek Cu prospect, where drilling has defined a crudely zoned ore body, there is an upper pyrite-sphalerite zone above the chalcocite ore zone (Fig. 7.8). The configuration of the till Cu and Pb anomalies in the Canfield Creek area suggest similar zonations may occur laterally. The Cu anomalies in the till occur several kilometres east of the ore body and the Pb anomalies occur immediately adjacent to the occurrence. Stea et al. (1986) indicate that the glacial dispersion of the till should be approximately equal for all of the samples in this area, and therefore the displacement of the anomalies in relation to the ore zone may reflect mineral zonations within the occurrence. At Skinner's Cove, Pictou County, a boulder of galena-sphalerite mineralized channel lag was found along the beach, this occurrence may represent a Pb-Zn zone of mineralization adjacent to a Cu-Ag occurrence.

7.5 TEMPERATURE OF COPPER MINERALIZATION

In order to better understand the mineralizing processes for these occurrences attempts to quantify temperature constraints were undertaken as part of this research.

Examination of the polished sections from the various occurrences in the study area revealed a paucity of two-phase fluid inclusions directly correlative to the mineralization, and therefore temperature estimates by this method could not be ascertained.

The mineralogy of the ore does give some constraints to the temperature of mineralization. The cogenetic suite of digenite, chalcocite, and rose-colour bornite strongly suggests a low mineralization temperature. Lur'ye and Gablina (1976) examined and experimented with temperature stability on similar ore suites from the redbed Cu-Ag deposits of the Dzhezkazgan district in the U.S.S.R.; and concluded that these minerals could only coexist, as primary ore, at temperatures less than 75° C.

Vitrinite reflectance studies carried out for the author by the Atlantic Coal Institute, exhibit no significant difference in average reflectance values between the mineralized zones and the coeval unmineralized strata (Ro = 1.0; Fig.5.1). A few slightly elevated values occur in mineralized samples causing a bimodal Ro population (Fig. 5.2), however this variance is rarely greater than 0.20 Ro, and therefore is considered insignificant. Most of the mineralized samples have a unimodal distribution of vitrinite values with a mean Ro = 1.0. Variables other than temperature can lead to vitrinite reflectance variation (Heroux et al.,1979). The variables which might have influenced the samples with bimodal distributions from the study area are: (1) type of kerogen; (2) problems of temperature and time relations; and (3) secondary oxidation. The Cumberland Basin vitrinite reflectance study indicates that the mineralized beds were not subjected to temperatures greater than the normal geothermal gradients which affected all of the strata in the basin, therefore, the temperatures of mineralization must have been low (less than 120° C, based on the diagenetic features of the strata). The time-temperature paths coupled with the age of the reddening of the sandstones (related to the mineralization) suggest that the mineralization occurred in the late Permian or early Triassic at a point after and therefore temperature inferred here are maximum rather than minimum estimates.

7.6 SULPHUR ISOTOPES

Twenty samples were selected for sulphur isotope determinations, twelve from chalcocite, six from pyrite, and two from galena. These samples were collected from four occurrences in the Cumberland Basin. All of the sulphur isotopes are strongly negative and range in value between -29 and -51 permil. These values compare favourably with those of the Dzhezkazgan and the Kupferschiefer deposits (Fig.7.20), which have been interpreted as being derived from oxidizing meteoric waters (Gustafson and Williams, 1981). Strongly negative sulphur isotope distributions are generally considered indicative of sulphide formation by bacterial sulphate reduction (Schwarcz and Burnie, 1973; Haynes, 1986). The sulphur isotope values suggest similar mineralizing conditions for chalcocite, pyrite and the galena mineral phases in all of the occurrences in the Cumberland Basin.

The similarity of the sulphur isotope values between the pyrite and the Cu minerals can occur because of the inheritance of the sulphur isotope signature from the early diagenetic pyrite (cf. Brown, 1971; Gustafson and Williams, 1981). Haynes (1986) suggested that bornite or chalcopyrite would be expected to precipitate with chalcocite during the replacement of pyrite if the reaction was represented by:

$$2FeS_2 + 4Cu^+ + 3O_2 + 2H_2O \longrightarrow 2Cu_2S + 2Fe^{+2} + 2SO_4^{-2} + 4H^+$$

Brown (1971) suggested that the ferrous iron released during this equation might be removed by incorporating iron in the silicates such as chlorite. Haynes and Bloom (1987) suggest on the basin of modelling that bornite and or chalcopyrite precipitation would preclude the appearance of iron-bearing silicates under the pH range, oxygen fugacities, and temperatures likely in the host rocks. Haynes (1986a) suggested that the replacement of the pyrites and the inheritance of their sulphur isotope signature is unlikely because of an absence of bornite and Fe-silicate minerals with the chalcocite from the deposits that he studied. However, in the Cumberland Basin occurrences, bornite and to a lesser extent chalcopyrite are commonly associated with chalcocite. Given the mineral assemblage of the Tatamagouche occurrences it is unlikely that the depth and timing constraints on Cu mineralization proposed by Haynes (1986a) are applicable in the Cumberland Basin.

7.7 GEOCHEMISTRY OF THE COPPER DEPOSITS

In order to better understand these deposits geochemical studies were undertaken as part of this study. The geochemistry of the mineralized rocks in the Cumberland Basin is of general interest however it does not greatly enhance the understanding of the mineralizing processes. The results of the other geochemical investigations have a more direct bearing on the Cu-Ag metallogenesis and are therefore included. Ryan (1991) summarized the ore geochemistry and those readers interested in the results are referred to his paper.

7.7.1 LITHOGEOCHEMISTRY OF THE UNMINERALIZED SANDSTONES

All of the redbed mineral occurrences described in the previous section show a strong correlation with red to grey sandstone and shale colour boundaries. Ryan et al.(1989) and Ryan (1991) speculated that the oxidation and reddening of primary grey sandstones may have liberated the Cu and Ag which form the ore deposits in the area. Sediment dispersal patterns (Ryan, 1985), petrographic studies (Ryan, 1985), quartz surface textures (D'Orsay and Van de Poll, 1985) and stratigraphic correlation (Ryan, 1985; Van de Poll and Ryan, 1985), all indicate that the red sandstones were deposited as grey beds, and that both red and grey sandstones had the same source. Although many other factors may have had an influence on the original geochemistry of the rocks, it is probable that the red and the grey sandstones had very similar original composition. A brief summary of the preliminary results of this study were presented in Ryan et al. (1989), where they have described the geochemical variations in a few of the red and grey sandstones in the Cumberland Basin. In order to better understand the significance of this colour boundary, forty-eight samples of unmineralized red and grey Pictou Group sandstones were analyzed for both major and trace elements (Table 7.1). An additional 15 samples from unmineralized rocks were analyzed for Cu, Pb and Zn (R. V. Kirkham, personal communication, 1985).

Analyses reveal distinct geochemical differences between the red and the grey sandstones. The most striking of the differences between the red and the grey sandstones are: (1) the relative depletion of Cu and Zn in the red sandstones (Fig. 7.21); (2) the increase in SiO_2 in the red sandstones (Fig. 7.22); and (3) the FeO/Fe2O3 ratios (Fig. 7.23). Other variations in composition between the red and the grey sandstones are observed, however, the limited dataset and small variations make such observations difficult to interpret with any reliability.

In the Tatamagouche area the red and the grey sandstones have mean Cu values of 16 ppm and 33 ppm respectively (Fig. 7.22). Cu values for the grey sandstones exhibit no evidence of enrichment, and are in fact lower than the levels of Cu found in similar sandstones from Germany where the mean is 45 ppm Cu (Wedepohl, 1963).

The mean Zn value for the red and the grey sandstones from the Tatamagouche area are 46 ppm and 63 ppm respectively (Table 7.1). Data from other areas in the Cumberland Basin and Prince Edward Island, do not seem to show the same depletion of Zn in the redbeds (Table 7.1), suggesting that the depletion may be limited geographically. Within the Tatamagouche data, the standard deviations are high, and the two subsets could possibly be coincident. However, Zn depletion is found within the red clast subset of the till geochemistry which strongly suggests that Zn in the red sandstones are depleted. Additional analyses should help to quantify the observed depletion.

The total iron content in the red and the grey sandstones is similar. The differences in Fe are in the FeO /Fe_2O_3 ratios. The red sandstones have ratios of <1.2 whereas the grey sandstones have ratios of >1.2 (Fig. 7.23). The differences in the Fe ratios reflect the oxidation event that reddened the sandstones. The fact that the total Fe content of the grey and the red sandstones is the same suggests that the two were originally similar in colour and geochemical composition.

The relatively higher content of SiO_2 in the red sandstones is most likely the result of a slight depletion of other elements from the strata rather than any addition of silica to the rocks.

7.7.2 TILL GEOCHEMISTRY

Upon discovering the significant differences in the geochemistry of the red and the grey sandstones of the study area, it was decided to see if these variations were also discernable in the tills derived from these beds. The Cumberland Basin - Cobequid Highlands Massif area has been subjected to continental glaciation and is now covered by Late Wisconsinan glacial deposits. A south-southwestward ice flow deposited the Eatonville Till over most of the Cumberland Basin (Stea and Finck, 1984) .

Stea et al. (1986) and Ryan et al. (1989) demonstrated that there are significant variations in the element values that are related to the colour of the dominant till clasts. Ryan et al. (1989) divided the Eatonville Till into two subsets based on the colour of the clasts. The two subsets are: (1) till with greater than 80% red clasts; and (2) till with over 80% grey clasts.

The first subset consists of samples with greater than 80% red sandstone clasts and have a mean value of 27 ppm Cu in the clay fraction, whereas the second subset is composed of till samples with greater than 80% grey clasts which have an average of 56 ppm Cu within the clay fraction. A plot of Cu versus Zn for the Eatonville samples (N = 598) exhibits a distinct separation between the red and the grey subset populations (Fig. 7. 24). The distinct subset chemistry of the red clast till and the grey clast till further supports the evidence of chemical variations observed in the smaller dataset of the bedrock geochemistry.

The differences in the Cu values of the two till subsets are proportional to the chemical differences between the red and the grey sandstone bedrock of the area. Differences in the absolute values of Cu in the sandstone bedrock as compared to till occur because the till analyses are from the clay fraction. This clay fraction is composed of comminuted grey and red mudstone in addition to sandstone. The mudstones have higher Cu and Zn content than sandstones, and the relative abundances of the elements in the clay fraction of the tills primarily reflect the geochemical combination of the sandstone and the mudrock metal content.

The regional Cu values for the Cumberland Basin area are very low, which is surprising considering the abundant Cu occurrences in the area. The low values (negative anomalies) reflect the depletion of the Cu from the red beds which are the dominant lithology exposed at surface.

7.7.3 STREAM GEOCHEMISTRY

The stream sediment geochemistry also reflects the differences between the red and the grey sandstone geochemistry in the Cumberland Basin. The stream geochemistry data were divided into two subsets, one for streams that erode predominantly red sandstones and the other for streams eroding grey sandstone-dominated areas. Regional stream geochemistry data were investigated by Ryan et al. (1989). The mean Cu values for the streams in the red and the grey bed areas were 6 ppm and 10 ppm respectively. These data show relative Cu values for red and for grey sandstone areas which are similar to the bedrock and the till geochemical analyses (Fig. 7.25). Ryan et al. (1989) used a Cu-As catchment basin plot (Fig. 7.26) to illustrate distinct variations between the low Cu values of the Cumberland Basin and the relatively higher Cu values from the Cobequid Highlands, and the Minas Basin to the south. The Cumberland Basin shows a paucity of high values and abundant low values. The relatively low values reflect the abundance of redbeds which contain less Cu. The significance of the stream geochemical variations from red to grey sandstone areas is that it demonstrates that the
red sandstone to grey sandstone depletion of Cu is widespread and not a local affect.

7.8 GENETIC MODELS FOR REDBED COPPER DEPOSITS

Various genetic models have been proposed to explain fluid migration related to stratiform redbed-related copper deposits (Kirkham, 1989). In this section various models are introduced so that the reader may evaluate the model for the origin of the copper occurrences in the Cumberland Basin

7 8 1 SABKHA MODEL

A sabkha model invoking evaporitic pumping in a sabkha environment was proposed by Renfro (1974) and Smith (1976) to explain some stratiform copper deposits. This model suggests that evaporitic pumping of fluids in and beneath sabkha environments leaches and concentrates base metals. The metals are usually hosted by carbonaceous, black, stromatolitic supratidal carbonates This model is not applicable to Cumberland Basin copper occurrences because there is no evidence in the rock record of significant deposition in a sabkha environment.

7 8 2 FORMATION DEWATERING DUE TO COMPACTION

Formation dewatering related to compaction of a basin was suggested as a possible origin for stratiform copper deposits by White (1971) and Lustwerk and Wasserman (1989). Updip migration of metalliferous saline formation waters due to compaction within the sedimentary basin is a plausible explanation for many deposits Kirkham (1978) and Ravenhurst and Zentilli (1987) have proposed this kind of mechanism to explain basal Windsor Group carbonate-hosted deposits within the Maritimes Basin The Cumberland Basin redbed copper occurrences do not appear to be related to this process. The Cumberland Basin copper has associated redbeds which are depleted in copper and exhibit no elevation of copper in coeval greybeds. This would not be characteristic of dewatering of the basin because redbeds in the near surface are commonly represented by grey strata downdip and basinward. If metalliferous brine is moving updip why were the reduced beds basinward not mineralized and similarly why are there mineralized horizons of grey strata completely surrounded by red strata. The updip migration of metalliferous reducing basin brines may play a role as a reductant in the mineralizing process in the Cumberland Basin copper occurrences but it is unlikely that they were responsible for the transport of the copper.

7.8.3 GRAVITY HYDRAULIC HEAD AFTER A MARINE TRANSGRESSION

Paleotopographic gravity hydraulic head that persists in underlying fluvial strata after marine transgression have been suggested by Hoyningen-Huene (1963) and Lur'ye and Gablina (1972) as a cause of possible fluid migration process related to stratiform copper mineralization. Groundwater regimes are altered greatly by marine transgressions especially in basins below sealevel. Within the Maritimes Basin the Windsor Group rocks represent the only evidence of major marine transgression. Kirkham (1989) suggested that this mechanism may play a role in the copper mineralization at the Horton-Windsor contact. There is no evidence of major marine transgression during the Upper Carboniferous. A few hints of thin short-duration marginal marine incursions are found in the Sydney area but these transgressions were not significant enough to create a gravity hydraulic head in the underlying strata.

7.8.4 RELEASE OF PRESSURE DURING TECTONISM

Release of basin fluid (brine) pressure during tectonism was suggested by Breit et al. (1987) as a possible explanation for the formation of some of the stratiform copper deposits in Utah and Colorado. Fluids released in this manner would tend to be hot basin brines which would be reflected in the mineralogy of the deposits formed by this mechanism. The copper deposits found in the Cumberland Basin are not consistent with this hypothesis because of the low-temperature mineralogy and because the grey strata down dip of the occurrences have not been enriched in copper as one might expect if the mineralizing fluids were travelling up dip. The possibility remains that the fluids escaped through faults and therefore not reddened the down dip grey strata, however faulting has rarely been documented adjacent to the Cumberland Basin occurrences. Although this mechanism does not explain the redbed copper occurrences in the Maritimes Basin, Ryan and Boehner (1991) suggested that it is probably applicable to basin brine expulsion models for the carbonate-hosted and fault-related deposits in the basin.

7.8.5 THERMALLY INDUCED RISE OF FLUIDS

A decrease in buoyancy and rise of fluids caused by thermal activity has been suggested by Brown (1984), and Jowett (1986, 1989) as a mechanism related to stratiform copper mineralization. No evidence of increased temperatures related to deposits such as those seen at Annels (Hayes et al.,1989) has been documented in the Cumberland Basin examples. The thermal study undertaken as part of this research found no evidence to support a Triassic rift thermal event in the Maritimes Basin. The paleomagnetic studies of the reddening (intricately involved in mineralization) indicate that the development of the hematite predates rifting. The morphology, distribution of the occurrences, and the thinness of the underlying redbed succession are not compatible with a redistribution of copper within the Cumberland Basin by this mechanism. The copper occurrences with the Cumberland Basin are not confined to a particular bed or group of beds.

7.8.6 FLUID MIGRATION RELATED TO DIAPIRISM

The diapiric rise of salt structures causing and permitting fluid migration has been suggested by Light et al. (1987) and Kirkham (1989) as possible mode of fluid migration related to stratiform copper deposits. Diapirism in the Cumberland Basin is syndepositional and therefore predates the copper ore. Redbeds within the basin are secondary (originally grey). The grey sandstones and mudrocks which host the occurrences exhibit no evidence of being re-reduced beds. If the host greybeds were re-reduced by hydrocarbons as suggested for the Dzhezkazgan deposits in the USSR there would be abundant finely disseminated pyrite derived from the hematite. Beds immediately adjacent to diapirs in the Cumberland Basin are redbeds. If the diapir related fluids were migrating up from the diapir the adjacent beds should be reduced. Another feature of the deposits that does not fit this mode fluid migration is that there should be a significant heat flux related to diapirism and yet low-temperature mineral assemblages are found at these occurrences. It is hard to differentiate between the role of the diapirs as sources of chlorides for groundwaters and their possible role in providing brines or reductant hydrocarbons. The lack of evidence for re-reduction of the strata, the absence of hydrocarbons in the host rocks of the deposits, and the presence of similar deposits distal to the diapirs suggests that the mineralization was not controlled directly by fluid migration related to rising evaporite diapirs.

7.8.7 TOPOGRAPHIC INVERSION METEORIC GROUNDWATER FLOW

Topographic inversion and subsequent groundwater flow has been proposed as a possible fluid migration mechanism related to redbed copper deposits (Gaven and Freeze, 1984; Bethke, 1986; and Oliver, 1986). Shockney et al. (1974) and Sangster and Viallancourt (1990) have suggested that this type fluid migration resulted in mineral deposits. This type of fluid movement seems to be compatable with the observations of morphology and nature of the copper occurrences in the Cumberland Basin and will be discussed in more detail in section 7.9 of this chapter.

7.9 GENETIC MODEL FOR THE CUMBERLAND BASIN CU OCCURRENCES

The Cu mineralization occurs at, or near, the boundary between red sandstones and grey sandstones. This spacial relationship implies a genetic link between the coloration of the strata and the concentration of copper. It is therefore very important to ascertain whether the red coloration was primary or secondary in nature. The mudrocks of the study area are mostly red in colour. The presence of abundant soil horizons (calcretes and rooted horizons) and the presence of red mudrock clasts within grey channel lags suggests that most of the mudrocks were reddened by early diagenetic mechanisms while exposed during drier periods on the floodplain. The sandstones, on the other hand, are believed to have remained grey until post-lithification and have [pbeen subsequently reddened by late diagenetic oxidation.

Turner (1980) summarized the criteria for the recognition of secondary redbeds, and many of these are present in the redbeds of the Pictou Group in the Cumberland Basin. Paleoclimatic conditions, as interpreted from quartz grain surface textures, indicate little variation in paleoclimate within the Late Carboniferous red, and grey rocks of the Maritimes Basin (D'Orsay and Van de Poll, 1985). Fossil floral evidence suggests that climatic variations within the Late Carboniferous were minor although Permian flora may indicate a drier climate (Van de Poll and Forbes, 1984). Little or no variation in the style of sedimentation can be observed, when comparing the red and the grey Pictou Group strata.

The most convincing evidence for the secondary nature of the red coloration in the sandstones comes from the paleomagnetic studies (See Section 5 3 5) In the CB most of the red sandstones in the Pictou Group are of secondary origin (Ryan et al , 1989) and paleomagnetic studies carried out as part of this research by Morris and Associates (Morris, 1987) confirmed this hypothesis This work and the work of Symons (1990), Roy (1963, 1966) and Tanczyk (1988) have indicated the magnetization for the Pictou Group strata is late Carboniferous to late Permian in age (Fig 5 11) Care must be taken in the interpretation of data because the fine grained overbank rocks of the Pictou Group are primary redbeds as opposed to the secondary (late diagenetic) red coloration of most of the sandstones (See Chapter 5 for discussion). Morris (1987) suggested that the Cu4 age of the hematization present in the mineralized sandstones is related to late Permian oxidation by mineralizing fluids.

Many of the diagenetic features also suggest a secondary diagenetic origin of the reddening. For example, hematite occurs as grain coatings, however, it is absent at grain to grain boundaries (Fig 7 27) suggesting that the hematite coating post-dated deposition and lithification (cf. Van Houten, 1973). The overbank mudstones immediately below red channel sandstones are commonly grey to green in colour, which indicates reducing conditions prevailed during sedimentation Other features such as the near-absence of primary ferromagnesian minerals in the redbeds, the alteration of siderite and pyrite concretions to hematite, the occurrence of reddened plant material, and the replacement of coal material by carbonates, all indicate secondary diagenetic reddening Vitrinite reflectance studies carried out for the author by the Atlantic Coal Institute on 10 correlative red and grey rocks, also suggest that the red coloration may be secondary The vitrinite in the red beds has been oxidized, at some time, after the regional basin maturation was achieved Clay mineralogy XRD studies (Colwell, 1987) were carried out on the same samples as part of this study The red sandstones usually contained zeolites whereas these minerals were absent in the grey beds The presence of these zeolites suggests that the redbeds underwent a thermal or oxidizing event that did not appear to affect the grey strata.

Van de Poll and Ryan (1985) suggest that the reddening is diachronous, and it occurs from the top down, as is the case in the redbeds of the Upper Coal Measures of the United Kingdom

(Trotter, 1954; Mykura, 1960). Archer (1965) and McBride (1974) proposed that such reddening events result from the syndepositional lowering of the water table and the development of well drained, oxygenated conditions within a basin. Contrary to the vertical interpretation of reddening proposed by Van de Poll and Ryan (1985), it is more reasonable to assume that lateral infiltration of oxidizing fluids occurred in permeable sandstone aquifers as opposed to downward percolation through relatively impermeable mudrock interbeds.

The arid conditions that prevailed at the time of the Permian-Triassic transition in the Maritimes Basin area (cf. Van de Poll, 1978), could possibly be responsible for the reddening of the Pictou strata. Under these circumstances, in a basin margin onlap setting, oxygenated surface water runoff from the Cobequid Highlands may have flowed into the sandstone aquifers and flowed to the north forcing the interface between the basinal waters and the oxygenated groundwater deeper into the basin (Fig.7.28). The timing of these event apparently corresponds to the erosion event documented by the fission track study. Rose (1976) and Rose and Bianchi (1985) have demonstrated that, at low temperatures oxygenated groundwater is an efficient transport medium for metallic ions, especially when chloride or carbonate complexes are present in the groundwater. Early Carboniferous salt-evaporite diapirs of the Windsor Group occur in the Tatamagouche area and may provide the chloride and carbonate to form complexes necessary to facilitate transport of the Cu and Ag (Fig. 7.29). Haynes and Bloom (1987) suggest that alluvial fans which contain basalt or granite-rhyolite lithic fragments can generate metal-transporting fluids. The sandstones and pebbly sandstones of the Upper Carboniferous strata of the Cumberland Basin contain abundant lithic fragments of both basalt and granite-rhyolite composition. The breakdown of these lithic fragments can also generate the metals necessary for mineralization (Haynes and Bloom,1987). Zielinski et al. (1983) have demonstrated, in a study of redbeds, that metals migrate from detrital phases in the sediment to secondary ferric oxides. These authors also suggest that leaching of the metal fraction will increase with the intensity of the ferric iron production. Although no depletion was observed by Zielinski et al. (1983) from their examples, it is clear that the depletion of the Cu in the redbeds of the Tatamagouche area are consistent with the leaching mechanism which they proposed. Lur'ye (1978) points out that if highly oxidizing groundwater is transporting the Cu, the physicochemical parameters lie outside of the stability field for Cu(I) therefore, high chloride concentrations are not required to increase the copper level in the solution. Boyle (1968) suggests that the most likely sources of Cu-Ag for redbed deposits were: (1) volcanogenic beds, (2) petroliferous shales, dark mudrocks and limestones, and (3) the redbeds themselves. Boyle (1968), Lur'ye (1978), Zielinski et al (1983) and Haynes and Bloom (1987) postulate that redbed Cu-Ag deposits need no external source for the Cu-Ag because deep intense weathering and leaching would liberate enormous amounts of these elements under oxidizing conditions and these metals would be absorbed by Fe and Mn oxides and clays. Later diagenesis and groundwater movement would reconcentrate the Cu-Ag at redox boundaries creating redbed mineralization. The observations of the various workers, based on geochemical principles, led all of them to the conclusion that, in most cases, the Cu-Ag in redbed Cu-Ag deposits comes from the sedimentary pile itself. Holmes et al. (1983) similarly propose, based on geochemistry and petrography of mineralized and unmineralized sandstones of Triassic age from England, that redbed mineralization involves the dissolution and release of trace metals from the detrital minerals during diagenesis. They suggest that the metals are retained in saline interstitial solutions which migrate to suitable sites where precipitation and deposition occurs by reaction with trapped hydrocarbons or reducing sulphur. The details of composition and the thermodynamics of transport and precipitation of the Cu ores is beyond the scope of this study, however the composition may be assumed to be similar to the proposed by Haynes and Bloom (1987; Rose, 1989). Haynes and Bloom (1987) suggest that although the metal-transporting fluid compositions are based on the hypothesis of 50 cm depth at a temperature of 25°C, the compositions are applicable to later diagenetic processes up to 100°C.

The geochemical characteristics of the rocks, tills and stream sediments in the Cumberland Basin are consistent with Cu-Zn depletion in Pictou Group redbeds. The till and stream sediment samples delineate large areas of low Cu values throughout the Cumberland Basin, which is unexpected considering the numerous Cu-Ag occurrences. The depletion of Cu and associated elements within the reddened strata, and little evidence of anomalous Cu values in the grey beds, except in close proximity to redbeds, strongly suggest diagenetic model of ore formation.

7.9.1 SOLUTION FRONTS

The Cu-Ag solution front deposits described by Shockney et al. (1974) for the Paoli, Oklahoma area appear to be similar to mineralization of the occurrences in northern Nova Scotia. The redbed Cu deposits of New Mexico, in particular the Nacimiento Deposit (LaPoint, 1979) and the Dzhezkazgan Cu-Ag deposits of the U.S.S.R. (Baskov, 1987), also show striking similarities to the occurrences in the study area. These occurrences have cogenetic bornite and chalcocite with strongly negative sulphur isotope values. The Tatamagouche and these occurrences differ from many other redbed Cu deposits in that they represent Cu mineral replacement of original early diagenetic pyrite.

In the proposed model (Fig. 7.30) the Cu and Ag were subject to selective leaching and transport during the diagenetic reddening event by mechanisms similar to those proposed by LaPoint (1979) for the New Mexico redbed Cu-Ag deposits. These metal-bearing solutions migrated until they encountered reducing conditions. The reducing conditions necessary for precipitation occur primarily: (1) where sufficient coalified plant material and pyrite was preserved within the channel lags; (2) at contacts with pyrite-bearing organic-rich grey shales; and (3) presumably at the interface between the oxidizing groundwater and reducing basinal fluids (Fig. 7.28). In the Dzhezkazgan redbed Cu-Ag district of the U.S.S.R., the grey strata are interpreted as being re-reduced by hydrocarbons (Baskov,1987). The physicochemical parameters for migration of metal-bearing solutions in these strata are very similar to those proposed for the Nova Scotia examples, however, the Nova Scotia occurrences do not contain any evidence of a secondary origin for the greybeds.

7.9.2 UNCONFORMITY KUPFERSCHIEFER TYPE

Kupferschiefer deposits are named for the mining district at Mansfeld in Germany. The name refers to the "copper shales" which were first mined around 1199 and are still being mined today. The term Kupferschiefer comes from the fact that the deposits are hosted by grey to black organic-rich shales and carbonates. These shales typically overlie red sandstone sequences and therefore form a natural reduction oxidation boundary. Jowett (1989) provides a succinct summary of the evolution of ideas as they relate to the genesis of these deposits. The term Kupferschiefer-like as referred to herein refers to the fact that the deposits are shale-hosted Cu deposits that are hosted by the first grey bed overlying a thick redbed succession of rocks. The fine-grained grey strata act as a site for reduction of metal-bearing solutions migrating upward out of the red strata. Kupferschiefer deposits have been interpreted as resulting from mineralizing brines from the underlying redbeds that migrate updip to the organic-rich beds by convective flow, in response to rifting (Jowett, 1986, 1989). The metal-bearing solutions in the Cumberland Basin are interpreted to be due to oxygenated groundwater downdip flow from the basin margins or from fault zones and therefore although similar in geological setting the mechanisms of mineralization differ from the European examples. Chemistry of the groundwater was similar to that proposed for the solution front mineralization of the area. The similarity of mineralogy and proximity of this type and the solution front mineralization suggests that the mechanism of transport and deposition of Cu and Ag were also similar. It is proposed that the chloride-bearing oxygenated groundwaters entered the red coarse clastics that underlie the Boss Point Formation, leached and transported Cu-Ag as chloride or carbonate complexes out of the redbeds, and precipitated the metals at the redox boundary with the overlying pyrite-bearing grey shale beds. The relative importance of updip migration of basin brines is difficult to assess for these occurrences, although some influence on mineralization may be assumed (Fig. 7.31). The economic potential of this type of occurrence is very significant because of the high probability for lateral continuity of the mineralized horizon.

7.10 EXPLORATION MODEL FOR THE CUMBERLAND BASIN CU OCCURRENCES

Figure 7.32 outlines the response of the various geochemical methods in the Cumberland Basin and should be a guide to expected results in similar geological settings.

Exploration for mineralization should take into account the following criteria and procedures: (1) large areas containing regionally low Cu values (negative anomalies) that contain numerous Cu-Ag occurrences have a good potential for this type of mineralization; (2) the presence of red to grey colour boundaries is essential for this type of mineralization; (3) the grey horizons are usually found in association with coalified plant material in channel lags, at the interface with reducing basinal waters and in zones where H2S and hydrocarbons were trapped adjacent to evaporite diapirs; (4) small positive anomalies can be found by combining bedrock prospecting, till geochemistry, and stream sediment analyses; (5) many of the smaller occurrences are associated with channel lags and therefore sediment dispersal patterns and fluvial modelling must be undertaken to define the distribution of the carbon-rich (potentially mineralized) zones; (6) drilling programs should be carried out on a closely spaced grid pattern to maximize the potential for intersection of the mineralized channel lags; (7) exploration for grey to red boundaries of greater extent, like those in the Dzhezkazgan USSR region, e.g., adjacent to diapirs, and at basinal facies transitions, should be carried out to maximize the potential tonnage of such deposits.

The integration of geochemistry with sedimentology and geological mapping provides the basic data necessary to suggest a exploration models for these Cu-Ag-U occurrences. The association of Au with these occurrences enhances their attractiveness as exploration targets. Stream sediment gold anomalies in the study area (Ryan, 1988), with several values greater than 860 ppb, can, for the most part, be correlated to the conglomeratic units and therefore are believed to be related to paleoplacer gold enrichment (Ryan, 1988). However, numerous anomalies in the area north of Pugwash, near Northport, Cumberland County, may be related to remobilization of gold by solution fronts. Although there are no documented mineral occurrences in outcrop in this area, several Cu-bearing mineralized boulders have been found along the beach. In support of the Au mobilization hypothesis, Boyle (1968) and Maynard (1983) suggest that under the conditions of redbed Cu mineralization Au should be geochemically mobilized along with the Cu and Ag.

The Cu-Ag occurrences and deposits in the Cumberland Basin are related to diagenetic reddening caused by the percolation of oxygenated groundwaters. The reddening of the sandstones within the sedimentary succession liberates Cu-Ag and associated minerals and deposits them at a boundary with reducing grey strata or where the groundwater mixes with basin brines. All of the deposits in the Maritimes Basin that are associated with groundwater mobilizing the metallic ions and redepositing the elements at redox boundaries can collectively be referred to as groundwater diagenetic deposits. This group or type of deposit is referred to in chapter 1 as genetic affinity type 3, stratabound shale and sandstone-hosted deposits.

The following conclusions can be drawn from the study:

1) There are numerous known Cu-Ag mineral occurrences within the study area, and more to be discovered;

2) Some of these occurrences contain high concentrations of Ag, Au, Co, etc. which may enhance their eventual economic potential;

3) The ore mineralogy and the vitrinite reflectance studies indicate a low temperature of mineralization (< 100°);

4) Bedrock, till, and stream sediment geochemistry indicate that there are low values of Cu in the redbeds of the area;

5) Diagenetic indicators, surface textures, paleobotany, sedimentological features, sediment dispersal patterns, vitrinite reflectance, and paleomagnetics indicate that the red coloration of the sandstones is a late diagenetic feature;

6) The mineralization occurs at or adjacent to red-grey boundaries;

7) Sulphur Isotopes indicate mineralization was sulphur produced by bacteria;

8) The grey sandstones are not enriched in Cu Ag or Zn relative to the normal concentrations for similar rocks elsewhere;

9) Mineralization was diagenetic with the Cu, Ag, Zn, U being leached and transported during the reddening event and deposited at the redox boundaries;

10) If laterally extensive redox boundaries can be defined within the study area they will delineate areas which may have great potential as hosts for large ore deposits.

7.11 POSSIBLE IMPLICATIONS OF THIS STUDY ON THE METALLOGENESIS OF THE MARITIMES BASIN

The following section places the mineral occurrences of the Cumberland Basin into the context of the larger Maritimes Basin. Late Paleozoic metallogeny is intimately linked to the complex sedimentary and tectonic history of the late Paleozoic and early Mesozoic to Cenozoic basins. The stratigraphy and tectonic setting of the basins are summarized diagrammatically in Figure 7.36. Late Paleozoic to Mesozoic rocks in Atlantic Canada record a complex history of sedimentation, tectonics and volcanism in the northeast Appalachians. The strata contained within these successor basins reach a maximum thickness of 12 km (Howie, 1988) in the central Gulf of St. Lawrence (Magdalen Basin). They are a complex molassic succession dominated by continental deposition (Fig.7.32). Sediments were derived both locally (especially in the Late Devonian and Early Carboniferous) and regionally (Late Carboniferous) from the Appalachian Orogen. These transient source areas and shifting depocenters represent the waning stages of the Devonian Acadian Orogeny and the subsequent uplift of the orogen following the docking of the Avalon Composite Terrane and the Meguma Terrane (Fralick and Schenk, 1981). The early Mesozoic records the initial rifting phase of the Proto-Atlantic Ocean and the late Mesozoic to Cenozoic records its subsequent opening. Nova Scotia is roughly bisected by the Cobequid-Chedabucto Fault System which separates the Avalon and Meguma terranes. Consequently the diversity of mineral deposits reflects the complexity inherent to this tectonically active setting.

The previous sections of this chapter have examined examples of the unconformity and groundwater related deposits from the Cumberland Basin. Included below are brief descriptions of the other important mineral deposits occurring in the Maritimes Basin.

7.11.1 BASE METAL AND BARITE DEPOSITS

Carbonate-hosted occurrences and deposits are most numerous and widely distributed in the pre-Westphalian basin fill (Gays River, Walton and Scotsville) and are especially common near the basal carbonate of the Windsor Group. Although genetic interpretations of various authors are not always consistent, data compiled from numerous reports describing discordant mineral deposits in late Paleozoic basins indicate a close spatial and temporal relationship with late Carboniferous tectonism. Many of the more significant occurrences and deposits are discordant to stratabound, carbonate-hosted (replacement and space fill), at or near the base of the Windsor Group (Macumber or Gays River Formation) or are hosted within pre-early Westphalian basin fill (and locally basement?) within or near the Cobequid-Chedabucto Fault System and its subsidiaries. They have general characteristics compatible with, but not exclusively indicative of, classification as diagenetic-epigenetic. The major source of mineralizing fluids, furthermore, is consistent with derivation within the basin system during a Late Pennsylvanian tectonic episode and possible accompanying elevated geothermal gradients.

The mineral assemblages and mineralization styles are diverse giving the illusion that they are genetically unrelated. Definite differences in the details of the mineralization style occur however, when considered as a time constrained metallogenetic unit these deposits can be grouped together as a family, such as the case of mineral deposits described by Dunham (1978) in Carboniferous basins in Great Britain (e.g. Pennines). The variations in mineralizing style and mineral assemblages generally reflect: (1) contrasts in basin fill competency and permeability and subsequent related fracturing and fluid flow patterns and (2) the complex and evolving mineralizing fluid system in general and the interaction with local physio-chemical conditions at the mineralized sites in particular.

7.11.1.1 Gays River Pb-Zn Deposit

The most comprehensively studied of this type of deposit in the Maritimes Basin is the Gays River Pb-Zn deposit which is the largest economically significant carbonate hosted deposit. The deposit is located in the Gays River Bank complex between the Shubenacadie and Musquodoboit basins. The buildup extends for approximately 10km along strike, is variably mineralized with several major economic zones containing galena and sphalerite at Gays River and a smaller satellite zone in the southwest extremity near Dutch Settlement. The Gays River deposit is hosted by the basal carbonate of the marine Windsor Group. The mineralized carbonate is a dolomitized algal bioherm bank which developed on a basement topographic high of the Meguma Group. The mineralization is a replacement of the original carbonate. The replacement of the carbonate by the sulphides was a relatively rapid event given the very fine grained nature of the sulphides, especially the sphalerite. In some instances sphalerite completely permineralizes fossils within the carbonate and preserves many of the delicate structures of the fossil. The mineralization is concentrated around the periphery of the bank (or reef) and the high grade massive ore appears to be restricted to areas adjacent to a Cretaceous paleokarstic trench at the interface with the overlying gypsum and anhydrite (Fig. 7.33). Akande and Zentilli (1984) also noted the presence of high grade brecciated shoots of ore within the interior of the bank. These do not represent significant reserves, however they may be important clues to aid in interpretation of the origin for the deposit. The bank is flanked by, and was formerly overlain by a thick anhydrite dominated evaporite package. At present, the carbonate is overlain by unconsolidated early Cretaceous sediments and Quaternary glacial deposits. The complex paleokarst fill penetrates a solution trench to nearly 100m down the evaporite-carbonate contact.

The major mineralized zones at Gays River extend in an area roughly 3.5km x 200m and range from 1 - 40m thick (average 6.5m). Reserves are approximately 12 million tonnes of 7% Pb + Zn. Total production has been 0.9 million tonnes (1978-1981), additional high grade ore has been mined by Westminer Canada Ltd. in the last few years. The most abundant ore minerals are galena and sphalerite and the trace to minor accessory minerals include: chalcopyrite, pyrite, marcasite, calcite, barite, fluorite, and bituminous organic material (petroleum). Akande and Zentilli (1984) described the following genetic history: (1) host dolomitization + diagenetic marcasite (early Carboniferous- Visean) (2) after an undetermined period of time there was an infusion of hydrothermal metal rich brine into a porous, hydrocarbon saturated? reservoir constrained by impermeable evaporites, (3) precipitation of sphalerite, galena, chalcopyrite and calcite in the fractured porous dolostone (4) breaching of evaporite seal (late Carboniferous?) allowing escape path for hydrothermal fluids (5) post ore calcite, fluorite, barite, marcasite, pyrite and selenite. (6) uplift exposure and erosion dedolomitization, faulting, karstification during the early Cenozoic (Cretaceous).

Isotopic, thermal, and petrographic studies have been undertaken by numerous workers (Akande and Zentilli, 1984; Ravenhurst et al., 1988, Arne et al., 1990; Kontak, in prep.). The results of these studies indicate that the chemistry and thermal constraints posed by the research is consistent with a basin brine mineralizing fluid. Ravenhurst and Zentilli (1987) suggested that a hot basin brine expulsion event may have caused the stratiform carbonate-hosted mineralization in the MB. Carbonate diagenetic studies by Savard (1991, 1992, in prep.) indicate that the carbonate paragenesis is consistent with this working hypothesis. Recent work on the REE of the carbonates and the fluid inclusions of the deposit by Kontak (1992, in press) suggests that there may have been a significant reheating of the deposit post mineralization and he suggests that the mineralization may not be related to a basin brine expulsion event. The purpose of this study was not to confirm a basin brine expulsion mode of origin for the stratiform carbonate deposits of the Maritimes Basin but rather to thermally constrain such hypotheses. The debate on the origin of these deposits is left for other workers; this study merely places thermal constraints on the timing of the various mineralizing events.

7.11.1.2 Walton Ba-Pb-Zn-Cu Deposit

The Walton Deposit is another significant occurrence of carbonate hosted mineralization. Numerous base metal, silver, barite, manganese and iron deposits and occurrences occur near the structurally disturbed Horton-Windsor Group contact. The occur in a 10km long area located along the northern border of the Kennetcook (Windsor) Basin between Cheverie and Tennycape. This area is extensively faulted and folded and is situated with 10-20km of the Cobequid Chedabucto Fault Zone and immediately south of the superimposed early Mesozoic Bay of Fundy Rift.

The Magnet Cove (Walton) deposit near Walton is the largest and is hosted by basal Windsor Group Macumber Formation limestone and limestone breccia (Pembroke) and overlying anhydrite/gypsum. The deposit occurs as adjacent but discrete steeply plunging (rakes 35 degrees to the east) pipe-like massive fine-grained barite with an underlying down dip massive sulphide body. It is situated in a complex brecciated "s" shaped fold at the intersection of east-west and northwest trending fault sets. Brecciated ore indicates some post-ore fault movement.

The deposit has a pear shaped, lensoidal outline near surface and extends to a depth of 500 m+, has a length of 500m + and ranges up to 50 metres thick. The barite body (and underlying sulphide body) has Tennecape Formation (Visean?) redbeds as a hanging wall, and extends to a depth of approximately 330m. Below this point only the sulphide body continues and the hanging wall is anhydrite/gypsum. A mining breakout into the water saturated mud-redbed hanging wall limited mining to the section above the 1030 foot level (314m) although the sulphide zone extended to at least the 1650 foot level (503m). Approximately 4.5 million tonnes of greater than 90% $BaSO_4$ were produced. Between 1961 and 1970, 360,000 tonnes of sulphide ore grading 0.56% Cu, 4.33% Pb, 1.44% Zn and 11 oz./tonne Ag were produced.

Five types of mineralization (dominantly structurally controlled) were described by Boyle et. al. (1976): (1) Macumber (Pembroke) limestone-hosted massive barite and massive sulphides at Walton (Magnet Cove deposit), (2) Macumber (Pembroke) limestone (locally Horton sandstone) hosted barite-siderite without sulphides associated, (3) Macumber Horton limestone-sandstone hosted manganese, manganite-pyrolusite, (4) Macumber-Horton limestone-sandstone hosted iron, hematite-limonite (setting similar to 3), (5) Horton sandstone hosted chalcopyrite, pyrite, malachite-atacamite. Sabkha-like nodular textures in stratiform barite has recently been reported by Mossman and Brown (1986) from barite zones in the Walton-Cheverie area. They suggested that a barite may have been replacing nodular anhydrite in a ferroan dolomite host.

The mineralogy, zonation, geochemistry and genesis of the deposit has been described in detail by Boyle (1972) and Boyle et al. (1976). The mineralogy is complex comprising: barite, siderite, pyrite-marcasite (Ni enriched), galena, sphalerite, chalcopyrite, and silver minerals including: tennatite, prousite, pearceite and acanthite, various manganese oxides and hematite. Associated secondary supergene minerals at Walton include: limonite, various manganese oxides, malachite, jarosite, erytherite, moorhousite and apolowite. In addition, there are locally abundant hydrocarbons present as liquid petroleum and carbonaceous material associated with the barite and sulphide mineralization.

Boyle (1972) and Boyle et. al. (1976) describe the paragenesis from oldest to youngest as: 1) siderite and/or barite, 2) replaced or veined by pyrite and marcasite, 3) sphalerite, galena, chalcocite, tennatite, prousite, pearcite and stromeyerite, and 4) the supergene minerals. A vertical zonation was described and related to deposition under different oxidation-reduction conditions. Manganese siderite, sulphides and sulphosalts were deposited at depth under reducing conditions, with manganese and iron oxides, and calcite in near surface oxidizing conditions. Barite occurred in both environments replacing the gypsum/anhydrite.

According to Boyle et al. (1976) the mineralogy-geochemistry is unusual for sediment hosted redbed-carbonate-evaporite environment in the Carboniferous in that it is so highly enriched in Ag (copper-silver sulphosalts with low As) and the geochemical similarity to Ni-Co arsenide and native silver deposits of the Cobalt Ontario Type.

Isotopic and fluid inclusion data indicate the barite (fluid inclusion = 187°C Ravenhurst et al.,1987) may not have been contemporaneous with, or the same origin as the sulphides. The sulphur isotopic composition for the sulphides and sulphosalts are - 0.9°/oo to - 39.6o/oo and is a sulphur source linked to biogenically altered (reduced) deep brines (Boyle et al.,1976). The barite composition in contrast is +33.6°/oo to +5.7o/oo similar to the replaced basal anhydrite of the Windsor at +19.1/oo (average).

Boyle (1972) and Boyle et al. (1976) described a mineralization model for the diverse mineral occurrences and deposits in the Walton-Cheverie area. During the late Carboniferous, tectonic activity including faulting and fracturing related to the Cobequid-Chedabucto Fault Zone allowed penetration and circulation of brines and connate water. These fluids derived primarily from dissolved Windsor Group evaporites, moved into the underlying red and grey continental clastics of the Horton Group. Mineral deposit related elements were leached for an extended period of time. The fluids were mobilized, accelerated or triggered by elevated geothermal gradient driven circulation and tectonism (rifting? and volcanism). The fluids were moved and expelled through various pathways, especially fault-fracture systems and reacted with chemically replaceable rocks. These reactive rocks were especially abundant at the Horton-Windsor contact with the Macumber

Formation limestone, Pembroke limestone breccia and the overlying basal anhydrite as primary hosts and aquacludes. Syn- and post- mineralization tectonics together with near surface dissolution-karst processes have further complicated the original complex geology. Lydon (1978) drew a structural comparison of Walton to deposits at Silvermine in Ireland and the Meggen deposit in Germany. A key structural link was made to the major faults and their prolonged movement history.

7.12 GENETIC AFFINITIES IN THE MARITIMES BASIN

The purpose of this study was not to determine the detailed nature of the deposits but rather to provide time-temperature constraints on the mineralization of the basin. It is beyond the scope of this study to examine in detail the various mineral deposit types found within the Maritimes Basin and therefore only brief summaries of two deposits were included in section 7.10, in order to demonstrate the variability of the deposits. In Chapter 1 the concept of three metallogenetic affinities for the Maritimes Basin was introduced. Most of the Late Paleozoic mineral deposits may be divided into three main genetic affinities: (1) related to sedimentary processes with a possible sedimentary exhalative event during the Visean, (2) related to large-scale basin tectonics and diagenetic hot-fluid migration within basins, and (3) related to near surface groundwater diagenetic processes. Following is a brief discussion of the rational behind the classification of the occurrences into the various genetic affinity types.

7.12.1 GENETIC AFFINITY 3 NEAR SURFACE GROUNDWATER RELATED

The sandstone-hosted and shale-hosted deposits are closely related to unconformities (depositional hiatus), paleoclimate, and groundwater processes. The diagenetic-syngenetic stratabound deposits occur locally in the early Westphalian strata (Yava) but more commonly as redox redbed solution fronts in: (1) late Tournasian-early Viséan rocks, especially near the Horton-Windsor Group contact, and (2) in late Westphalian to Stephanian strata (see section 7.9). Ryan and Boehner (1991) in a preliminary report on this study suggested that the sandstone and shale hosted Cu occurrences of the Cumberland Basin can be grouped together with the Yava Pb in sandstone occurrence as well as Kupferschiefer-like Cu occurrences at the Horton to Windsor Group contact All of these occurrences share the common characteristic of being hosted near a reduction-oxidation boundary. Although the occurrences at the Horton-Windsor contact are numerous they are of little economic significance and should not be confused with the Pb-Zn-Cu or Ba deposits hosted by the Windsor carbonates (see section 7.11.2). For the purpose of this thesis the emphasis is placed on the sandstone-shale hosted occurrences of the Westphalian to Permian strata and their relative timing.

7.12.2 GENETIC AFFINITY 2 HOT BASIN-BRINE EXPULSION

Even though there are obvious differences in the characteristics of the deposits several workers (Ravenhurst and Zentilli, 1987; Ryan and Boehner, 1991) have grouped the various occurrences together on the basis of the empirical, spacial and temporal similarities Ravenhurst (1987) explained many of the Pb-Zn-Cu and barite deposits of the Maritimes Basin as being the result of fluid expulsion due to basin dewatering. He postulated that hot basin-brines carried metallic ions from the basin centre to the flanks of the basin where they were deposited in suitable hosts (mostly carbonates at the base of the Windsor Group). Ravenhurst and Zentilli (1987) suggested on the basis of modelling that the weight of the sedimentary pile forced the basin fluids towards the basin margins. Ryan and Boehner (1991) tied the fluid expulsion events not only to the weight of the sedimentary cover but suggested that the Late Paleozoic tectonics of the Maritimes Basin may have influenced the timing of the expulsion events and further suggested that fault related deposits hosted by Pre-Carboniferous rocks may be genetically linked to hot basin-brines escaping up through fault systems. In Figure 7.1 and Figure 7.4 mineral occurrences have been classified by the host rock and the geological environment, the basin-brine expulsion genetic affinity would include. 1) fault related, 2) most if not all of the concordant carbonate-hosted deposits, and 3) carbonate-hosted fault related deposits.

7 12.3 GENETIC AFFINITY 1 - SEDIMENTARY PROCESSES AND SEDIMENTARY EXHALATIVE

Alternatively, or perhaps in addition to the basin-brine expulsion genetic affinity, Russell (1976, 1978) viewed the concentrations of manganese in the vicinity of the Walton Deposit as possible syngenetic geochemical halos related to sedimentary exhalative processes. The paragenesis as inferred by Boyle (1972, 1976) would not be compatible with such a mineralizing mechanism Ravenhurst and Zentilli suggested that the deposit may be another manifestation of the basin brine expulsion event, where the basin brine fluids interacted with the infiltrating surface waters as postulated by Boyle (1972, 1976). The answer as to the origin of the Walton Deposit is beyond the scope of this study and the information provided is included in order to give a balanced view of the various hypotheses. The possibility of earlier synsedimentary exhalative origins for carbonate-hosted deposits during the Viséan, cannot be eliminated using the available data. This mechanism may better explain a few of the occurrences. The influence of extra-basinal hydrothermal fluids has not been documented and perhaps may be significant, especially in the vicinity of the deep seated Cobequid-Chedabucto Fault System. The potential extent of earlier and/ or contemporaneous exhalative phases may have been rendered unrecognizable by tectonic disruption. Recently Hudgins (1990) and various mineral exploration companies have undertaken exploration in the Carboniferous strata of the Maritimes Basin with the working hypothesis that many of the occurrences are sedex related. In particular some of the occurrences in the Loch Lomond Basin in Cape Breton have been attributed to this mechanism (Fig. 7.1). Similarly recent work by Hein et al.(1989) on the Jubilee Pb-Zn deposit of central Cape Breton has also suggested the possibility of a sedimentary exhalative origin.

Ryan and Boehner (1991) suggested that possible sedimentary exhalative deposits (e.g. Loch Lomond Basin, Codroy Newfoundland) can be grouped together with syngenetic deposits such as sulphate-hosted type and paleoplacers (see Fig. 7.4) and together they can be classified as genetic affinity type 1, related to sedimentary processes.

7.13 POSSIBLE METALLOGENETIC HISTORY OF THE MARITIMES BASIN

Using the time and temperature constraints posed by the thermal part of this thesis it is possible to suggest a probable chronological order to the various mineral deposit affinities in the Maritimes Basin (Fig. 7.34). Following is a brief synopsis of the possible metallogenetic evolution of the basin.

7.13.1 LATE DEVONIAN - VISÉAN (370-333 Ma)

The late Devonian to early Viséan was characterized by crustal instability with initial molassic deposition of coarse- to fine-grained alluvial, fluvial and lacustrine sediments, and locally rift-related volcanic deposition in intermontane basins (Fountain Lake Group and Horton Group). These rocks are rarely mineralized except near the contact with the overlying marine evaporitic rocks of the Viséan Windsor Group. A possible exception may be the late Devonian(?) Lochaber Lake copper deposit, which could be interpreted either as synsedimentary or as epigenetic (late Carboniferous?). Rare paleoplacer deposits also occur, such as the gold placer deposit at the unconformity between Horton Group conglomerate and Meguma Group slate near Gays River.

The basin complex was breached in the Viséan by a major evaporitic mari e incursion of the sub-sea level landscape (Kirkham, 1978). Nonmetallic mineral deposits are abundant (e.g. limestone, dolomite, anhydrite, salt and secondary gypsum hydrated from anhydrite). Significant potash salts (sylvite and carnallite) were deposited at several stratigraphic levels during periods of extreme restriction and evaporation. Although economic potash deposits have not yet been identified in Nova Scotia, two deposits are currently exploited in New Brunswick.

Syngenetic mineralization appears to be limited to low grade enrichment in Cu, Pb and Zn sulphides, pedogenic-diagenetic Fe and Mn, and locally barite and celestite replacements especially near disconformity redox boundaries between marine carbonates and evaporites or redbeds. The basal Windsor Group carbonate (Macumber Formation) contact with the Horton Group is a locus for numerous occurrences. Syngenetic models for the Gays River Pb-Zn deposit have been questioned and a diagenetic-epigenetic model has been proposed by Akande and Zentilli (1984) and Ravenhurst and Zentilli (1987). The syngenetic-exhalative origin for the Jubilee Pb-Zn deposit recently proposed by Hein et al. (1989) and Hudgins (1990) contrasts with earlier structurally controlled-epigenetic interpretations and is not yet established (Fig 7 34)

7.13.2 NAMURIAN - PERMIAN (333-280 Ma)

In the late Viséan-Namurian the basins returned to continental sedimentation, evolving into a broad, low relief floodplain - lacustrine depocenter (Belt, 1968) dominated by fine grained sedimentation (Mabou Group). This was succeeded by coarse fluvial braidplain deposition with locally developed alluvial fans in the Westphalian A. In the Silver Mine (Yava deposit) area of southeastern Cape Breton Island early to late diagenetic lead deposits formed in early Westphalian sandstone. These deposits are located at the unconformity where grey sandstone onlaps felsic basement (rhyolite porphyry) at or near the pinchout of evaporitic Windsor and Canso Group strata.

Major lateral (dextral transform) motion along the Cobequid-Chedabucto Fault System culminated in the mid to late Westphalian with complex and locally intense deformation with thrusting, especially in southern New Brunswick (Nance, 1987) as well as other areas adjacent to the fault zone (eg. the Cumberland Basin).

Tectonic-related epigenetic mineral deposits, in contrast, are numerous and widespread, especially along the Cobequid-Chedabucto Fault System (CCFS). The late Pennsylvanian early Permian event involved fault and fold deformation related to dextral motion on the CCFS and its subsidiaries. It coincided with locally rapid uplift and subsidence, and thick sediment accumulation, especially in the Cumberland Basin and the central part of the Maritimes Basin in the Gulf of St. Lawrence. Elevated geothermal gradients may have accompanied the deep seated tectonism, (possibly including plutonism in highland and platform areas) especially in the deeper, rapidly subsiding basins and near the CCFS. The thermal study undertaken as part of this study did not indicate that there was a significant increase of the geothermal gradient into the basin areas, however the next step in the thermal study of the basin should be to find and define the timing of thermally anomalous areas.

The basins, therefore, experienced optimum conditions for potential hydrothermal mineralizing events. Based on their thermochronological studies included in chapter 5 it can be shown that the maximum temperatures attained by the Paleozoic strata were at circa 290 Ma and correspond to the period of maximum burial (Fig. 7.35). Metalliferous brines, developed deep in the basin fill and constrained by the impermeable Viséan evaporites, were driven toward the basin margin, particularly toward the Meguma Platform to the south (Ravenhurst and Zentilli, 1987). They interacted with reactive host rocks both along escape paths provided by faults and fractures as well as in reservoir-stratigraphic trap settings where physical and chemical conditions were conducive to mineral precipitation and replacement. The basal Windsor Group carbonate was a primary host and deposit examples may include Gays River, Smithfield, Upper Brookfield, Pembroke, Middle Stewiacke, Walton and vicinity, and Jubilee. This fluid expulsion event may be the most significant with respect to metallogenesis in the Late Paleozoic basins in Nova Scotia (Fig. 7.36).

Fracture-fill vein mineralization is locally hosted in pre-Carboniferous basement rocks and may be related to this event. Examples include vein barite along the CCFS on the south side of the Cobequid Highlands and some of the barite-fluorite veins near Lake Ainslie. These deposits may be compared with the structurally controlled Pb, Zn, F, Ba and Cu mineralization of the Pennines in Carboniferous basins of central Great Britain (Dunham, 1978).

The late Permian in Nova Scotia was dominated by a major hiatus coincident with an important reddening episode in late Carboniferous strata, especially in the Cumberland Basin. This reddening event corresponds to the erosion event postulated by Ryan et al. (1991b) based on apatite fission track analysis. This reddening, associated with low water tables and rapid erosion, generated numerous solution-roll front mineralizing settings represented by Cu, Ag, and Pb sandstone-hosted mineral occurrences (Fig. 7.1). At the same time there were local concentrations of metals at the redox boundaries within the basin strata where redbeds are overlain by reducing grey shales and mudrocks (Fig. 7.31). These boundaries are similar in style to the Kupferschiefer deposits of Europe except hosted by terrestrial sedimentary strata.

7.14 CONCLUSIONS

The following are the conclusions of this chapter:

1) The Cu-Ag occurrences within the Cumberland Basin study area are late diagenetic groundwater related.

2) The timing of these late diagenetic groundwater related mineralizations is in part defined by the exhumation event constrained by the apatite fission track analysis, circa 270-290 Ma.

3) The timing of the maximum burial, and the most likely time for basin brine expulsion events is at some time between 300-270 Ma.

4) The maximum temperatures attained below the Windsor to Horton contact within local sub-basins was sufficient to explain the temperatures interpreted for the carbonate-hosted mineral deposits of the basin, and therefore it is not necessary to invoke transport of basin brines for great distances as suggested by Ravenhurst and Zentilli (1987).

5) Tectonism during the Late Carboniferous and Early Permian may have triggered basin brine expulsion events.

6) Sedimentary exhalative events could have possibly occurred during the period of rapid deposition and burial of these Carboniferous strata.

7) All of the various mineral deposit affinities can be place into context relative to the thermal history of the basin.

Sample	SiO2	Al2O3	FeO(T)	MgO	CaO	Na2O	K2O	TiO2	MnO	P2O5	Ba	Rb	Sr	Y	Zr	Nb	Th	Pb	Ga	Zn	Cu	Ni
	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
RJR-1	72.85	12.94	3.92	1.80	0.41	1.67	2.48	0.83	0.08	0.19	228	79	82	25	190	15	5	15	14	82	20	24
-8	75.92	10.39	2.16	1.33	1.88	1.60	1.19	0.79	0.40	0.10	169	48	73	24	196	13	7	11	12	77	69	16
-15*	78.22	10.35	4.18	1.09	0.00	1.27	1.39	0.95	0.06	0.13	446	56	109	34	395	18	9	26	11	66	10	21
-26*	79.72	9.05	3.52	0.81	0.37	0.95	1.21	0.55	0.11	0.13	1126	51	186	21	138	9	8	15	11	52	14	14
-28	83.85	6.86	1.36	0.79	1.55	0.96	0.63	0.24	0.24	0.10	86	24	45	13	63	5	2	10	7	32	12	8
-30*	79.62	10.65	2.62	1.05	0.20	1.45	1.23	0.65	0.06	0.11	706	51	75	16	128	10	6	12	11	51	8	16
-61*	81.81	6.47	1.87	1.57	1.63	1.33	0.47	0.27	0.23	0.10	75	16	35	15	86	6	4	13	7	35	9	9
-77*	78.13	8.75	3.52	0.86	1.16	1.23	0.96	1.36	0.28	0.14	596	40	254	23	211	15	5	20	9	59	16	15
-116	76.1	11.36	3.45	1.59	0.45	1.71	2.14	0.62	0.09	0.16	527	70	74	21	134	12	7	16	12	65	28	16
-121	86.70	5.56	1.59	0.76	0.42	1.17	0.37	0.14	0.07	0.11	75	12	29	11	59	3	2	12	4	33	7	4
-127	69.49	3.44	1.16	1.13	10.66	0.57	0.44	0.28	0.71	0.10	121	13	70	22	98	6	2	9	6	41	10	8
-130	77.14	10.63	2.43	1.23	1.25	1.83	1.28	0.92	0.18	0.14	575	51	85	25	299	13	10	17	11	49	40	14
-139	76.33	4.93	1.03	0.46	4.91	0.84	0.49	0.16	0.29	0.10	139	14	218	11	56	4	1	10	6	23	26	8
-229	74.56	7.47	1.84	0.61	3.75	1.29	0.53	0.32	0.20	0.11	1194	20	453	13	81	6	0	17	6	114	58	4
-237*	70.71	6.69	3.74	0.66	6.02	0.90	0.64	0.28	0.35	0.13	532	23	459	16	87	6	2	10	5	33	12	8
-242	73.68	13.31	3.82	1.53	0.24	1.53	1.93	0.94	0.10	0.14	332	70	94	25	208	15	6	12	17	111	71	24
-245	82.57	8.03	2.49	0.68	0.74	1.45	0.59	0.25	0.11	0.13	438	23	61	14	70	5	3	11	7	30	14	8
-261*	79.17	9.83	3.70	1.34	0.08	1.80	1.17	0.66	0.04	0.16	153	47	63	16	206	11	6	13	11	52	16	17
-275*	84.29	6.11	2.49	0.91	1.01	0.90	0.79	0.79	0.18	0.12	201	20	65	20	96	10	2	11	6	46	16	8
-276*	81.79	6.37	3.16	0.84	0.45	1.01	0.64	0.65	0.21	0.11	121	40	70	21	59	11	3	15	14	45	14	17
-277*	80.19	6.39	2.41	1.35	0.96	1.16	0.59	0.59	0.18	0.14	301	23	88	20	106	11	4	26	22	47	18	16
-278*	82.17	6.12	1.92	1.53	0.70	1.29	0.69	0.32	0.52	0.11	75	26	29	19	126	11	6	10	11	50	16	15
-301*	86.14	6.10	3.16	1.01	0.45	1.06	0.83	0.79	0.31	0.12	126	50	33	17	211	10	5	12	10	42	25	12
-302*	80.11	5.31	2.94	1.03	0.79	1.51	0.91	0.01	0.19	0.15	81	69	46	25	130	9	5	20	9	59	17	11
-303*	80.17	6.39	1.97	1.14	0.96	1.21	1.34	0.77	0.29	0.11	206	69	28	22	121	9	5	12	10	38	14	1
-306*	82.26	6.48	3.41	0.93	1.01	1.33	1.28	0.66	0.54	0.12	512	60	128	21	119	8	4	16	9	46	28	61
-309*	80.79	7.16	2.61	0.87	0.97	1.30	0.49	0.59	0.18	0.12	139	28	101	23	111	5	5	20	8	61	16	8
-314*	81.11	9.97	1.98	0.79	0.98	1.41	1.28	0.71	0.35	0.11	176	71	35	20	110	7	7	13	9	29	25	9
-318*	80.19	5.11	3.24	1.14	0.99	1.15	0.44	0.55	0.23	0.12	333	66	76	22	109	8	10	12	6	70	17	7
-320*	80.16	5.33	1.79	1.16	1.45	1.25	0.97	0.49	0.14	0.11	88	70	88	20	131	11	4	10	11	23	17	10
-321*	83.21	4.71	3.38	1.20	1.31	1.27	0.99	0.70	0.28	0.12	253	29	61	19	128	9	4	15	10	69	16	11
-326*	82.22	8.01	1.52	1.35	0.96	0.95	1.01	0.54	0.13	0.11	511	64	60	23	99	9	6	20	9	23	15	9
-329	79.24	6.75	1.58	0.93	1.21	1.45	1.11	0.48	0.16	0.12	87	80	134	26	101	10	5	11	9	60	26	12
-331	79.99	6.19	1.02	0.99	1.30	1.23	0.54	0.69	0.37	0.11	169	61	73	20	117	9	5	13	6	69	37	16
-332	79.16	7.85	1.84	0.84	1.11	1.70	0.64	0.66	0.11	0.14	79	29	61	19	129	8	0	12	8	63	28	10
-333	79.54	7.66	1.96	1.13	1.21	0.56	0.71	0.53	0.57	0.12	63	55	88	20	110	6	1	10	8	75	33	9
-341	80.01	8.95	1.97	1.14	1.31	0.83	0.73	0.46	0.16	0.11	511	60	72	21	96	6	1	17	4	90	37	8
-343	81.01	8.18	2.01	1.09	0.45	1.28	0.79	0.63	0.27	0.12	275	30	90	16	84	4	10	10	7	20	29	7
-344	79.16	4.11	2.23	0.87	0.39	0.84	0.65	0.52	0.52	0.11	168	54	221	15	57	11	6	10	8	49	40	4
-345	78.14	8.07	1.45	0.88	0.77	0.57	0.61	0.47	0.12	0.12	366	50	66	13	66	11	5	10	11	69	26	14
-346	79.11	6.54	1.99	0.99	0.97	1.81	0.93	0.62	0.36	0.11	44	53	91	21	91	11	9	9	12	73	25	19
-347	80.11	4.11	1.10	0.79	1.49	1.70	1.12	0.51	0.21	0.12	501	31	70	34	117	10	7	11	6	75	48	22
-349	79.96	7.75	2.01	1.01	2.45	0.59	1.01	0.46	0.17	0.11	66	59	90	24	128	12	6	15	4	79	51	11
-350*	79.19	7.19	2.64	1.02	2.10	0.96	0.65	0.61	0.52	0.13	281	40	131	35	126	15	5	20	6	61	15	15
-401	79.14	8.94	3.01	1.15	1.17	1.03	0.35	0.48	0.11	0.11	169	33	63	35	117	13	5	15	11	59	34	14
-404	80.40	6.01	3.06	1.35	0.91	1.66	0.28	0.55	0.57	0.12	377	20	71	19	90	15	6	12	12	49	32	11
-441	83.91	7.97	2.95	0.96	1.11	1.17	1.35	0.50	0.32	0.13	71	79	95	16	81	9	8	13	11	69	36	16
-461	82.22	9.09	1.66	0.87	1.25	1.90	1.23	0.60	0.21	0.13	395	36	65	15	114	6	8	10	10	57	30	12

Table 7.1 Geochemistry of unmineralized sandstones, Cumberland Basin. * indicates red sandstone.

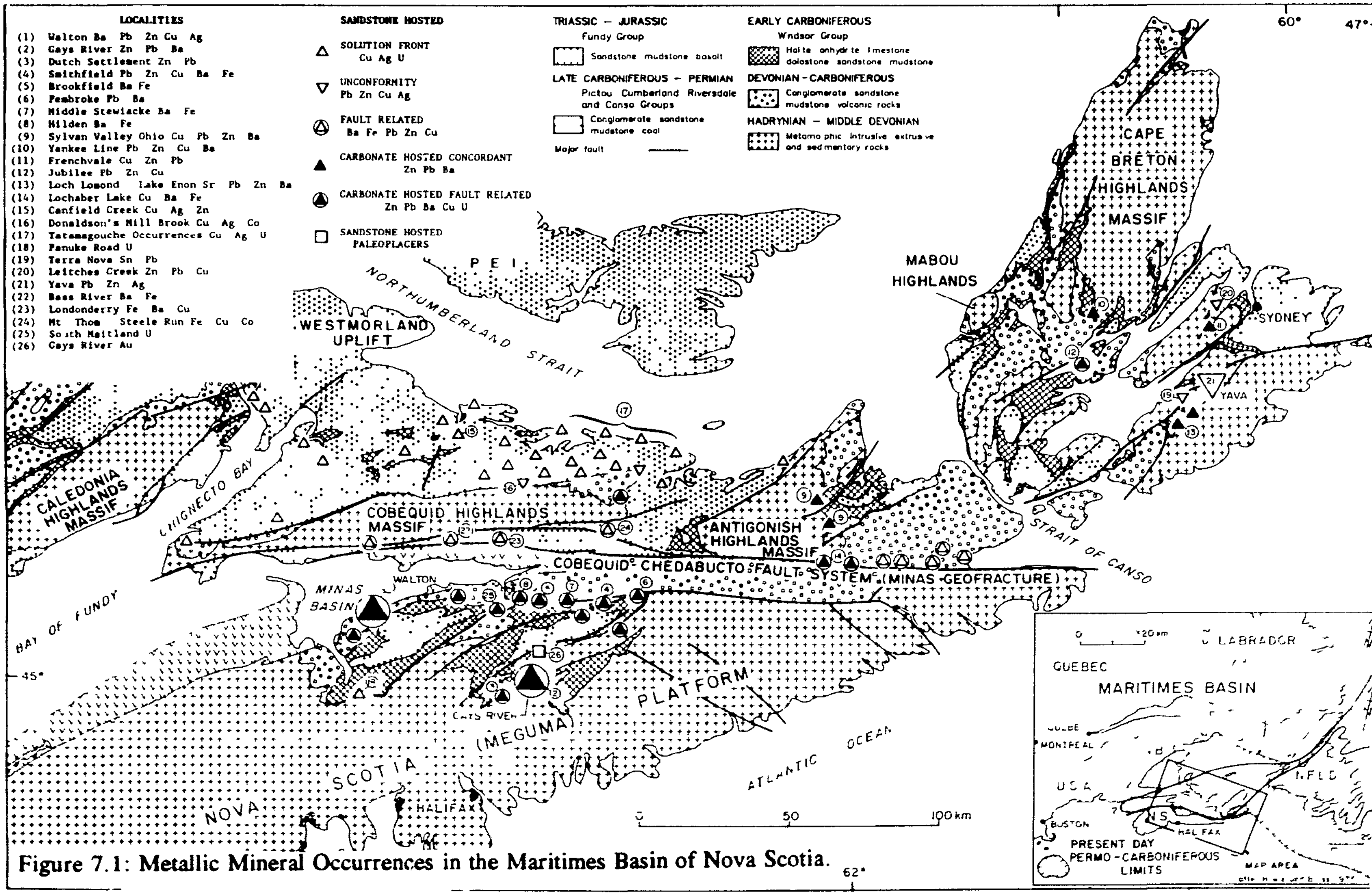


Figure 7.1: Metallic Mineral Occurrences in the Maritimes Basin of Nova Scotia.

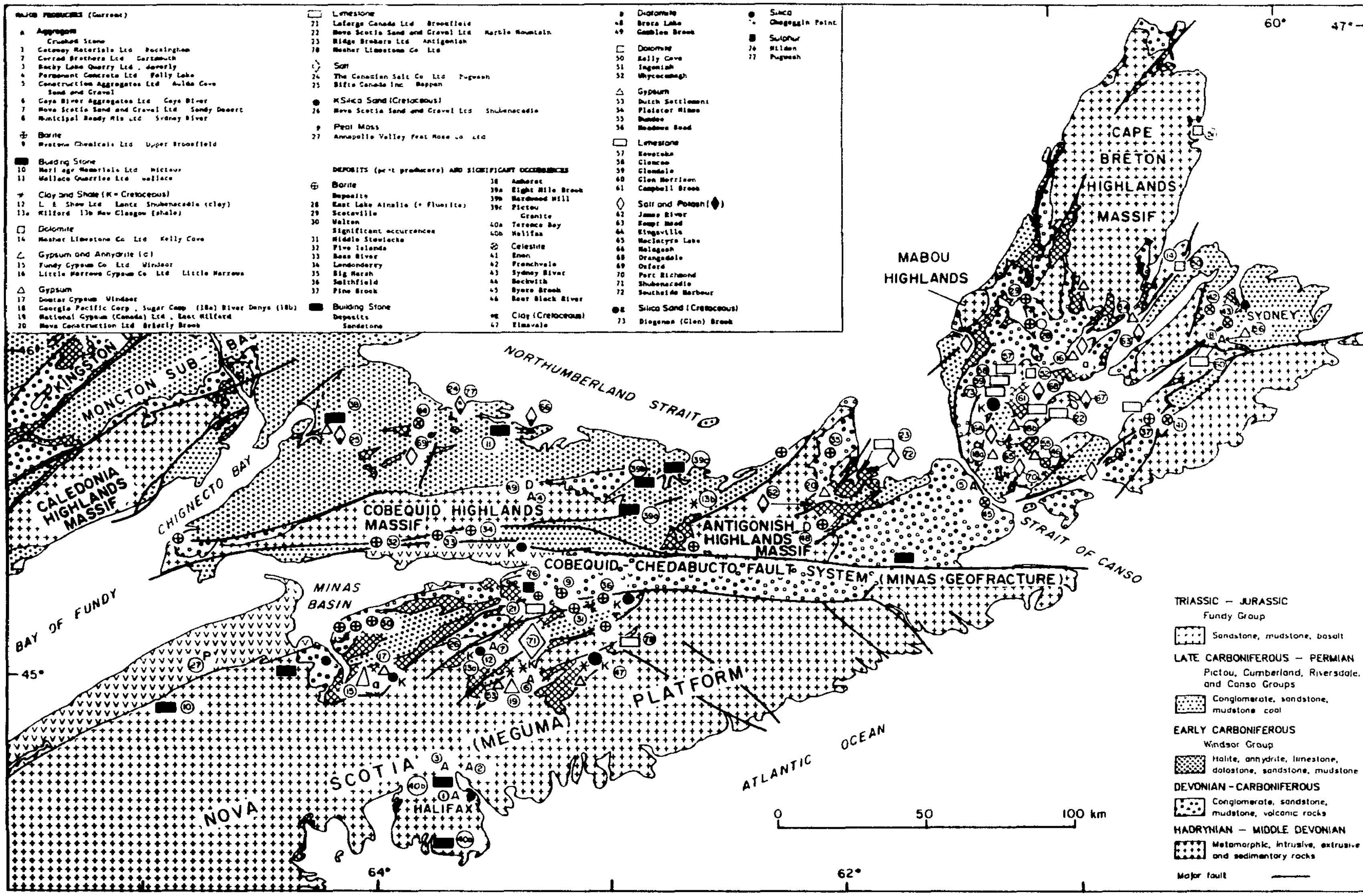
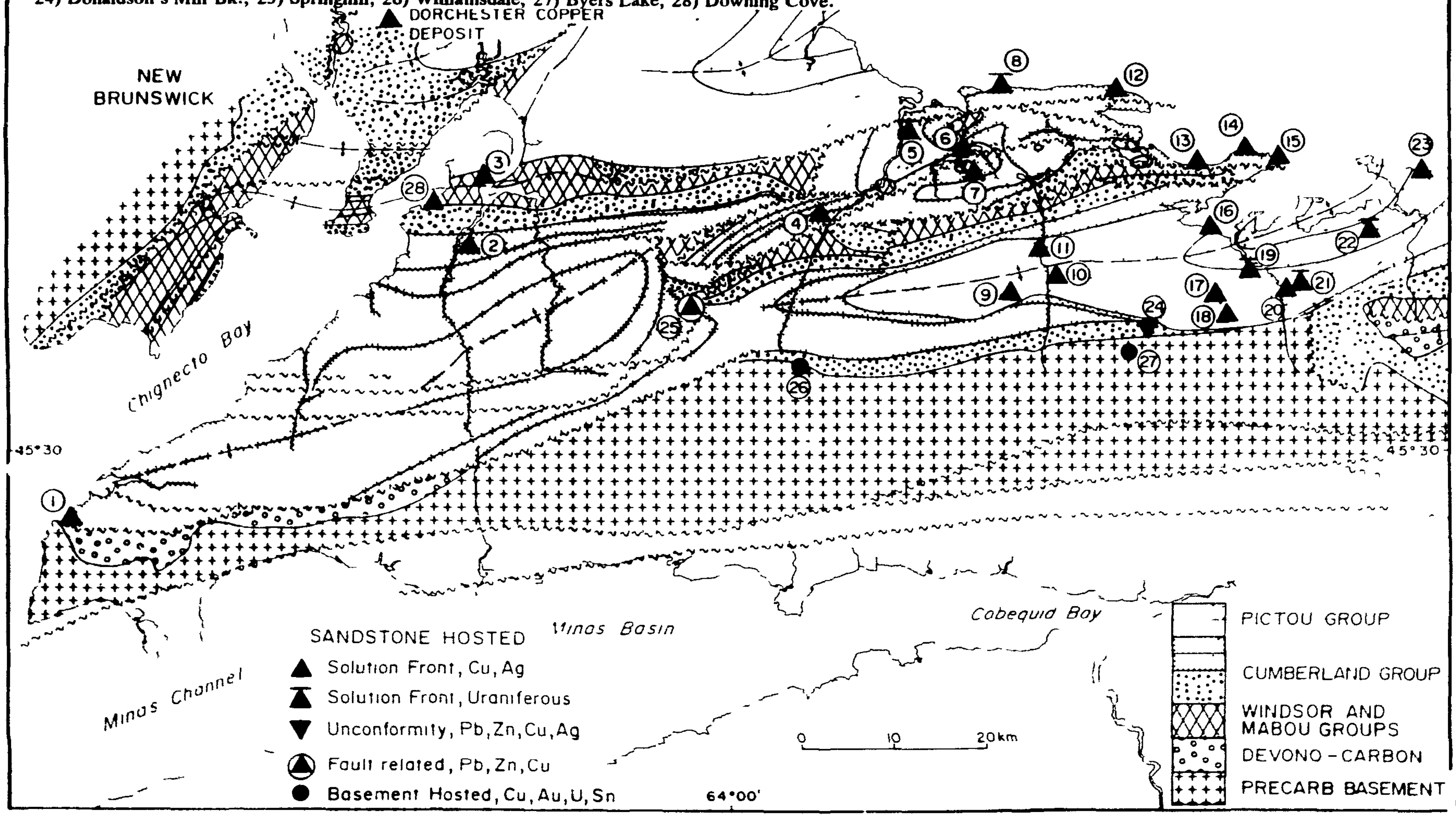


Figure 7.2: Industrial mineral occurrences in the Maritimes Basin of Nova Scotia.

Figure 7.3: Mineral Occurrences in the Cumberland Basin, 1) Spicers Cove, 2) Maccan, 3) Minudie, 4) King Mine, 5) Port Howe, 6) Chisholm Brook, 7) Canfield Creek, 8) McLean Point, 9) Palmer Mine, 10) Feely Mine, 11) Flemming Bk. Mine, 12) Cape Cliff, 13) North Shore, 14) Treen Point, 15) Malagash Point, 16) Blockhouse Point, 17) North Oliver, 18) Oliver, 19) Woodlock Bk., 20) Balfron, 21) Black River, 22) Louisville, 23) Skinners Cove, 24) Donaldson's Mill Bk., 25) Springhill, 26) Williamsdale, 27) Byers Lake, 28) Downing Cove.



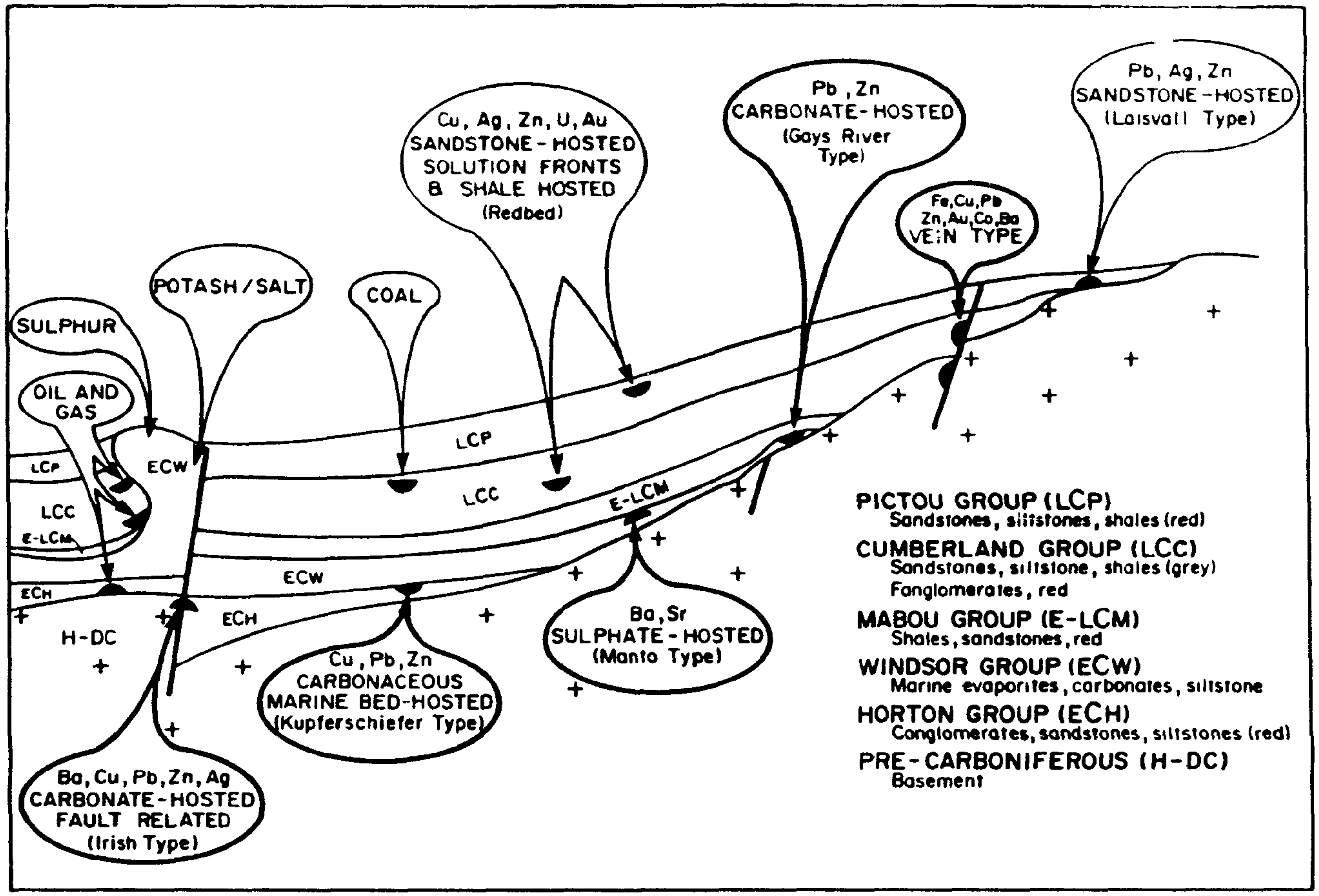


Figure 7.4: Cartoon representation of the mineral occurrence types in the Cumberland Basin, after Ryan (1986).

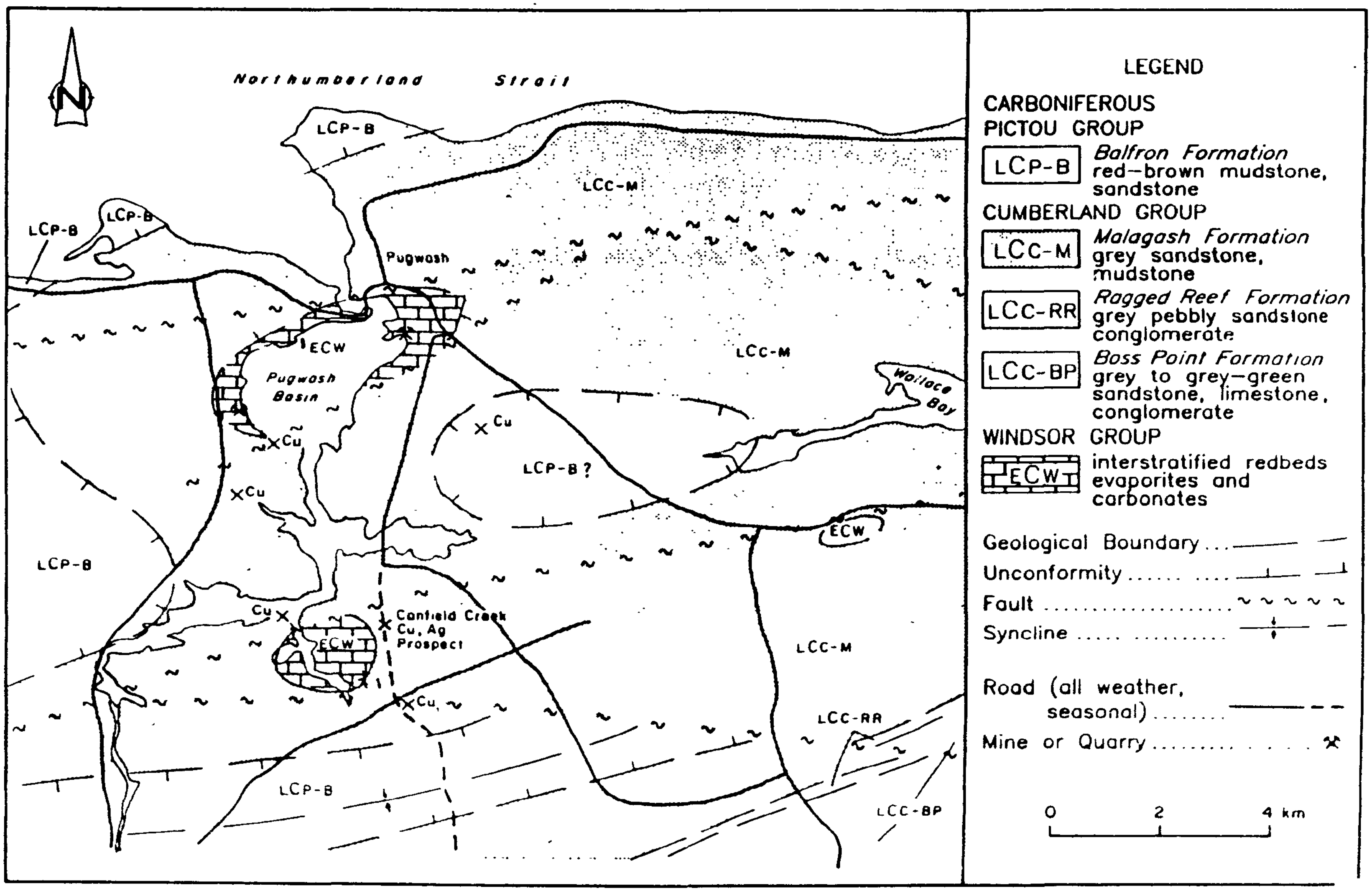


Figure 7.5: Location and generalized geology of the Canfield Creek occurrence.

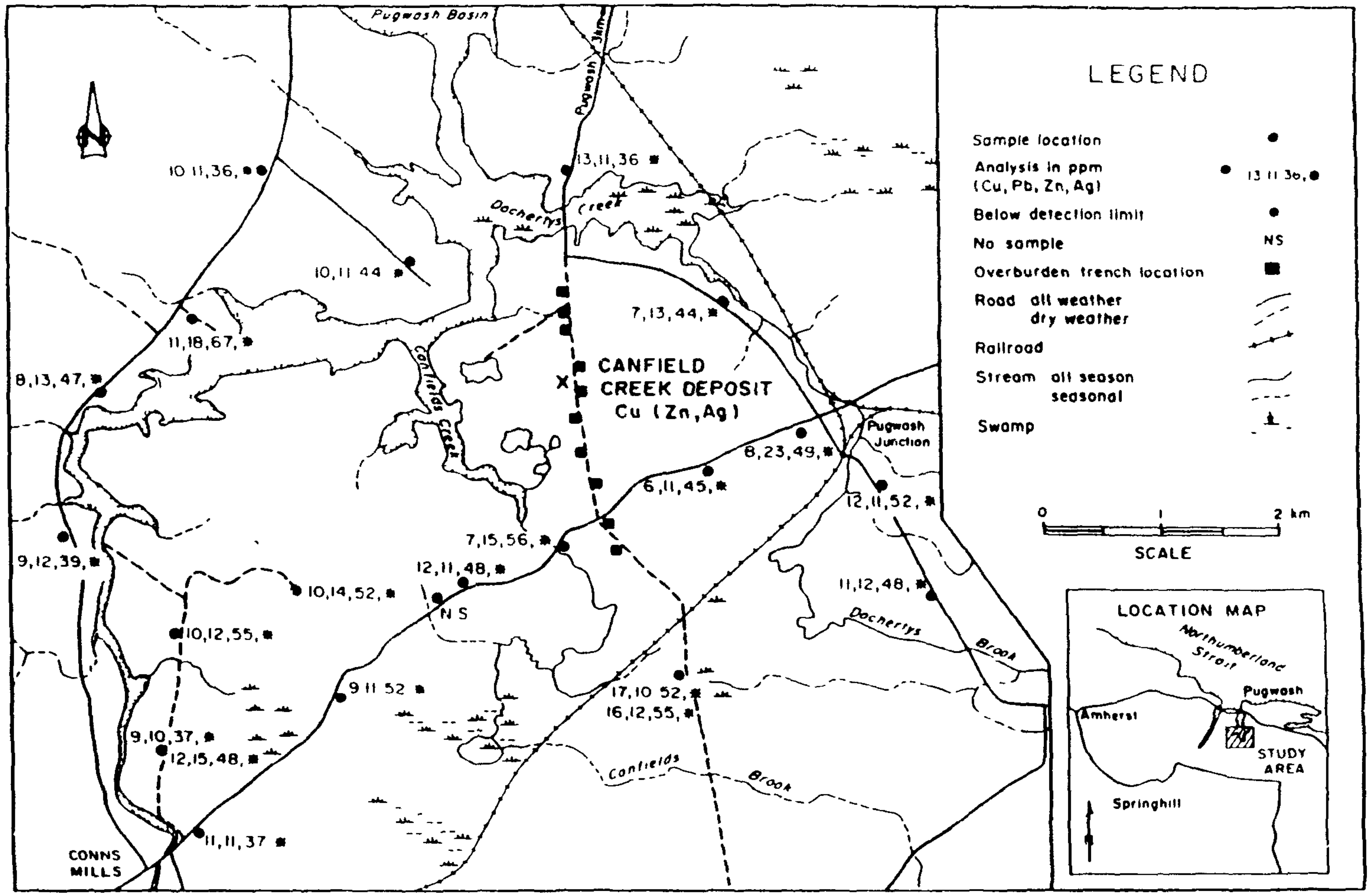


Figure 7.6: Detailed location map of the Canfield Creek deposit and a plot of the -230 mesh fraction of the regional till samples (after MacDonald et al., 1992).

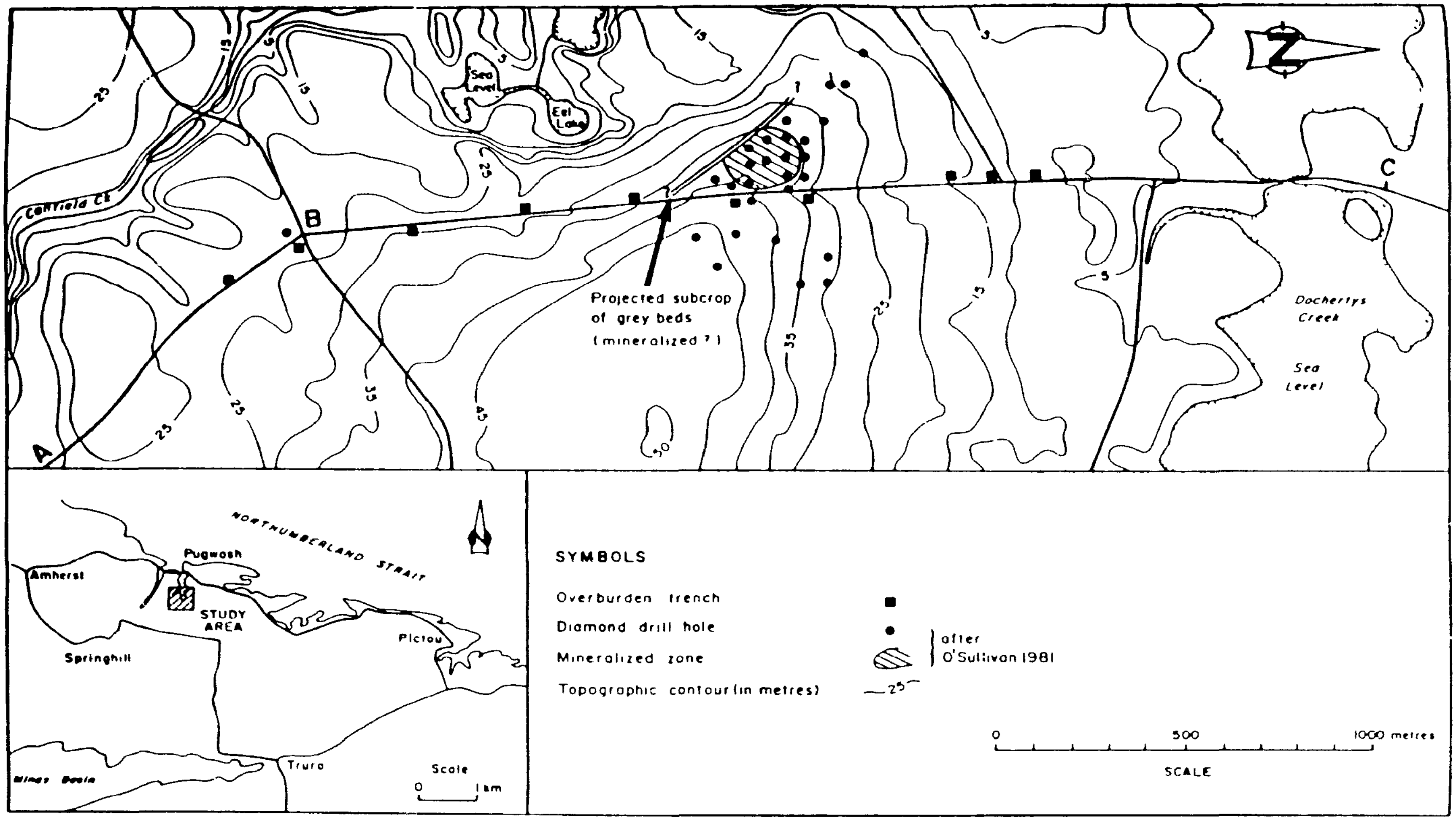


Figure 7 7: Location of the drilling, trenches, and ore zone at the Canfield Creek deposit (after MacDonald et al. 1992)

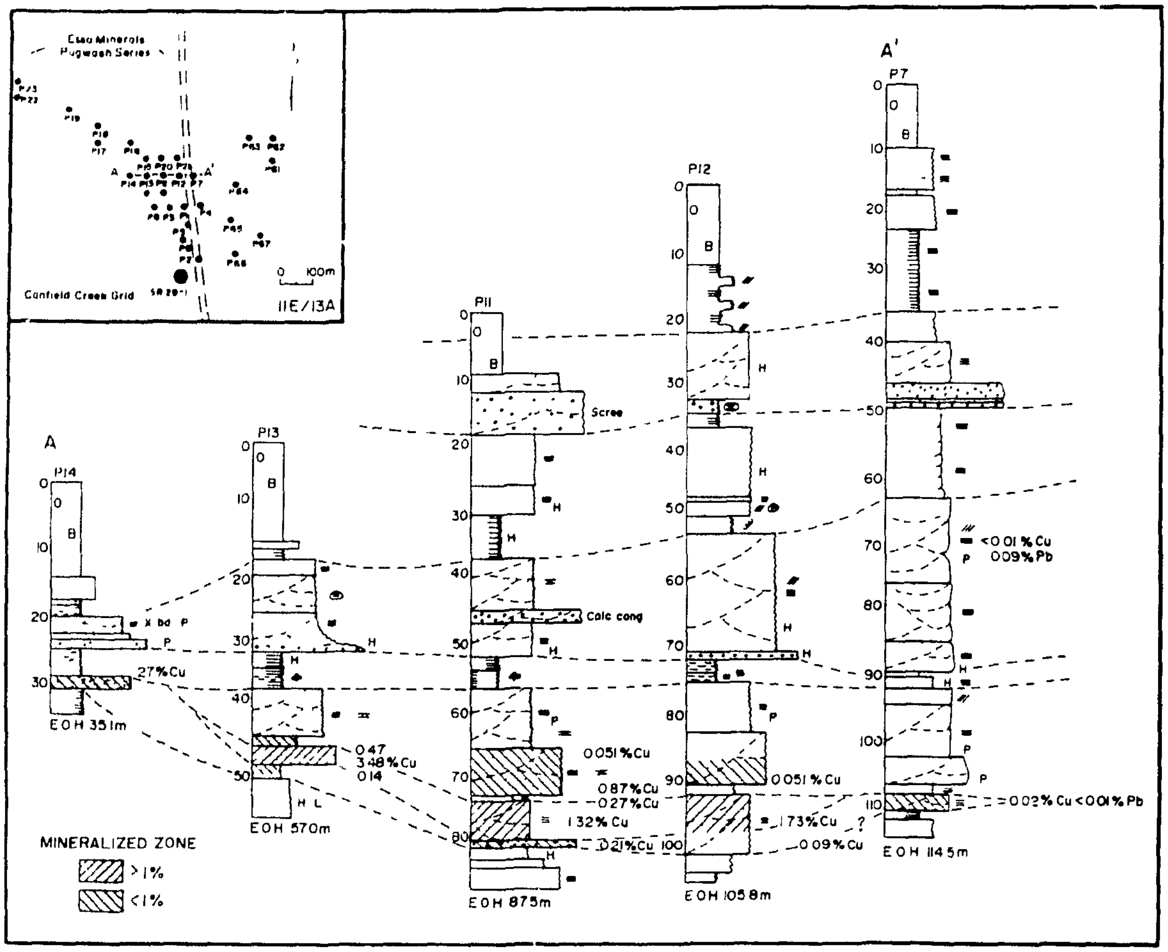


Figure 7.8: Drill hole cross section of the Canfield Creek deposit.

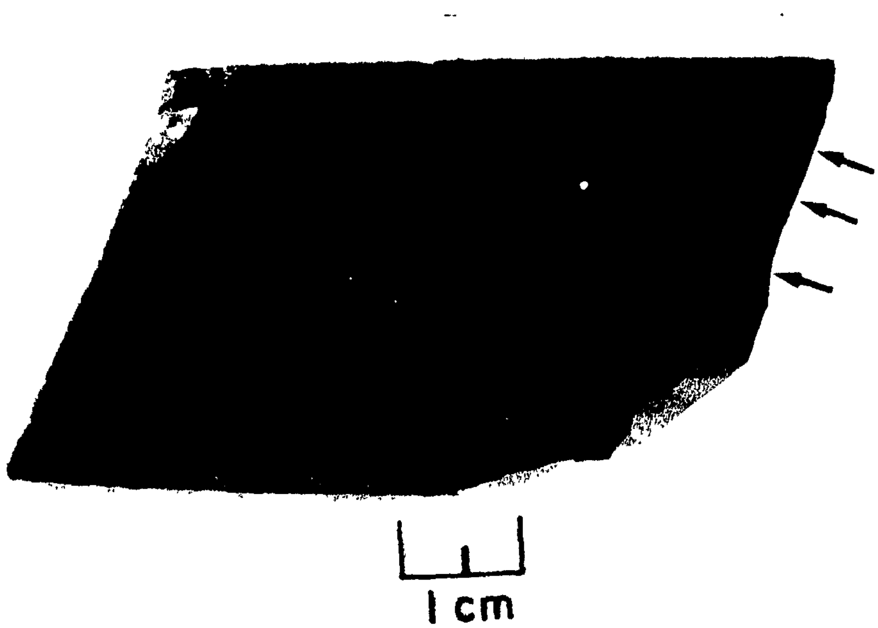


Figure 7.9· Disseminated chalcocite in core from the Canfield Creek deposit.

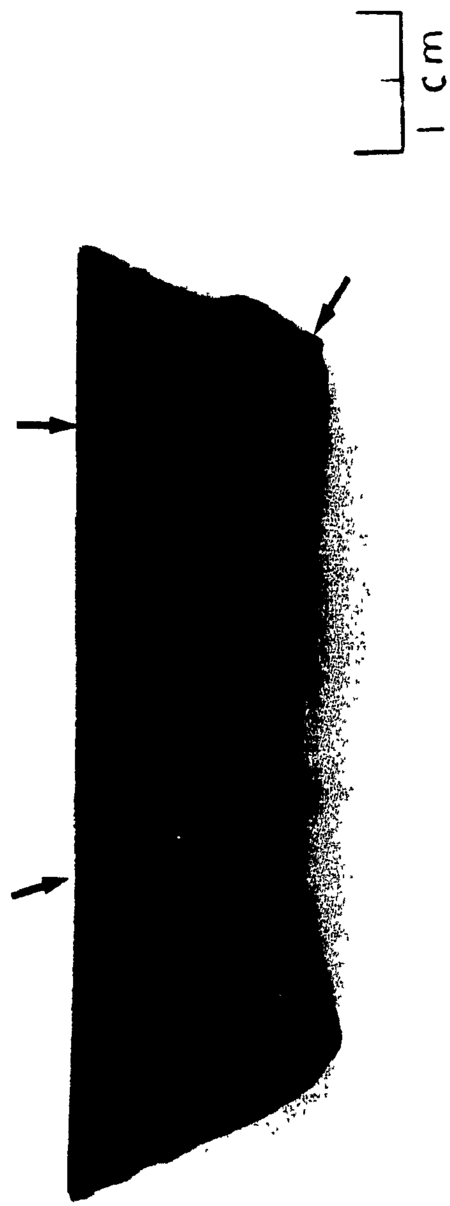


Figure 7 10: Chalcocite nodules in core from the drilling at the Canfield Creek deposit

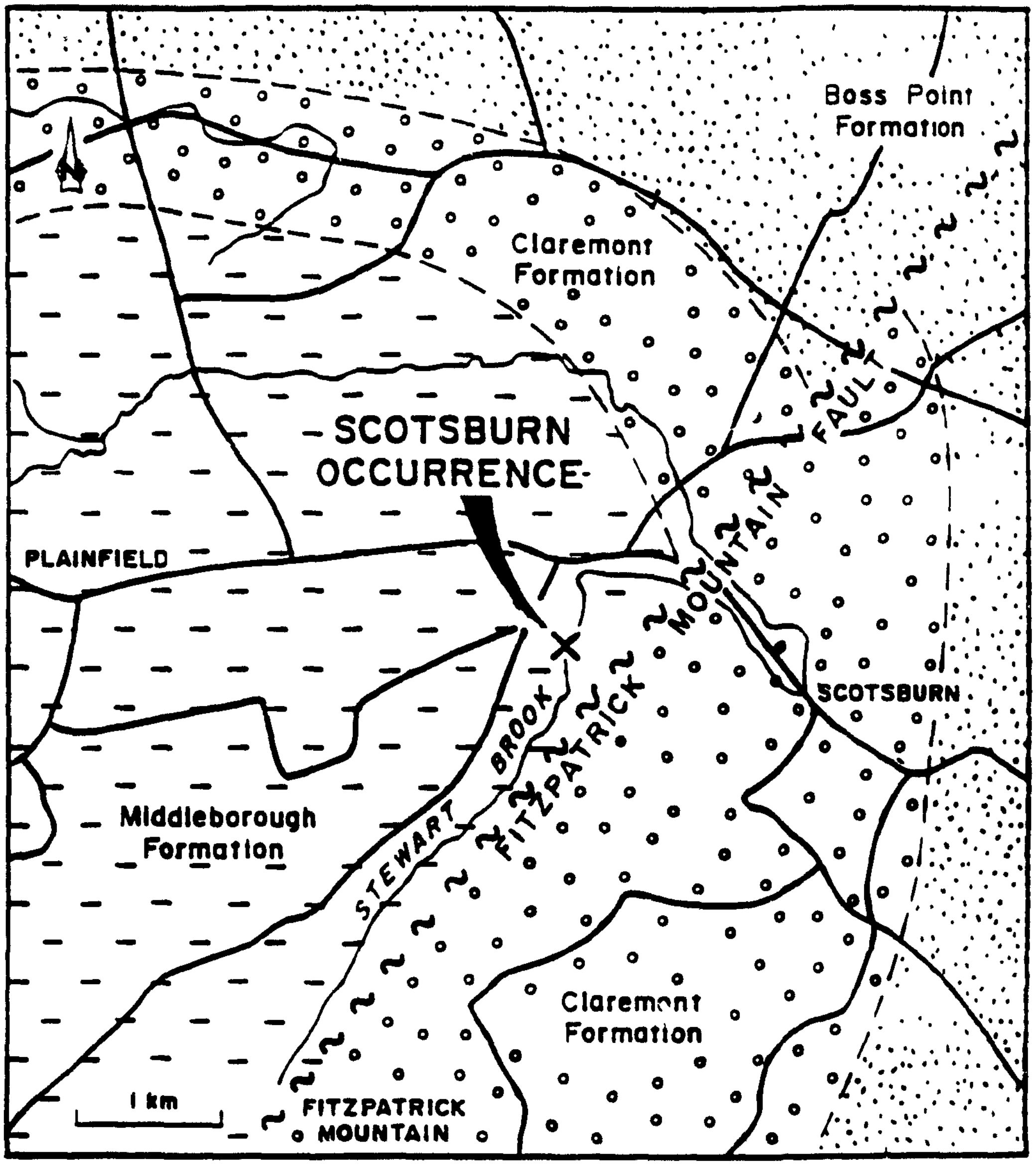
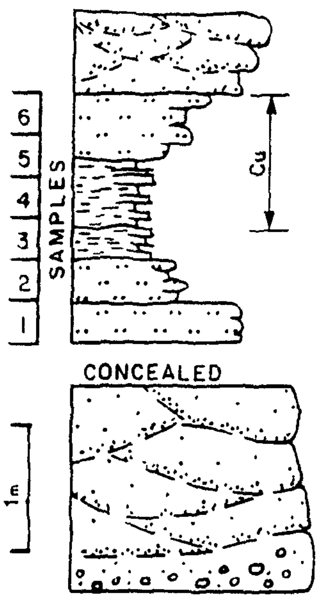


Figure 7.11: Location and geology of the Scotsburn Copper occurrence.

SCOTSBURN BROOK

Samples are roughly 30 cm channel samples



Sandstone, med. grained, light grey-brown, abnt. plant **debris**, *trough cross stratification*, trace of malachite **staining**, laminated.

Siltstone, fine grained sandstone, grey, abnt. plant **debris**, coarsening upward, malachite is abundant.

Mudstone, grey, abundant plant debris, no apparent **laminations**, pervasive malachite and a few blebs of chalcocite-bornite, the chalcocite appears to be replacing pyrite permineralization of plant detritus.

Mudstone, red-grey transition zone.

Siltstone, red-brown, minor grey mottling.

Sandstone, fine grained, reddish-grey, slightly arkosic, **small** trough cross strata, paleocurrent at 330°, **med. grained at** base, basal calcareous mud-chip conglomerate inter-cross bedded with the sandstone.

SAMPLES	Cu %	Ag ppm	Co ppm	Cr ppm	Au ppb
# 6	0.09		20		<2
# 5	0.36		21		<2
# 4	3.95		15		<2
# 3	2.86	6	14		<2
# 2	0.99		20	110	<2
# 1	0.16		29	120	<2

1.5 m of 1.66% Cu

Figure 7.12: Detailed section as exposed on the stream at the Scotsburn occurrence.

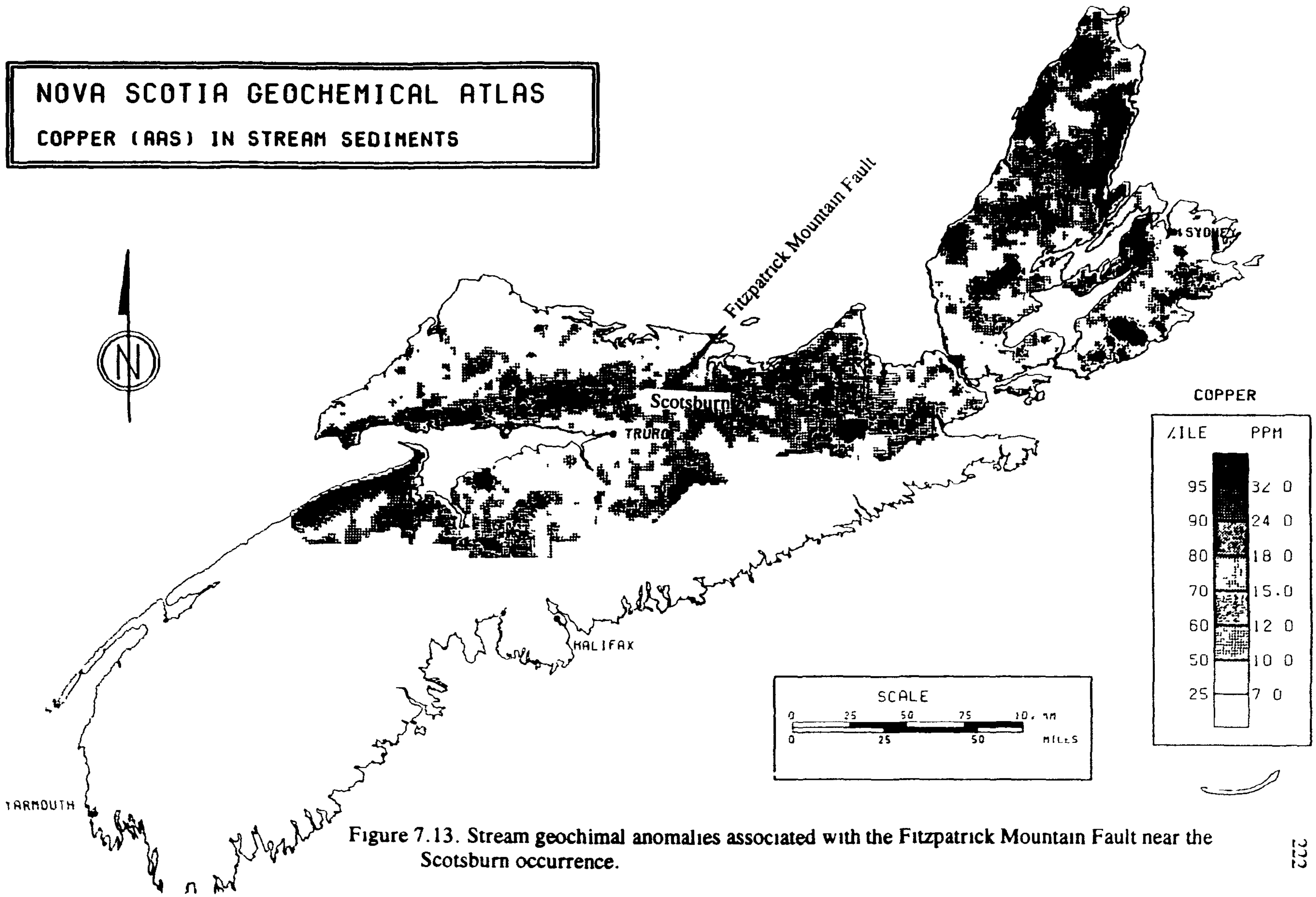


Figure 7.13. Stream geochimal anomalies associated with the Fitzpatrick Mountain Fault near the Scotsburn occurrence.

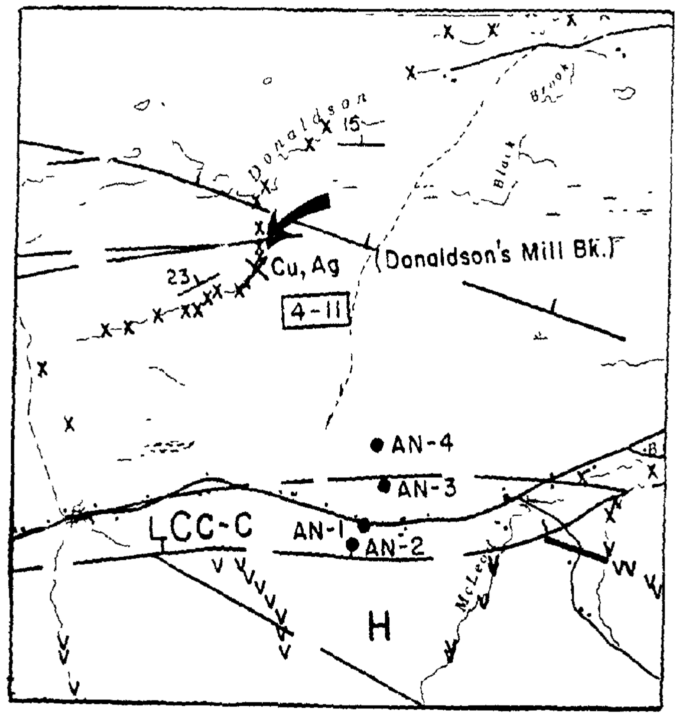


Figure 7 14: Location and generalized geology of the Donaldson's Mill Brook occurrence.

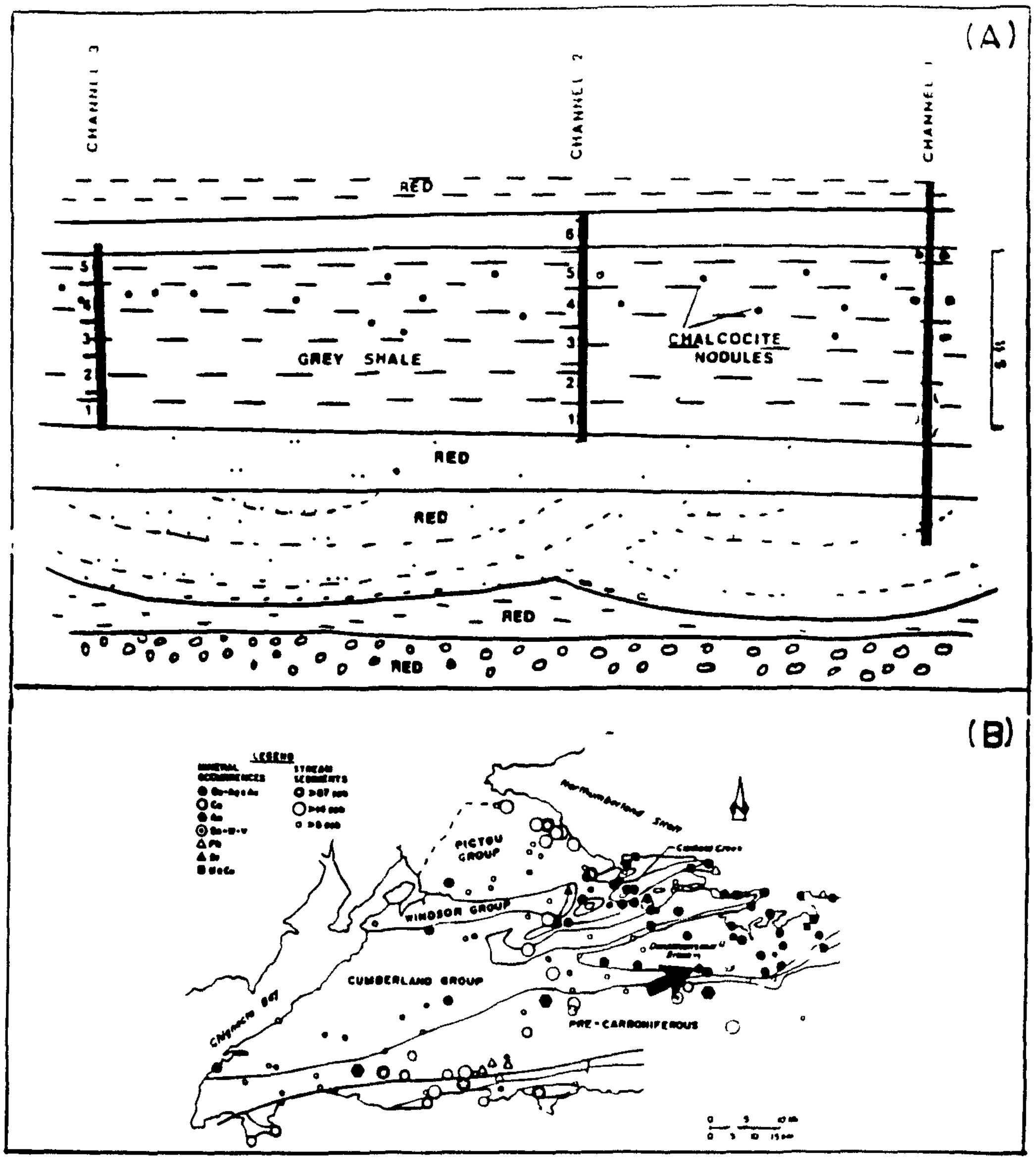


Figure 7 15. Sketch of the mineralization and assay sample locations at Donaldson s Mill Brook

Figure 7.16: Permineralized plant cell structure, replaced by pyrite, chalcocite, and minor bornite, Oliver occurrence, French River. Note the detail that is preserved by the sulphide minerals. Some workers have argued that this proves that the copper mineralization was early diagenetic, however only the pyrite need be early as the other minerals replaced the pyrite. Py = pyrite, BO = bornite, CC = chalcocite, Dg = digenite.

Figure 7 17. Pyrite replaced by bornite and chalcocite, sample is from a chalcocite nodule from the Oliver Copper Mine, on the French River This sample is the exception to the rule as there is perhaps a little late stage pyrite present Py = pyrite, BO = bornite, CC = chalcocite, Dg = digenite

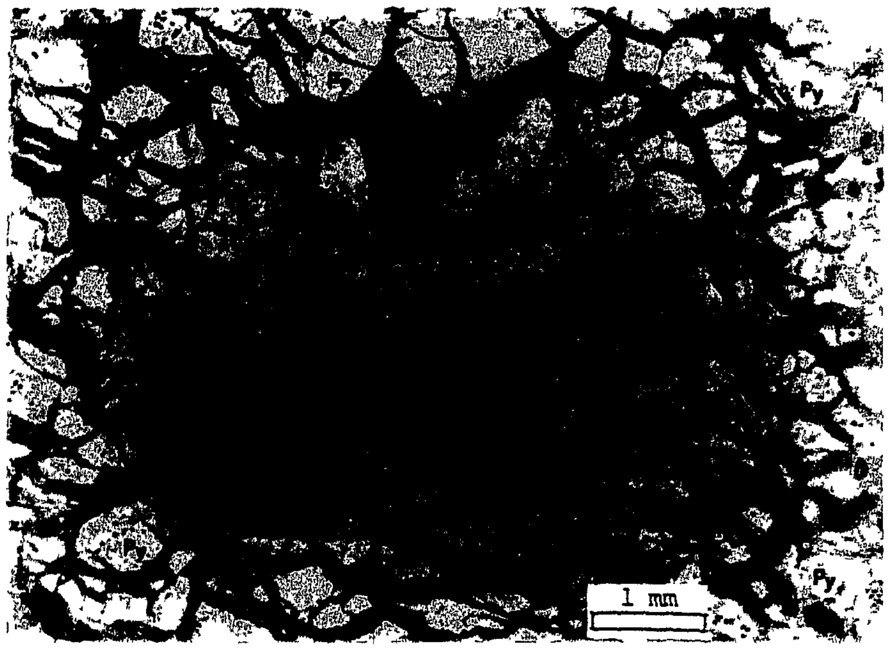


Figure 7 18 Exsolution features in pyrite and bornite, replaced by chalcocite and digenite. Py = pyrite, BO = bornite, CC = chalcocite, Dg = digenite.

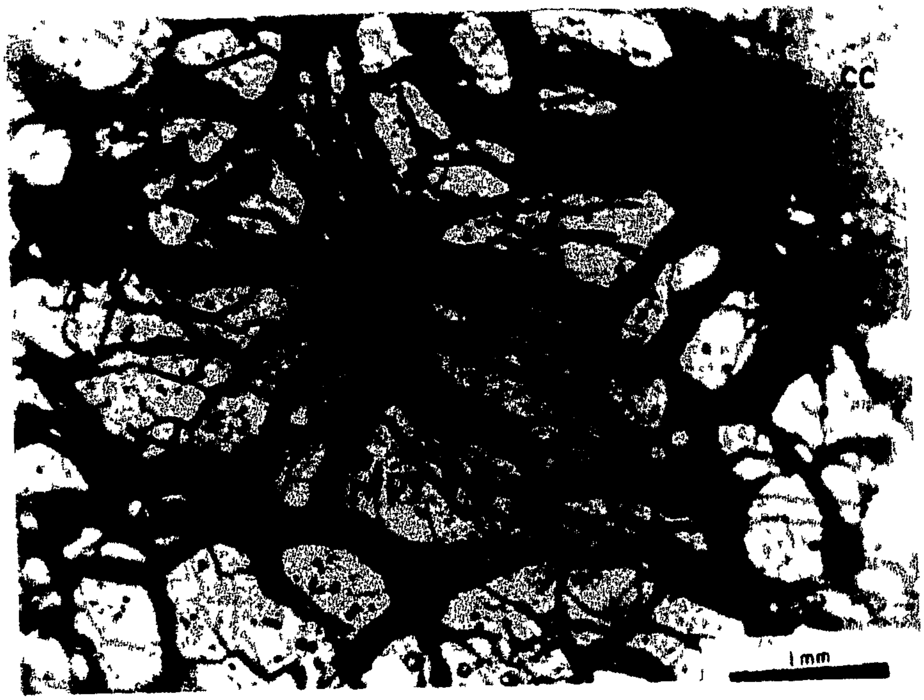


Figure 7.19: Star-shaped blebs of bornite in a pyrite matrix, from large nodules collected at Donaldson's Mill Brook occurrence, outer parts of the nodule are massive chalcocite Py = pyrite, BO = bornite, CC = chalcocite, Dg = digenite.

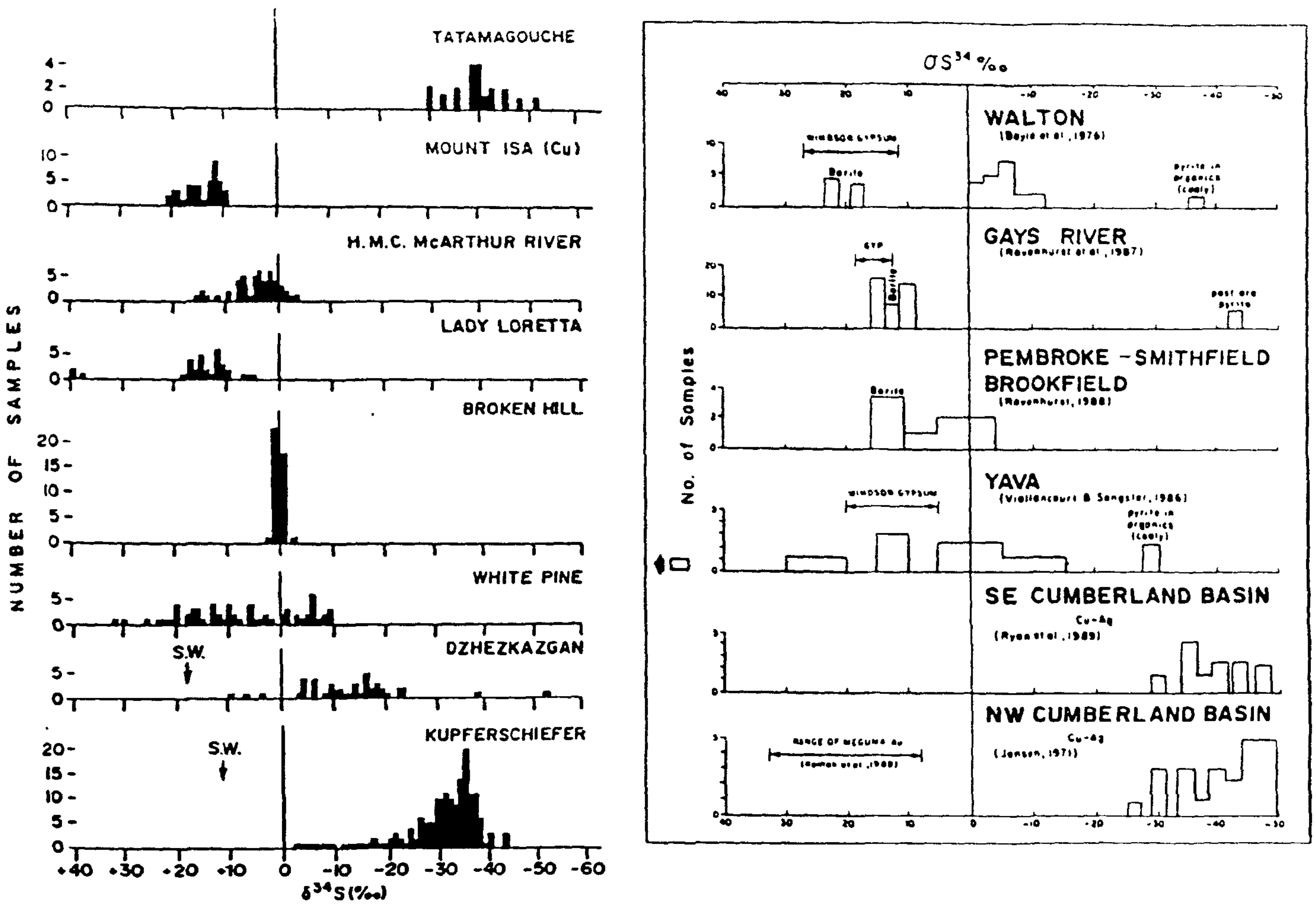


Figure 7.20: Sulfur isotopes from the Cumberland Basin, a) compared to regional values, b) compared to world class deposits.

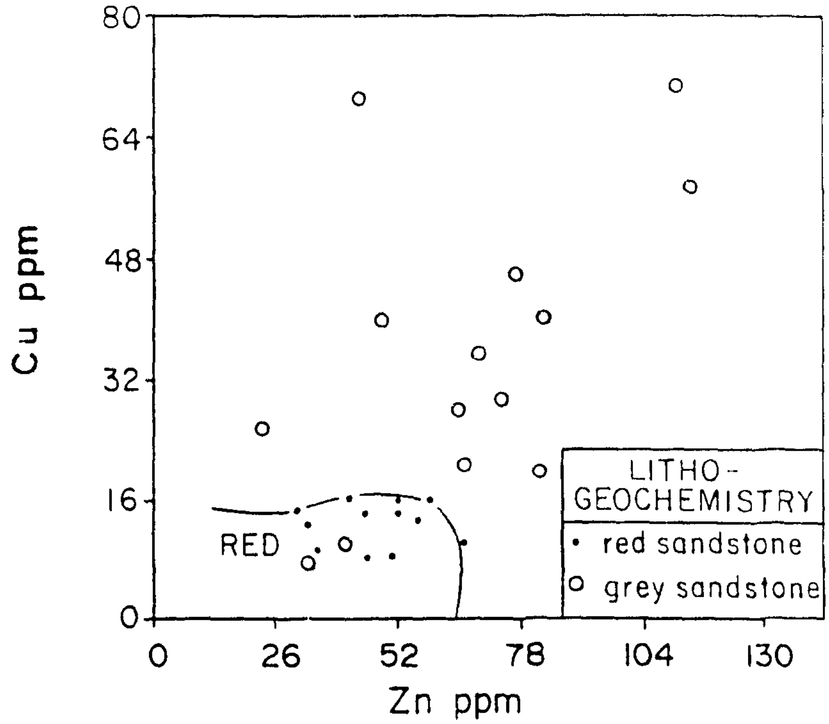
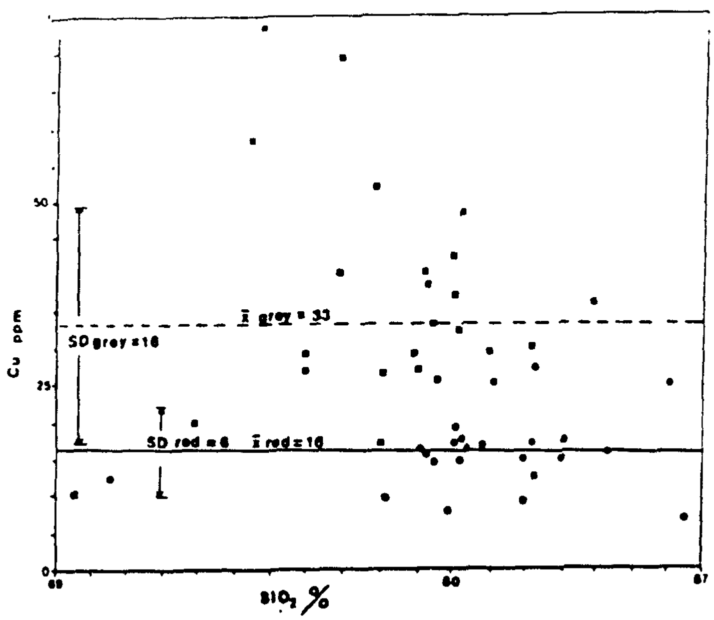


Figure 7.21: Plot of copper versus zinc for red and grey unmineralized sandstones from the Cumberland Basin.



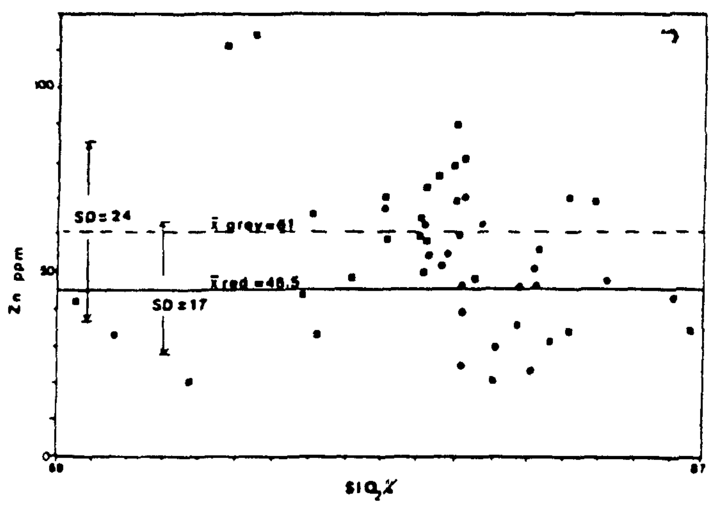


Figure 7.22: Plot of the increased SiO_2 content of the red sandstones as compared to the grey sandstones.

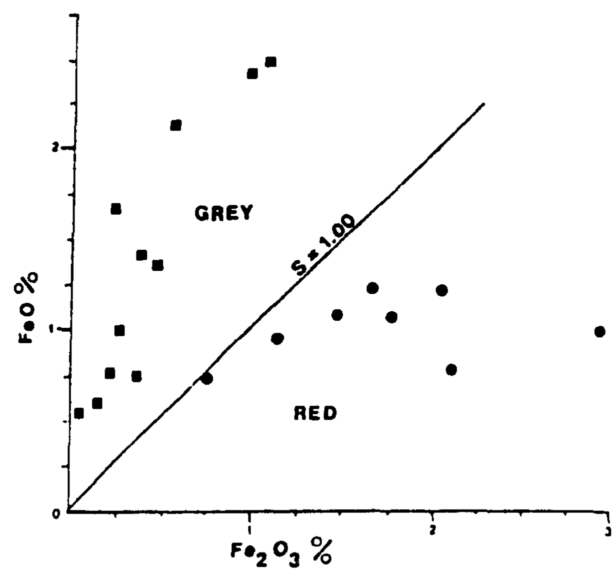


Figure 7.23: Plot of the FeO versus the Fe_2O_3 for the red and grey unmineralized sandstones of the Cumberland Basin study area.

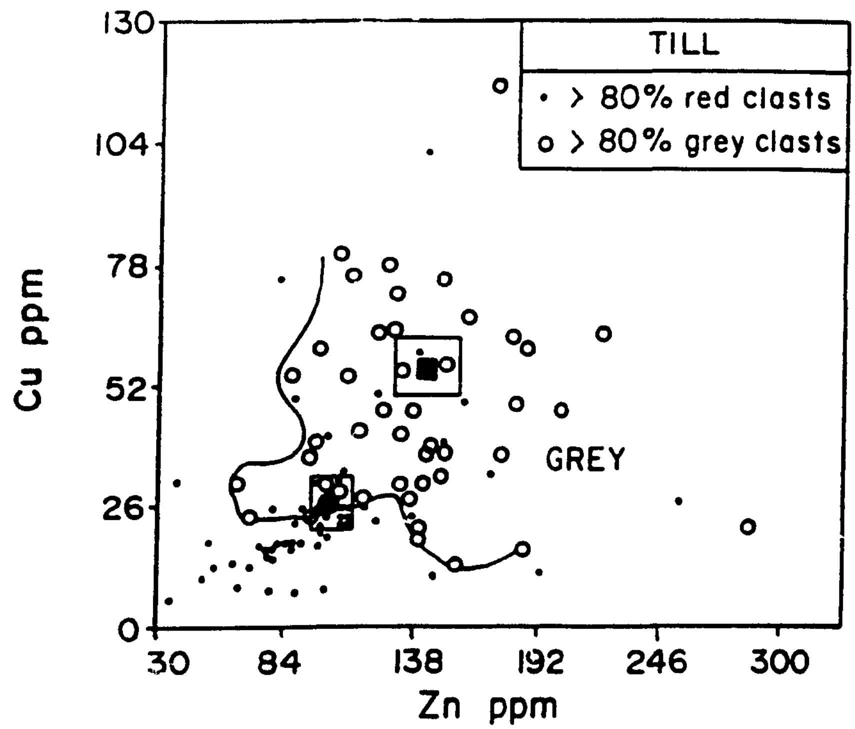
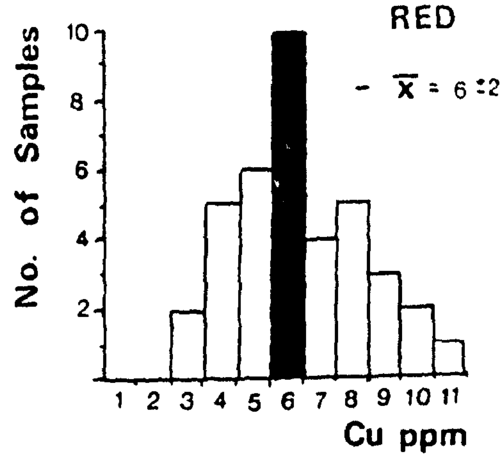


Figure 7.24: Till geochemistry (clay fraction) copper versus zinc for two sets of data, one with greater than 80% red clasts and the other with greater than 80% grey sandstone clasts.



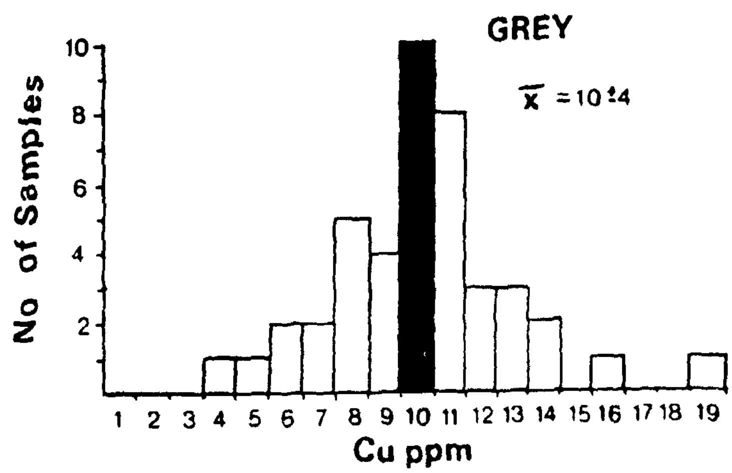


Figure 7.25: Plot of the stream geochemistry comparing areas where redbeds predominate versus areas where streams are cutting through grey strata. Once again there is a depletion of Cu within the red strata as compared to the grey strata.

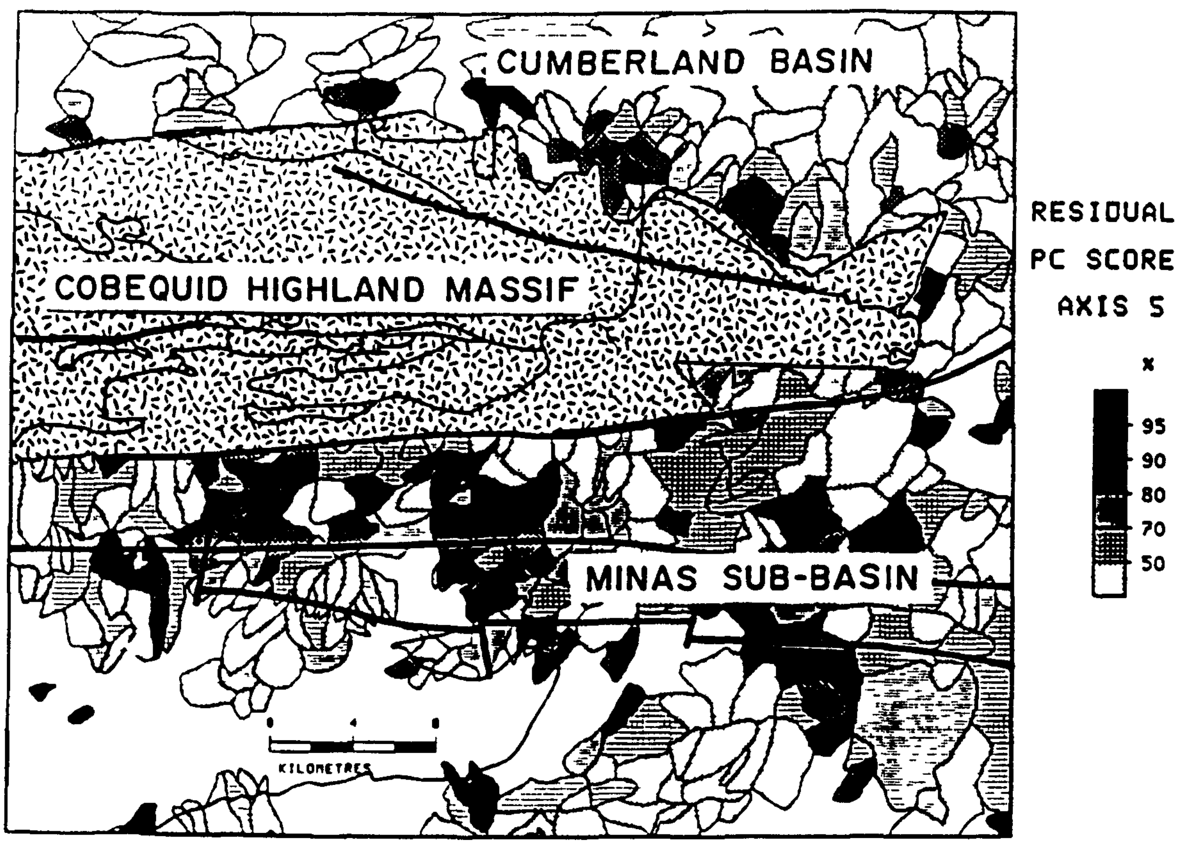


Figure 7 26. Cu-As plot of the catchment Basin stream geochemistry, note the paucity of high values in the Cumberland Basin (after Ryan et al., 1989).

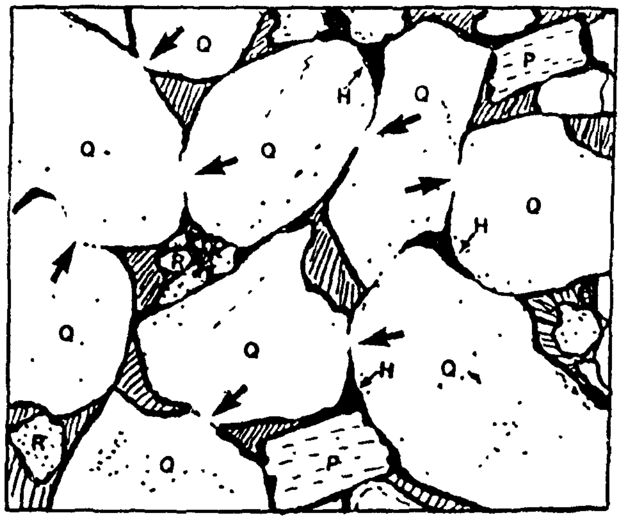


Figure 7.27: Nature of hematite coatings of quartz grains in the red sandstones in the Cumberland Basin. Note that there is no hematite occurring at the grain to grain contact indicateing that the introduction of the hematite post-dates the lithification of the rock

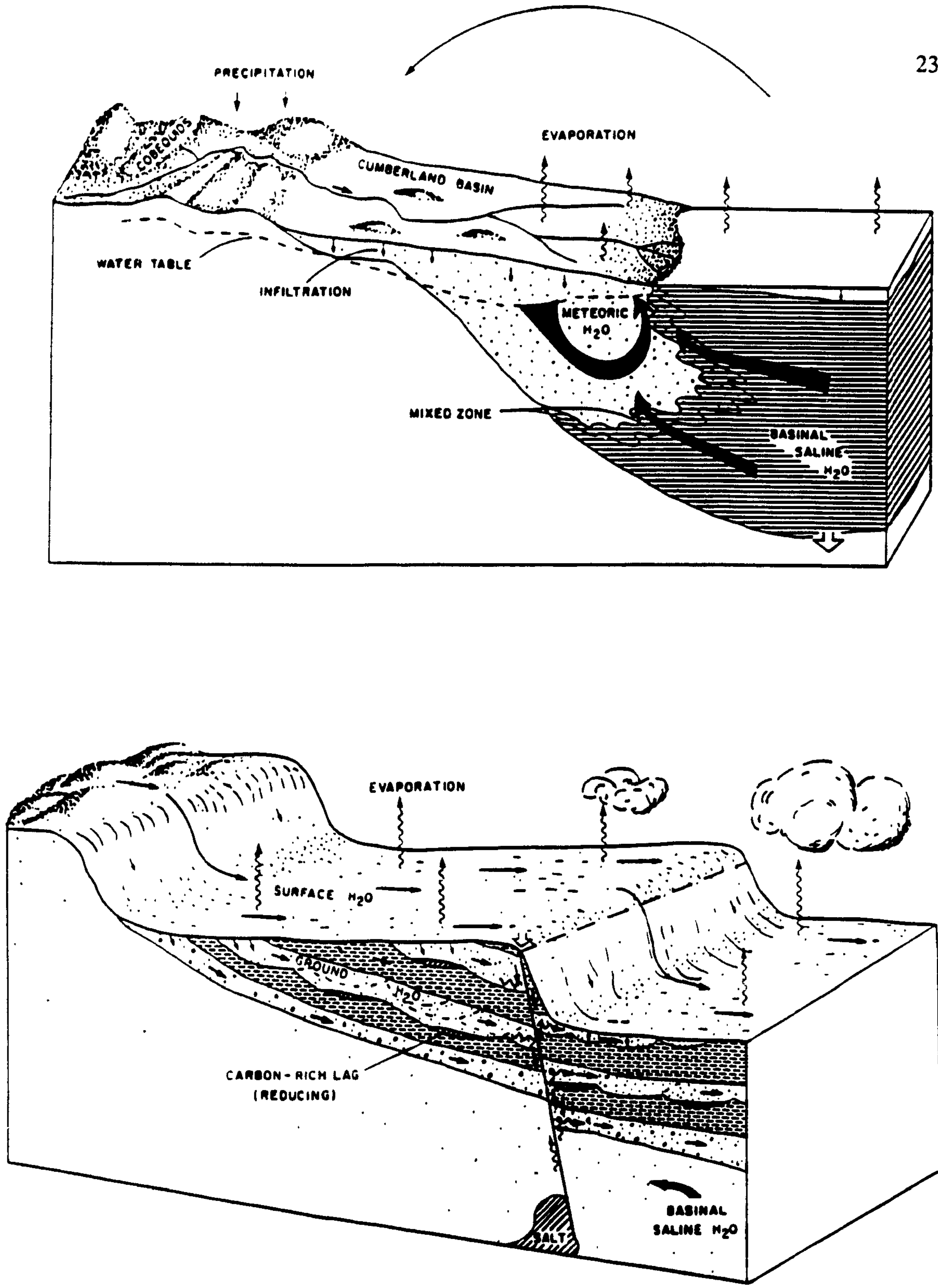


Figure 7.28: Models for groundwater flow and oxidation of grey sandstones to red in the Cumberland Basin.

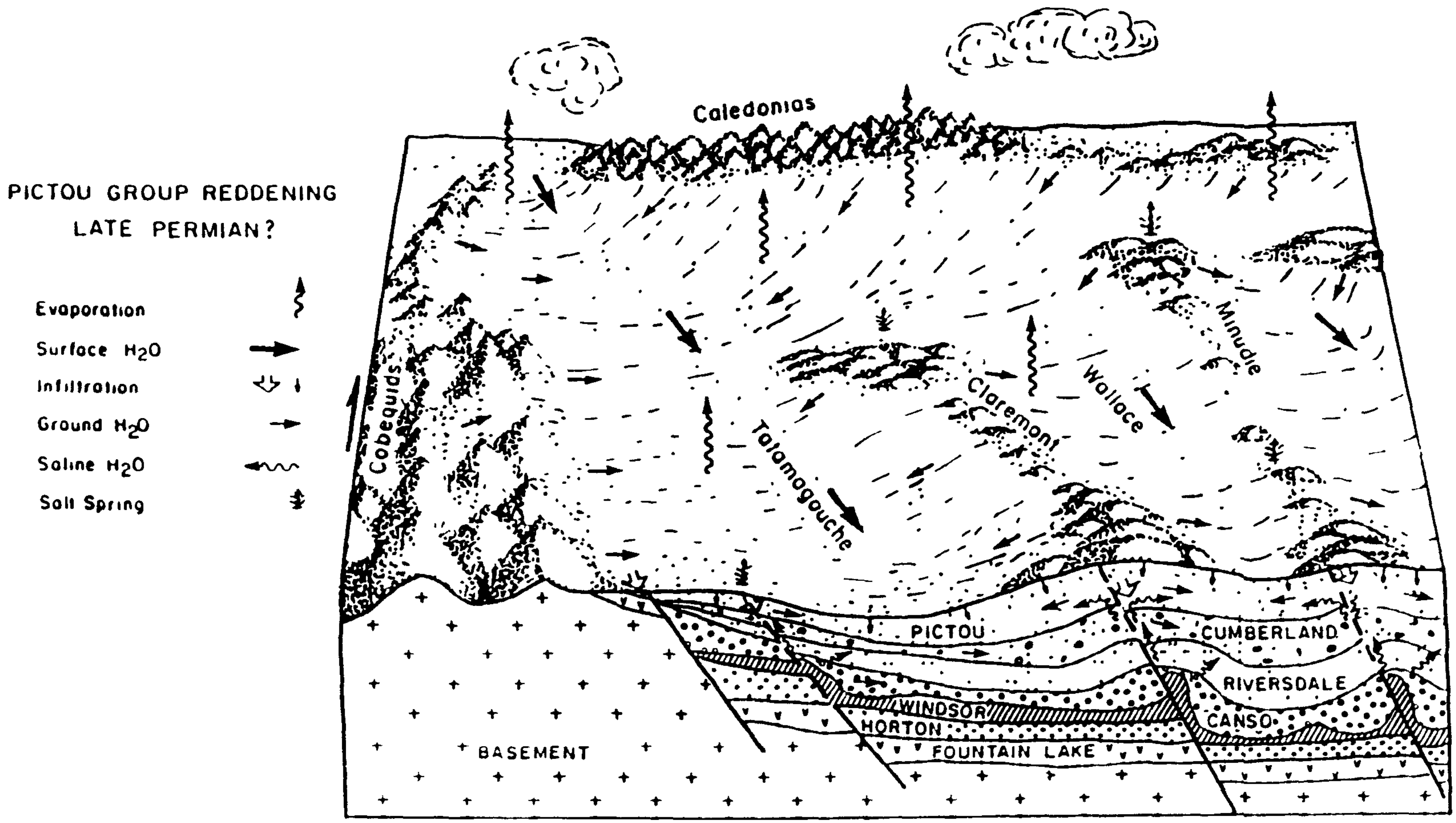


Figure 7 29. Paleogeographic reconstruction model for the reddening and mineralizing event in the Cumberland Basin, view is looking southwest

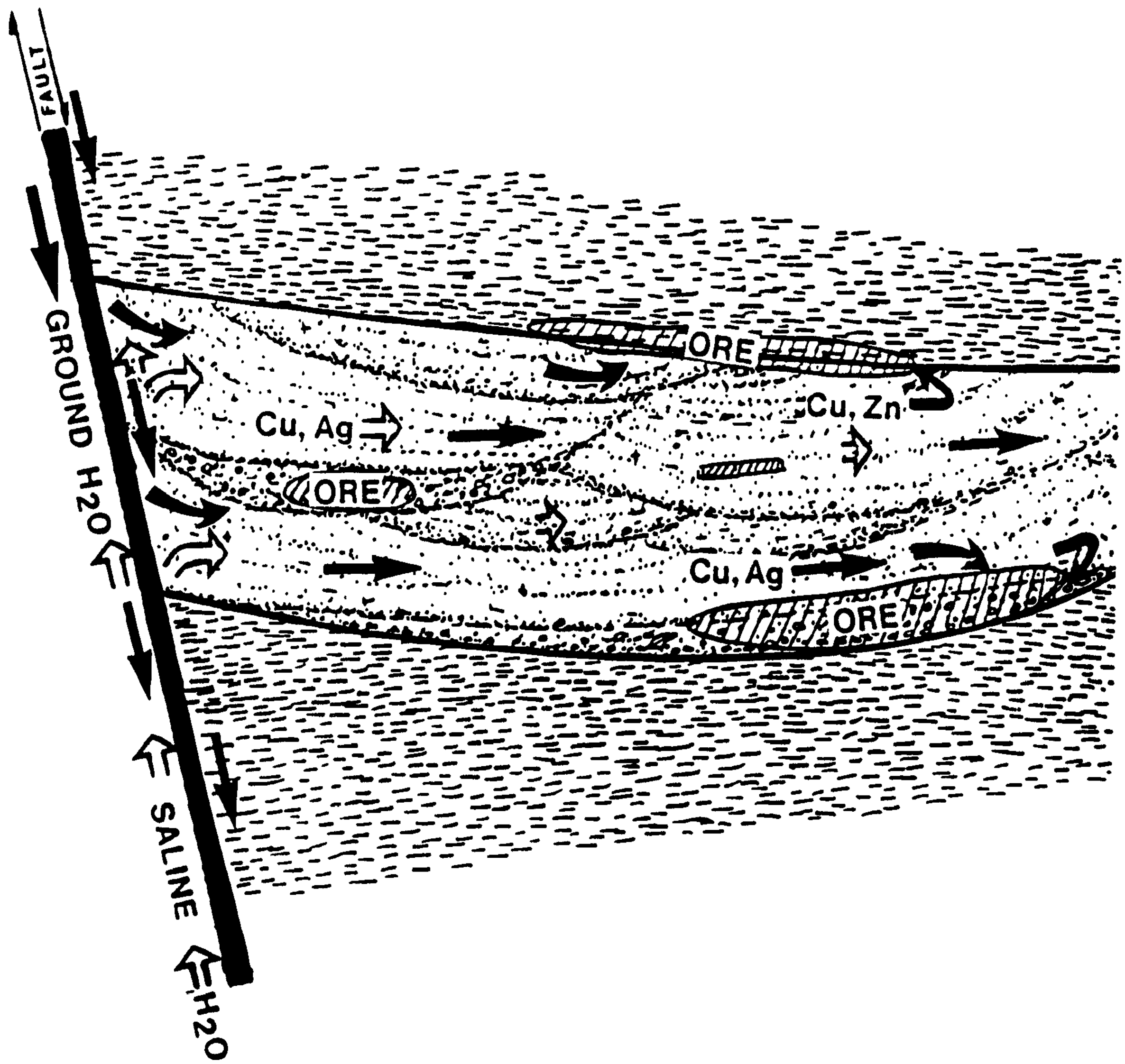


Figure 7.30: Detailed model for the sandstone hosted Cu-Ag occurrences in the Cumberland Basin.

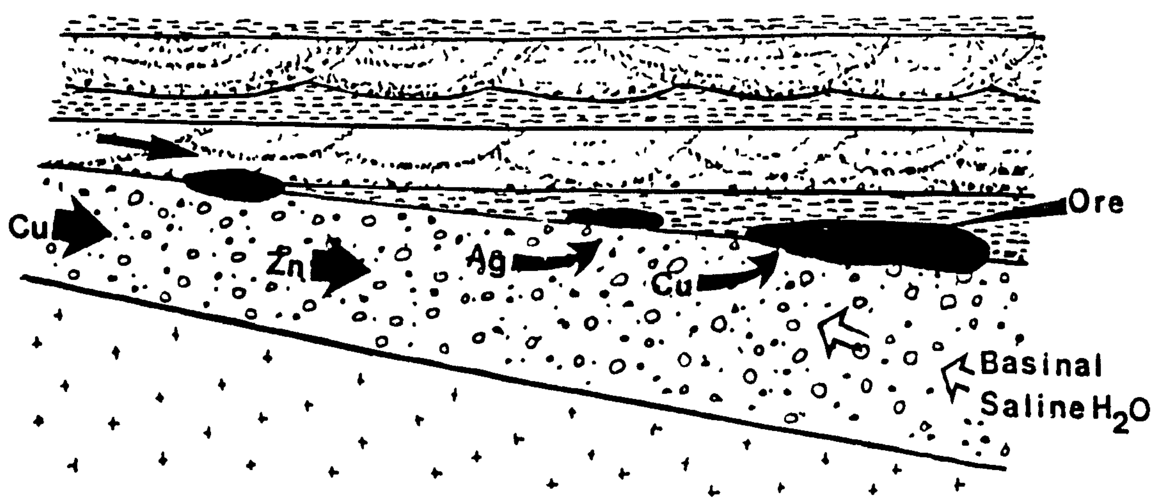


Figure 7 31 Detailed model for the shale hosted Cu-Ag occurrences in the Cumberland Basin

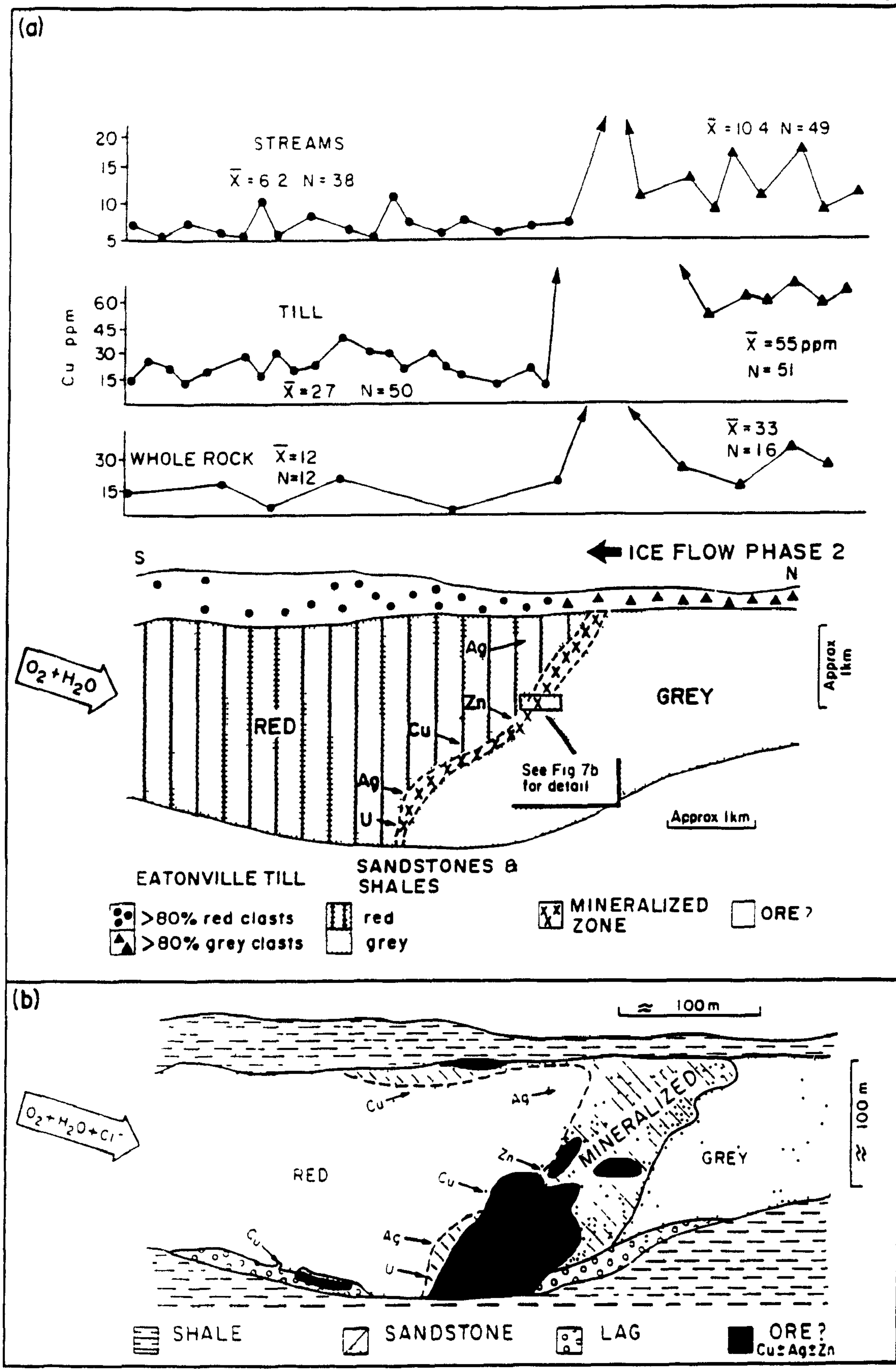


Figure 7.32: Exploration model depicting the response of the various sampling media in relation to the mineralization (modified after Ryan et al., `9).

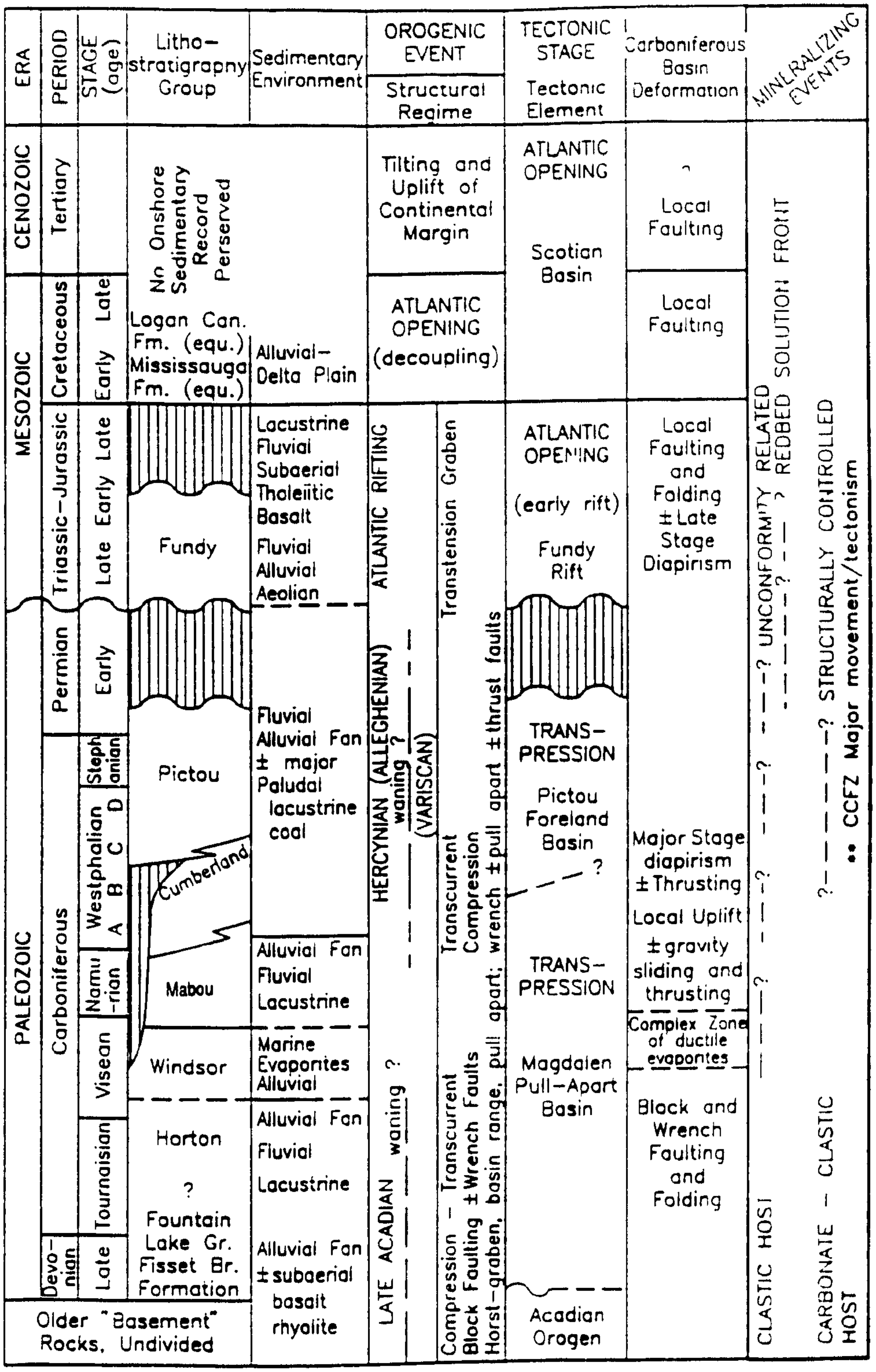


Figure 7.33: Stratigraphic and tectonic compilation for the Cumberland Basin correlated with the mineralizing events.

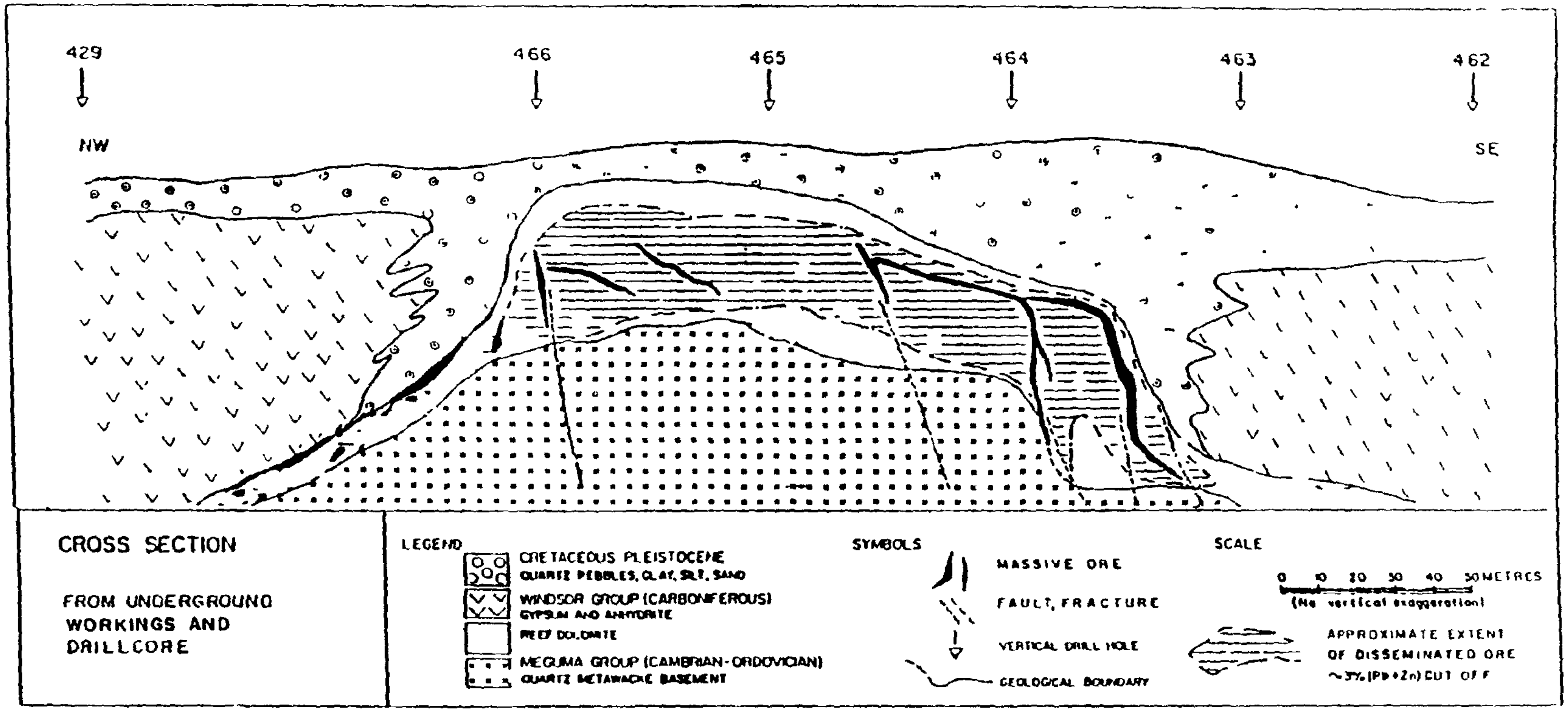


Figure 7.34: Cross section of the Gays River Deposit, after Akande and Zentilli (1984).

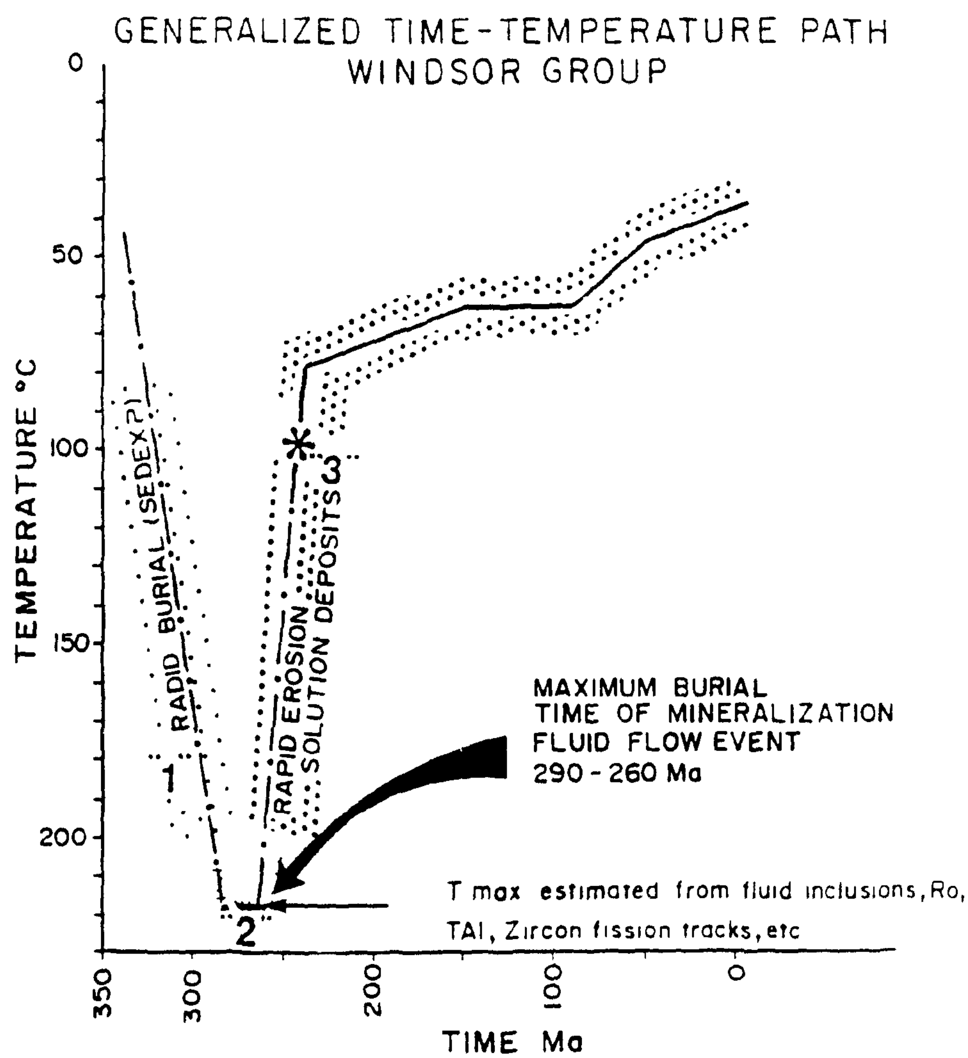


Figure 7.35: Generalized time-temperature path for the Windsor Group strata away from the basin margin. Note that all three mineralization affinities can be explained in relationship to the time-temperature path.

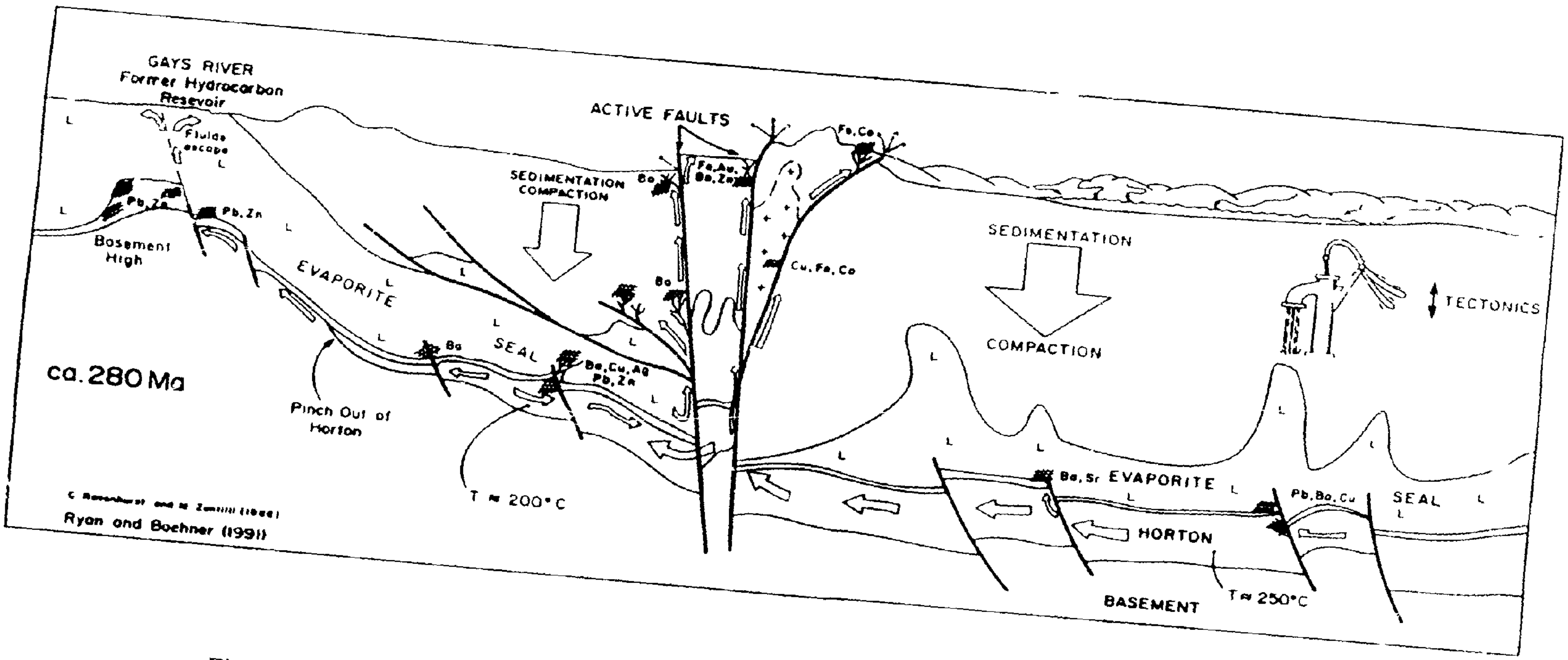


Figure 7.36: Modified Ravenhurst and Zentilli (1987) model for bawsin brine expulsion, note the addition of tectonics to the model (after Ryan and Boehner, 1991)

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

1. The most important contribution of this thesis is the documentation of an additional 2-4 km of strata which was deposited on the top of the Maritimes Basin strata during the period up to 280 Ma. A subsequent exhumation of these strata from 270 to 200 Ma removed them from the geological record. Although other authors (e.g Hacquebard, 1986) have suggested the existence of additional cover, this thesis, through the use of apatite fission track analysis, is the first study to accurately constrain the timing of this additional cover throughout the whole basin The fission track study also permitted a better interpretation of the other thermal indicators, and provided the thread that tied all of the thermal data together. The additional sedimentary cover and its subsequent erosion or exhumation explains why the structure and diagenetic state of the strata at the present day surface are difficult to interpret. The Maritimes Basin is therefore an erosional remnant of a formerly much larger basin and the ramifications of the exhumation of this cover are far reaching. It has direct bearing on the organic maturation, the basin forming mechanisms, and the metallogenesis in the Maritimes Basin. Interpretation of the geological record, both within and adjacent to the basin, must take the additional sedimentary cover into account. Most organic maturation models do not easily lend themselves to the modelling of a basin that is an erosional remnant and therefore the documentation of (post-maximum burial) exhumation of a basin is an important question to ponder before embarking on modelling in any basin.

2. The additional cover documented through this study, and the subsequent exhum event place time constraints on the basin-brine expulsion mineralizing models proposed for the basin. This study neither confirms nor denies the validity of the basin-brine expulsion model as proposed by Ravenhurst and Zentilli (1987) however if such an event took place it must have

occurred prior to the onset of the exhumation event, that is before 280 Ma.

3. The diagenetic process of reddening event that affected the Upper Paleozoic sandstone hosts to the Cu-Ag deposits in the Cumberland Basin, must have been active during the time of exhumation of these strata. The reddening has been dated by paleomagnetic studies as Late Permian. The reddening of the sandstones has been linked to the mineralization by this study and the timing of the reddening corresponds well with the exhumation of the basin. This exhumation provided the opportunity for the permeable sandstones of the basin to be infiltrated by oxygenated groundwaters that leached Cu-Ag and associated elements from the sandstones and concentrated these elements in areas where reductants were encountered.

4. Many other geological features can be assessed in light of the time-temperature paths determined for the basin. Synsedimentary mineralization (such as sedimentary exhalative deposits, if they exist) would have been metamorphosed (diagenetically altered) by the subsequent burial in the basin (Fig. 7.35). Post mineralization heating may be one of the reasons why this type of deposit has not been documented in the Maritimes Basin.

5. The exhumation event itself brings up a serious question as to its mechanism. The basin is so evenly exhumed that it is here proposed that the later stages of the basin-fill occurred above sealevel in an intercontinental setting, and that denudation back to the base level throughout the basin explains the exhumation consistency (see chapter 6, section 6.5).

8.2 RECOMMENDATIONS FOR FUTURE WORK

The following are a few suggestions for future work that have come out of this study: 1) apatite fission track work on east coast Cape Breton to see if the Permo-Carboniferous burial history of that area is similar to the rest of the Maritimes Basin;

2) similar apatite fission track analysis could be carried out in on Carboniferous rocks in New Brunswick and in the Carboniferous of the St. Georges Bay Basin of Newfoundland and in the area of anomalously low maturation in the northwest part of the basin adjacent to the L-49 well;
3) basement rocks further away from the present day margins of the Maritimes Basin should also be investigated by apatite fission track analysis to see if the additional Permian cover extended to them, in particular Anticosti Island and the Gaspe Coast;
4) fission track analysis perhaps using zircon (which is sensitive to temperature ca. 175°C) should be conducted within the Maritimes Basin in areas where there has been anomalous heat flow,such as along the Cobequid-Chedabucto Fault system, adjacent to diapirs, areas adjacent to the E-49 well, etc., thus establishing fault-related thermal signatures in the basin;
5) more work should be done on determining the kerogen types present in the Maritimes Basin so that the kinetic oil generation thermal modelling can be applied to better assess the coal bed methane potential in the basin;
6) Apatite fission track analysis should be undertaken on the Triassic and Jurassic strata of the Atlantic region so as to assess the magnitude and extent of the Mesozoic-Cenozoic tectonism and sedimentation.

APPENDIX I: REVISED STRATIGRAPHIC NOMENCLATURE

Stratigraphic subdivision of the Early Carboniferous to Early Permian strata in the Cumberland Basin in Nova Scotia (Fig.2.3) has been formally introduced, revised and defined in by Ryan et al.(1991a). Significant revisions resulting from new subdivisions and reassignments affect the Windsor, Mabou, Cumberland and Pictou Groups and are discussed in detail by Ryan et al. (1991a) and therefore will not be presented here.

A summary of the stratigraphic units of interest is presented here (Fig.2.3). The Horton and the Fountain Lake Groups occur within the Cobequid Highlands Massif and in the subsurface of the Cumberland Basin, however these units do not crop out in the Cumberland Basin and are therefore not described below, for further information on these units the reader is referred to Ryan and Boehner (1992). Absolute ages for the units are from Harland et al. (1989). Although Hess and Lippolt (1986) provided more precise Upper Carboniferous ages, they did not include Permian ages and therefore for the purpose of simplification the Harland et al. time scale is used throughout this thesis (see section 2.3).

WINDSOR GROUP

General Statement: The Windsor Group is an important host for many mineral deposits in the Maritimes Basin. These marine strata contain: petroleum showings, carbonate-hosted Pb-Zn (Gays River, Jubilee), Cu,Pb,Zn,Ag deposits (Walton), barite deposits (Walton, Brookfield), and many industrial mineral deposits of gypsum, salt, potash, and limestone.

Age: Early Carboniferous; Early to Late Visean (333-350 Ma)(Utting, 1988; Giles, 1981)

Author: Dawson, 1873; redefined Bell, 1944; Kelley, 1967.

Description: Strata of this group are poorly exposed in the Cumberland Basin. Outcrops occur only along the axis of the Claremont and Minudie Anticlines and within and adjacent to isolated evaporite diapirs (Fig 1.1). The stratigraphy and correlation of Windsor Group rocks has been described by Wright et al. (1931), Rohff (1932), Bell (1944, 1958), Evans (1972), Carter (1987) and Boehner (1988). The Windsor Group is a complex cyclic sequence of interstratified evaporites, dominantly halite, anhydrite and gypsum with minor potash (sylvite and carnallite); redbeds, fine sandstone to mudstone, rare grit and minor grey to green mudstone, and minor fossiliferous marine limestone and dolostone. Two new lithostratigraphic units, the Pugwash Mine Formation and Limekiln Brook Formation, are introduced by Ryan and Boehner (1992) and Carter (1992), as subdivisions of the Windsor Group in the Cumberland Basin.

General Correlation: Placement of the Windsor Group-Mabou (Canso) Group boundary (Fig 2.2) has historically been a problem in the Cumberland Basin, especially in the Minudie-Minudie area (Fig 1.2). Bell (1944, 1958) placed the base of the Middleborough Formation, which Ryan et al. (1991a) considered the base of the Mabou Group in the Cumberland Basin, at the top of the highest carbonate unit in the main carbonate-bearing horizon. The contact was first interpreted as conformable by Bell (1944) but later as disconformable (Bell, 1958). The overlying nonmarine redbeds, even though age equivalents of the Windsor Group, occur above the limits imposed by the marine carbonate strata and are therefore not considered as part of the Mabou Group (Fig 2 2)

Thickness and Distribution: Evaporite tectonics has severely altered the original thickness and distribution patterns of the Windsor Group in the Cumberland Basin. Fragmented, incomplete sections indicate a probable original thickness in the range of 1000 m to perhaps as much as 1500 m, however, attenuated sections could be as thin as 500 m due to erosion or evaporite flowage and removal (Boehner, 1988).

Relationship to Other Units: In the Cumberland Basin, the contacts between the Windsor and Horton Groups are absent or poorly exposed at surface Elsewhere within the Maritimes Basin, the Windsor Group either conformably or unconformably overlies the Horton Group or older strata (Fig.2.2).

Subdivisions: The subdivisions are discussed in detail by Boehner (1988) and Ryan and Boehner (1992).

MABOU GROUP

General Statement: This unit has been the most enigmatic (in a stratigraphic sense) Carboniferous stratigraphic unit in the Maritimes Basin and is perhaps the most poorly documented geologically. This unit is not a significant host for mineral occurrences; the abandoned iron mine at Londonderry and gold occurrences at Cape Spencer in southern New Brunswick are the only notable exceptions.

Age: Late Carboniferous; late Visean to Namurian (330-318 Ma)(Neves and Belt, 1970; Howie and Barss, 1975b).

Author: formerly Canso Group of Bell,1927; redefined by Bell,1944 and revised by Kelley, 1967; Canso Group formally abandoned and replaced by Mabou Group by Belt, 1964, 1965; Ryan et al.,1991a; both group names are currently in use (nearly synonymous) in the Maritimes Basin.

Description: Rocks of this group are incompetent and poorly exposed in the Cumberland Basin case study area. Limited exposures of red siltstones, fine grained sandstones, and mudrocks are found primarily along the axial areas of the anticlines (see Fig. I.1). In the western part of the Cumberland Basin the strata of the Mabou Group are exposed along the shore at Joggins, where there are two distinct units: a red fine grained unit, the Middleborough Formation, and a coarser grained unit with distinctive interbeds of grey to greyish-red sandstone, the Shepody Formation (Fig. I.2). In the eastern part of the basin there are good but incomplete exposures of the Middleborough Formation. The type section is on the Wallace River where it cuts through the axis of the Claremont Anticline (Fig.I.1).

Relationship to Other Units: The Mabou Group conformably overlies the Windsor Group.

Subdivisions: The Mabou Group can be divided into two formations: 1) the Middleborough and 2) the Shepody.

Middleborough Formation (Fig.I.2, I.3):

The Middleborough Formation comprises red to red-brown and locally grey-green mottled mudstone, siltstone, and fine- to medium-grained litharenite with rare, thin polymictic conglomerate interbeds (nonmarine).

The Middleborough Formation is 968 m thick at the type section (Bell, 1944) and approximately 300 m thick in the incomplete reference section at Joggins (Ryan, 1988). It is widely distributed in outcrop and in the subsurface throughout the Cumberland Basin.

Shepody Formation (Fig.I.2, I.3):

The Shepody Formation comprises greenish-grey, medium grained sandstone with minor calcareous mudchip channel lag conglomerate, ripple laminated fine grained grey to red sandstone, interbedded with red mudstone and siltstone. The sandstone(sand) to siltstone (silt) ratio (strata of sand size or coarser / strata silt size or finer) is approximately 1.4 to 1 Plant detritus is common within the sandstones and malachite after chalcocite is locally abundant in the grey channel lags. The Shepody formation, where it is the first greybed unit on the redbeds of the Mabou Group, can be mineralized. The mineralization is primarily copper with varying amounts of associated uranium and zinc (see Chapter 7)

The Shepody Formation is approximately 700 m thick at the type section and has a limited distribution in the basin. The thickness towards the southwest decreases dramatically. Recognition of this unit outside of the western Cumberland Basin is difficult, as distinction from the Boss Point Formation is nearly impossible without good exposures of the overlying or underlying contact relationships.

CUMBERLAND GROUP

General Statement: This group of predominantly grey strata contains numerous Cu, Pb, Zn, U and industrial mineral occurrences, especially in the Cumberland Basin, however the economic significance of this unit is based primarily on the coal resources that this group contains.

Age: Late Carboniferous; Namurian to Early Westphalian D; (325-305 Ma)(Bell, 1944; Howie and Barss, 1975b; Dolby, 1989).

Author: Bell, 1924; redefined Bell, 1944; revised Kelley, 1967; revised to include units of the now abandoned Riversdale Group (Ryan et al., 1991a).

Type Locality: The Joggins and Springhill Coalfields of Cumberland County, Nova Scotia, constitute the type area. The type section is located along the shore of Chignecto Bay from Lower Cove, 3.2 km north of Joggins, to Squally Point, 51 km southwest (Fig. I.1). The shoreline between Sand Cove and Lower Cove is perhaps the most complete continuous section. The shore section has nearly continuous exposure, however folding and faulting in the gently dipping strike section repeats the upper part of the section several times.

Description: The group is of heterogeneous lithology comprising: red and grey boulder to pebble polymictic conglomerate; grey, medium- to coarse-grained, trough cross-stratified, subarkose to sublitharenite; grey to reddish grey, coarse-grained arkose; grey to reddish-brown mudstone and siltstone; red to grey, fine-grained litharenite; coal seams from 0.01 m to 3.5 m thick; and thin bituminous black limestone and shale.

As previously stated in Table 2.1, formations are assigned to the Cumberland Group using the following criteria: (1) strata are frequently but not always coal-bearing; (2) rocks are typically dominated by grey facies with subordinate red facies; (3) the stratigraphic position is disconformable to conformable above Mabou Group, and may be unconformable with older Carboniferous or basement rocks, and is conformably to unconformably overlain by Pictou Group; (4) subordinate to subequal fine grained facies are present; and (5) locally abundant coarse-grained conglomeratic facies may be present.

Relationship to Other Units: The Cumberland Group has a variety of contact relationships including: conformable, to disconformable with underlying Mabou Group; unconformable with basement rocks of the Cobequid Highlands; and angular unconformable with underlying Windsor Group and Mabou Group strata.

Subdivisions: Formal designation of seven formations within the Group in the Cumberland Basin was proposed by Ryan et al. (1991a): Claremont, Boss Point, Polly Brook, Joggins, Springhill Mines, Ragged Reef and Malagash Formations (Fig. I.2). Many of these formations are similar to the facies terminology used by Shaw (1951a). Although all seven occur in the western Cumberland Basin, only five have been recognized within the rest of the Maritimes Basin. For a complete description of the type localities and details of the lithostratigraphy the reader is referred to Ryan et al. (1991a). Included here is a brief description of the units and their thickness. For correlation of formations outside the Cumberland Basin area, see Figure 2.1.

Claremont Formation (Fig. I.2, I.3):

Red with minor green mottled, boulder to pebble polymictic conglomerates, with minor interbeds of coarse grained arkosic grit and sandstone. The conglomerates are subangular to subrounded, with moderate- to poor-sorting and can be matrix- or clast-supported. Clast lithology varies reflecting locally derived clasts typical of basement rocks exposed in the nearby highlands.

The thickness and distribution of this unit is extremely variable. In the eastern Cumberland Basin the thickness varies from a few metres to 1000 m. The formation is absent or very thin and distinctly finer grained in other areas of the Maritimes Basin.

The Claremont Formation conformably to disconformably overlies the Mabou Group. It forms the basal conglomeratic portion of the Cumberland Group (Fig. I.2) and is conformably overlain by the Boss Point Formation. In areas adjacent to the highlands the base of this unit may be significantly older, and deposition of conglomeratic rocks may have occurred from the late Visean to the late Namurian.

Boss Point Formation (Fig. I.2, I.3):

The Boss Point Formation is a widespread unit and is typically the first greybed succession on top of the redbed sequence of the Mabou Group. Because this red to grey boundary acts as a reduction-oxidation boundary, it is mineralized at many localities, with Cu, Pb, Zn, U, and other metals (see Chapter 7). The clean and relatively pure nature of the quartz-rich sandstones of this formation has nurtured long standing exploitation of the rocks as building stone.

Grey to greenish-grey, yellowish weathering, quartz-rich sublitharenites; limestone (rhizoconcretion-calcrete); mud-chip conglomerates; and minor quartz pebble conglomerates comprise the lithologies of the unit. Sandstones are generally medium grained, and trough cross-stratified. The sandstones are interbedded with, grey, with minor red, fine grained sandstones and mudstones, especially at the top of the formation. Rare impure coal seams and bituminous limestones are present. Coalified plant debris is ubiquitous. Sand (sand and coarser) to silt (silt and finer) ratio of 2.2 to 1. The sandstones greater than 1 m in thickness are usually multistoried and multilateral. The sandstones can be up to 45 m thick and average approximately 35 m in thickness at the base of the formation whereas at the top they are 5-10 m thick. Thinner splay and small channel sandstones occur as interbeds within the mudrock sequences (see Chapter 3)(Fig. I.2).

Various workers have subdivided the Boss Point Formation into mappable units (Bell, 1944; Shaw, 1951; Ryan and Boehner, 1988), however for the purposes of this study subdivision is not warranted. Ryan and Boehner (1988) indicate a thickness of 982 m for the type section. In the southeastern Cumberland Basin the Boss Point Formation varies in thickness between 200 to 650 m (Ryan, 1985). Interpretations of seismic data indicate that the thickness may be substantially greater, especially within the Athol Syncline area. The Boss Point Formation is widely distributed, and occurs in outcrop and in the subsurface throughout the Cumberland Basin and may occur throughout the Maritimes Basin, although none has been described from the Sydney Basin.

The Boss Point at the type section conformably overlies and interfingers in part with the Claremont Formation. Elsewhere in the basin the unit overlaps all of the older basin-fill units and the basement rocks of the highland massifs, with contacts being disconformities, angular unconformities, and nonconformities.

Polly Brook Formation (Fig. I.4, I.5):

This unit was deposited by alluvial fans near the basin margin (see Chapter 3) and its distribution has important ramifications for the tectono-sedimentary history of the basin (see Chapter 6).

The unit comprises ortho- and paraconglomerates ranging from boulder to pebble clast size. The clasts are moderately to poorly rounded and sorted. Clast lithology is variable, but most are clasts of rhyolite, granite, diorite, and metamorphic rocks derived from the Cobequid Highlands Massif. Reworked Carboniferous sedimentary clasts, especially of Boss Point Formation lithology (quartz-rich sublitharenites), locally form a significant component, and distinguish this unit from the Claremont Formation which is dominated by igneous and metamorphic clasts. Near the top of the formation scattered 5-10 m thick pebbly immature cross-stratified sandstones occur as interbeds within the conglomeratic package.

The Polly Brook Formation displays rapid thickness variation with a maximum of 1400m estimated in the type area (Fig. I.4). It thins dramatically east, west, and north of the Springhill area. Calder (1991) estimated a thickness of 600 m for the unit in the Springhill area. The unit appears to be absent in the eastern part of the Tatamagouche Syncline and along the shore at Joggins. It is best developed in the south central parts of the basin near the Cobequid Highlands.

This unit is laterally equivalent to, and interfingers with, the Joggins Formation and the lower beds of the Springhill Mines Formation (Ryan et al., 1990; Calder, 1991). The contact with the underlying Boss Point Formation is not well exposed in outcrop. The Polly Brook Formation also nonconformably overlies the basement rocks of the Cobequid Highlands Massif in the western part of the Basin.

Joggins Formation (Fig. I.2, I.3):

The Joggins Formation has traditionally been referred to as the lower coal measures in the Cumberland Basin area. The coals exposed along the Joggins shoreline and east to Chignecto were mined extensively for the thin but continuous coal seams.

The Formation comprises grey, mudstone, shale, and siltstone; grey, medium-grained, cross-stratified sublitharenite, forming multi-storied bodies averaging 6 m in thickness. There are numerous thin (less than 1 m) fine- to medium-grained sublitharenite to litharenite sandstones interbedded with the mudrocks. Numerous thin humic and sapropelic coal seams typically less than 1 m thick (Fig. I.2) also occur. These coals are commonly overlain by bivalve-bearing black shales with varying organic and carbonate content. Rare calcareous mud-chip conglomerates occur near the base of the sandstone sequences. Locally, as in the area north of the Claremont Anticline, the coals and calcareous shales are rare to absent. The sand to silt ratio of the formation is approximately 0.4 to 1.

The formation is 1433 m thick at Joggins, may be thicker in the central part of the Athol Syncline, but thins towards the south and the east. It may be absent in the Tatamagouche Syncline area and therefore restricted to the western part of the Cumberland Basin. Equivalent strata do occur throughout the Maritimes Basin

The Joggins Formation is conformably overlain by the Springhill Mines Formation Naylor et al. (1992) has suggested that the unit is the fine-grained basinward (distal) equivalent of the conglomeratic Polly Brook Formation which dominates the south-central part of the Cumberland Basin.

Springhill Mines Formation (Fig. 1 4, 1 5):

The Springhill Mines Formation contains thick coal seams that have been extensively exploited in the past. Although most of the shallow (less than 1000 m) coals have been mined out, potential exploitation of the deeper coals as a source for coal bed methane is currently being assessed.

Subequal amounts of medium grained, grey, sublitharenitic sandstones and grey shales and mudstones, with numerous thin coal seams, bituminous black shales, and limestones, constitute the principal lithotypes of this formation The sand to silt ratio at the Joggins section is 1 4 to 1, however the strata at Springhill contain more abundant mudrocks The sandstones can be as thick as 15 m, where they occur as multi-storied sandstone sequences, or as thin as 1 m, where occurring as planar-bedded splay deposits (for interpretation see Chapter 3)

The thickness of the reference section at Joggins is approximately 610 m (Fig 1 2), however it is approximately 500 m thick at the type area (Fig 1 4) Seismic data in the central Athol Syncline indicate that the unit may thicken substantially in the subsurface near the axis of the syncline. The unit is not exposed at surface in the eastern part of the basin, however it may occur in the subsurface in the Wallace Syncline area where drillholes OX-BP 5, 6, 7 and 8 intersected equivalent strata

The basal part of the Springhill Mines Formation in the type area is transitional with, and in part a lateral equivalent of, the upper portions of the Polly Brook Formation The unit conformably overlies and interfingers in a transition with the Polly Brook Formation in the Springhill area, and it conformably overlies the Joggins Formation in the Joggins section along the shore of Chignecto Bay where the Polly Brook Formation is absent. The unit is conformably overlain by, and may be partially transitional with, the Ragged Reef Formation.

Ragged Reef Formation (Fig. I.2, I.'

The Ragged Reef Formation is a newly recognized unit that represents a recycling event in the Carboniferous following the main episode of coal deposition in the Cumberland Basin. Minor coals do occur within the formation in the Cumberland Basin, and coeval coals and oil shales formed in the Stellarton Basin area (Fig. 2.1). There are a few copper occurrences in this formation but none of economic significance.

The Ragged Reef Formation comprises moderately to well sorted, coarse-grained, grey and red, sublitharenite and subarkose; polymictic pebble- to cobble-conglomerates; interbedded with red and grey mudstones and siltstones. The sandstones and the conglomerates are trough cross-stratified and form multi-storied and multi-lateral sandstone-conglomerate sequences up to 30 m thick. The mudstones are interbedded with fine grained, red to grey, planar-stratified sandstones which range from 0.5 to 2 m in thickness. Depending upon the area considered, the formation may be dominated by coarse sandy facies or by the red mudstone facies. Rare thin bituminous limestones and coal seams occur locally. The sand to silt ratio is approximately 1.5 to 1, but may be as low as 0.4 to 1 in the fine-grained facies in the central part of the Athol Syncline.

The Ragged Reef Formation is widely distributed in the basin, occurring in the major synclines, however it is poorly exposed at surface in the Tatamagouche Syncline and in parts of the Amherst Syncline. The thickness in the type section is 677 m, but this does not include the entire thickness of the unit, as the top of this unit is not exposed along the Joggins shore (Fig. I.2). Incomplete extensions of the section inland at Shulie, and correlations with the Spicers Cove area, indicate that an additional 200-300 m of strata may be present, giving a total thickness of approximately 1000 m. The unit thins towards the eastern part of the Cumberland Basin and is very thin in the Tatamagouche Syncline area. The unit occurs as a thin coarse facies in parts of the Wallace Syncline in the eastern Cumberland Basin where the thickness does not exceed 350 m.

The unit conformably overlies the Springhill Mines Formation, and may interfinger with the upper part of the Springhill Mines Formation in the subsurface. The unit is conformably overlain by the Malagash Formation.

Malagash Formation (Fig. I.6, I.7):

The Malagash Formation is the transition unit between the grey dominated beds of the Cumberland Group and the redbeds of the overlying Pictou Group. There are numerous copper-silver occurrences within this unit which are clearly related to the red to grey redox (reduction-oxidation) boundaries. The most significant occurrence is at Canfield Creek, south of Pugwash, and this occurrence is discussed in more detail in chapter 7.

The Malagash Formation is made up of grey to greyish-brown, subarkosic sandstones; red mudstones; and calcareous mud-chip conglomerates at the base of the coarse-grained sequences. The unit is characterized by the presence of variably distributed red coloration (diagenetic alteration) in some of the sandstones. Laterally persistent thin limestones and coal seams occur locally. The sandstone and conglomeratic bodies represent multi-storied and multi-lateral trough cross-stratified units with thicknesses typically 5 -20m. Thin (< 1 m) red sublitharenite to subarkose sandstones with planar bedding occur within the mudstone dominated sequences. The sand to silt ratio in the Malagash Formation is approximately 2 to 1. In the Athol Syncline the formation is distinctly finer grained with a ratio of approximately 0.25 to 1.

The Malagash Formation is widely distributed in the Cumberland Basin occurring in outcrop and in the subsurface of all the major synclines. The thickness of this unit at the type section is approximately 400 m (Fig. I.6), however the upper contact relationship is not exposed and the section is incomplete. In the River John section in the eastern part of the basin, the unit is bounded by disconformities and has a thickness of approximately 450 m (Fig. 1.8).

This unit conformably overlies the Ragged Reef Formation in the western Cumberland Basin and disconformably overlies the Boss Point Formation. It locally may overlie the Claremont Formation in the Tatamagouche Syncline in the eastern part of the basin. The Malagash Formation is disconformably overlain (low angle paraconformity) by the Balfron Formation redbeds of the Pictou Group. The Malagash Formation is approximately stratigraphically equivalent to the Cumberland 'Fine Non-coal Bearing Facies' of Shaw (1951), the Pictou 'Grey Beds' of Ryan (1985), and the Merigomish Formation of Yeo (1987). These units are all time equivalent and lithologically indistinguishable. They are grouped together into this unit for the purpose of this study.

PICTOU GROUP

General Statement: The Pictou Group is important because it records the final episode of Carboniferous basin-fill in the Maritimes Basin. Until recently there has been little effort made to subdivide the redbeds of the Pictou Group and therefore there was a paucity of information to be derived from the youngest basin-fill unit. The economic mineral resources of the strata have yet to be fully exploited, however the abundance of mineral occurrences (especially redbed Cu) indicates that there is excellent potential for the discovery of significant mineral deposits hosted by the Pictou Group strata (See Chapter 7).

Age: Late Carboniferous to Permian; Westphalian D to Early Permian (306.5-290 Ma), (Barss and Hacquebard, 1967; Dolby, 1987).

Author: Bell, 1926; revised Bell, 1944; additional revision, Kelley, 1967; Barss and Hacquebard, 1967; revised Ryan et al.,1991a.

Type Locality: The type locality is located on River John, downstream from the mouth of Mine

Brook, in the Tatamagouche Syncline area of the eastern Cumberland Basin (Fig. I.8, I.9). The lower grey strata of Bell's (1926) type section include beds that are considered herein as the uppermost formation of the Cumberland Group (Malagash Formation).

Description: The Pictou Group consists predominantly of redbeds with varying proportions of sandstone and mudstone. Lithologies include coarse- to fine-grained subarkose and sublitharenite, mudstone, siltstone, calcareous mud-chip conglomerate, rare thin coal seams, and light grey limestones Mudrocks are commonly interbedded with thin (<1 m) fine-grained sandstones with planar stratification This contrasts with the thicker (10 m) trough cross-stratified sandstones and conglomerates The overall sand (sandstone and coarser) to silt (siltstone and finer) ratio is approximately 0 4.

This unit is approximately 1650 m at the type locality (Fig. I.8), however it may be as thick as 3000 m in Prince Edward Island (Howie and Cumming, 1963). This unit is the most widespread of all of the Upper Carboniferous strata and occurs throughout the Maritimes Basin.

Relationship to Other Units: The Pictou Group may overlie any of the Carboniferous units or the basement rocks with disconformities, low angle paraconformities, angular unconformities, or nonconformities at its base This group previously has been correlated with, or encompassed all or parts of regional and local units including the Morien Group, the Stellarton Group, and the Prince Edward Island Redbeds. Using the assignment criteria proposed for the Pictou Group in this study (Table 1 2), only the Prince Edward Island Redbeds and equivalents (ie. the undivided Permo-Carboniferous redbeds in the Sydney Basin, redbeds in the Gulf of St Lawrence area, and probably the Broad Cove Formation in western Cape Breton Island) would be included in the Group

Subdivisions The group has been subdivided in the type area into three lithostratigraphic units formally introduced by Ryan et al.(1991a). In ascending order the formations of the group are: the Balfron, Tatamagouche and Cape John Formations.

Balfron Formation (Figs. I.10, I.11):

The formation comprises red-brown mudrocks, subarkosic sandstones, minor pebbly sandstone, calcareous mud-chip conglomerates, minor grey beds, and rare thin discontinuous limestones. The sand to silt ratio is approximately 1 to 1 . The thicker sandstone bodies (> 1 m) are typically trough cross stratified. The sandstones are usually coarse- to medium-grained, except where they occur as thin interbeds with the mudrocks in which case they are fine-grained. The sandstone bodies are multi-lateral and multi-storied. The multi-lateral nature of the sandstone bodies gives them a sheet-sand morphology, and sandstone horizons can be traced for several kilometres along strike (see Chapter 3). The sandstone - conglomerate packages are typically 10-15 m thick but can locally attain thicknesses in excess of 40 m.

The formation varies from 800 to 900 m in thickness within the Tatamagouche Syncline in the eastern part of the Cumberland Basin (Fig. I.8). This unit is widely distributed in the eastern part of the complex Wallace Syncline, as well as in the Amherst Syncline covering most of the northern part of the basin. It also occurs in the upper part of the Gulf et al. Hastings No. 1 well drilled near Amherst (Ryan et al., 1990).

The Formation overlies all of the older Carboniferous units in the basin and also may onlap the Pre-Carboniferous basement rocks. The contact relationships vary from disconformities, angular unconformities, to nonconformities.

Tatamagouche Formation (Figs. I.11, I.12):

This formation is dominated by red-brown mudrocks with subordinate, medium- to coarse-grained sublitharenites, minor pebbly sandstone, minor grey beds, and calcareous mud-chip conglomerates. Thin, laterally persistent light grey limestone beds locally are important marker beds. The formation has a sand to silt ratio of approximately 0.33 . The thick sandstone beds (> 1.5 m) are trough cross-stratified, whereas the thinner sandstone beds are planar bedded or ripple cross laminated. The thicker sandstones form sheet-like bodies which can be traced for tens of kilometres along strike The sand bodies are multilateral and multistoried. The sequences typically fine upwards and the scale of the sedimentary structures decrease upwards as well (see Chapter 3) This formation differs from the Balfron Formation primarily in that mudrocks are more abundant and in the presence of laterally persistent limestone beds.

The thickness of the Tatamagouche Formation varies from 300 to 350 m (Fig. I.8) The distribution of this unit outside the Tatamagouche Syncline in the eastern Cumberland Basin is unclear, although it is probable that redbeds exposed in the north central part of the basin, the Amherst Syncline, are equivalent to this unit.

Map relationships suggest that there is a paraconformity between this unit and the underlying Balfron Formation Similarly, the unit is overlain either conformably or paraconformably by the Cape John Formation. These low angle unconformities (paraconformities) are extremely difficult to map at individual outcrops due to the low angular discordance and the cross stratified nature of the sandstone bodies, however differences in the strike of the units is discernible from satellite imagery

Cape John Formation (Figs I 8, I 13):

The Cape John Formation is composed of red-brown mudstone and siltstone, coarse grained arkose to subarkose, pebbly sandstone, minor grey beds, and thin but laterally persistent limestones The sand to silt ratio is approximately 0.20 to 1. Sandstone sequences composed of pebbly sandstones, arkoses and subarkoses, with inter-cross-stratified calcareous mud-chip conglomerates. The sandstone sequences can be up to 35 m thick and are multistoried and multilateral. The multilateral nature of the sandstone bodies is not as well developed as it is in the other Pictou Group formations, and the sandstone sheets can only be traced for two kilometres along strike Most of the strata are red to red-brown in colour, however locally both sandstones and mudrocks are grey. The Cape John Formation differs from the other underlying Pictou Group formations in its lack of laterally continuity of the sandstone bodies and by a greater abundance of mudrocks.

The Cape John Formation is at least 400 m thick at the type locality (Fig. 1.8). The top of the formation in the eastern Cumberland Basin is incomplete due to erosion which limits the outcrop area to the axis of the Tatamagouche Syncline. The unit occurs as a limited outcrop area in the poorly defined axial area of the Amherst Syncline near Coldstream Head, north of Pugwash, along the shore of the Northumberland Strait, in the northern part of the study area. The Cape John Formation constitutes the youngest strata exposed in northern Nova Scotia and may be correlative to the lower part of the Prince Edward Island Redbeds of the Pictou Group in Prince Edward Island.

The formation overlies the Tatamagouche Formation with a paraconformity occurring at the contact. The distribution of the strata is restricted to the northern and eastern part of the Cumberland Basin, and throughout most of the Gulf of St. Lawrence area.

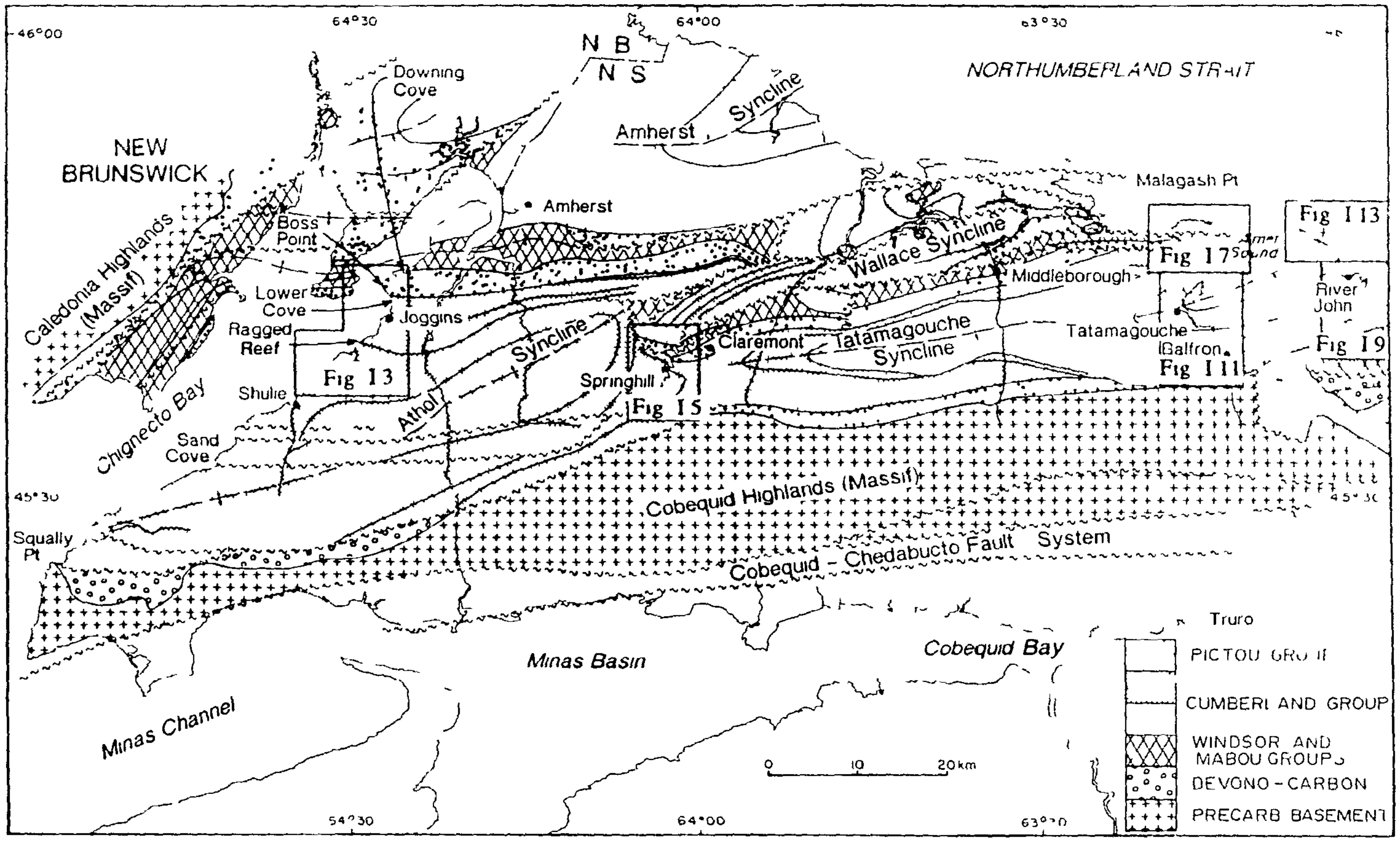


Figure I 1: Generalized geological map of the Cumberland Basin and location map for Appendix I

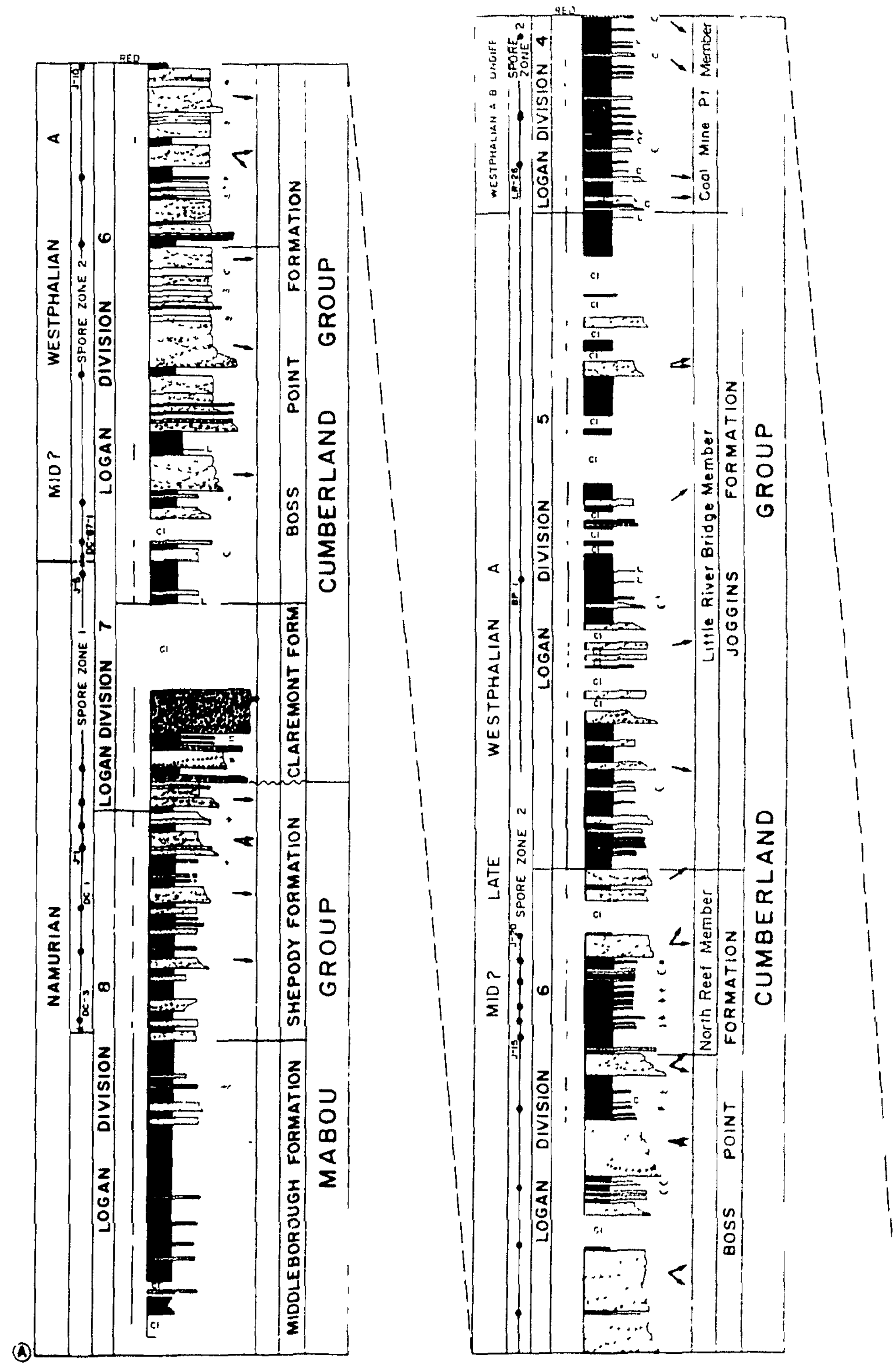


Figure I.2: Stratigraphic column of the classic Joggins Section along the shoreline in western Cumberland Basin. The original Dawson subdivisions are included for reference. The age of the units is determined by a palynological study (Dolby, 1987).

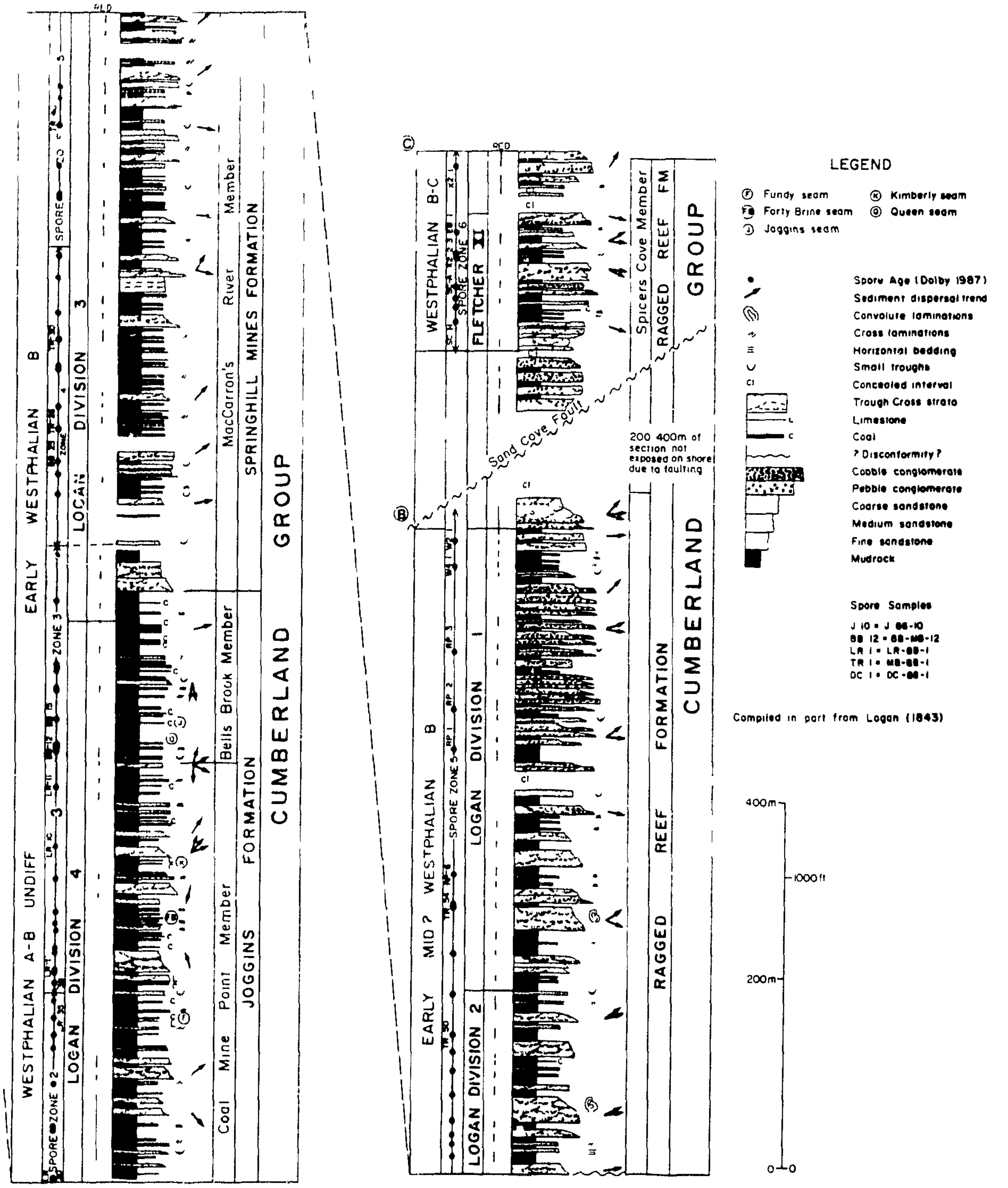


Figure 1.2 Stratigraphic column of the classic Joggins Section along the shoreline in western Cumberland Basin. The original Dawson subdivisions are included for reference. The age of the units is determined by a palynological study (Dolby, 1987).

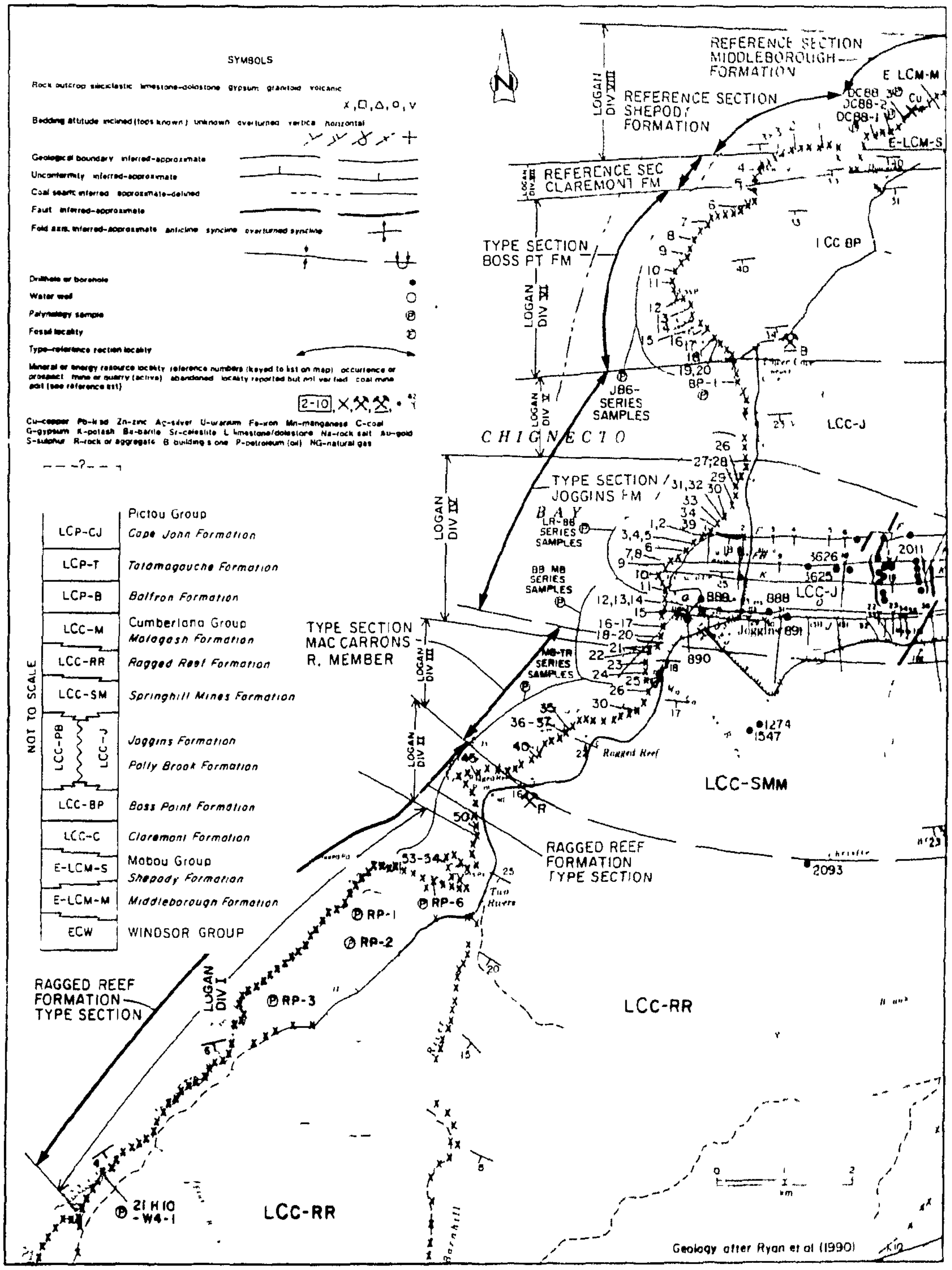


Figure I.3: Location map and generalized geology of the Joggins Shoreline, Cumberland Group Type Section, western Cumberland Basin. Sample locations of the spore samples are also shown.

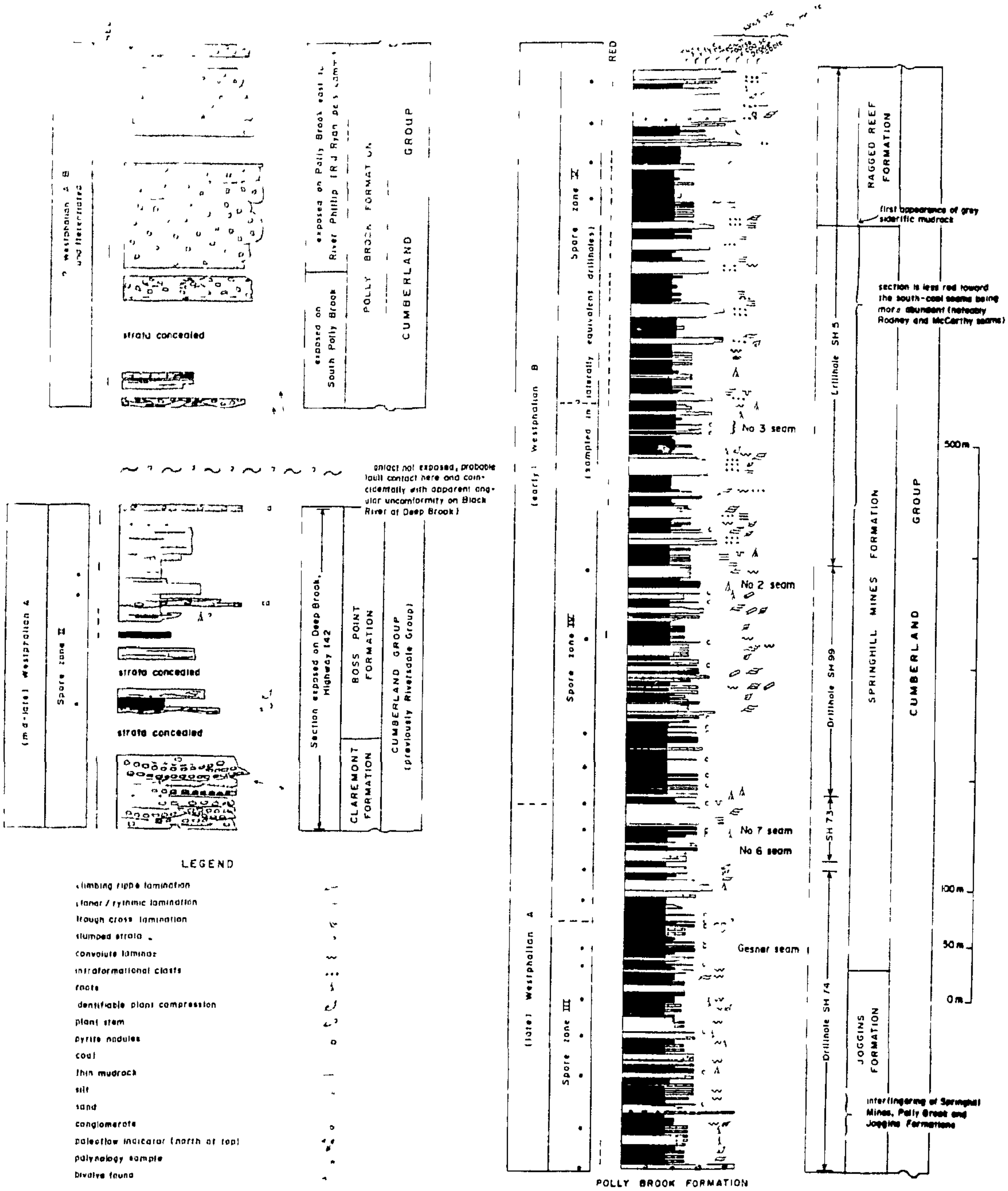


Figure 1.4: Stratigraphic column for the Springhill area. The stratigraphy is from a composite section of drill holes and from outcrop section (after Ryan et al., 1991). Palynological zones and ages are from Dolby (1987).

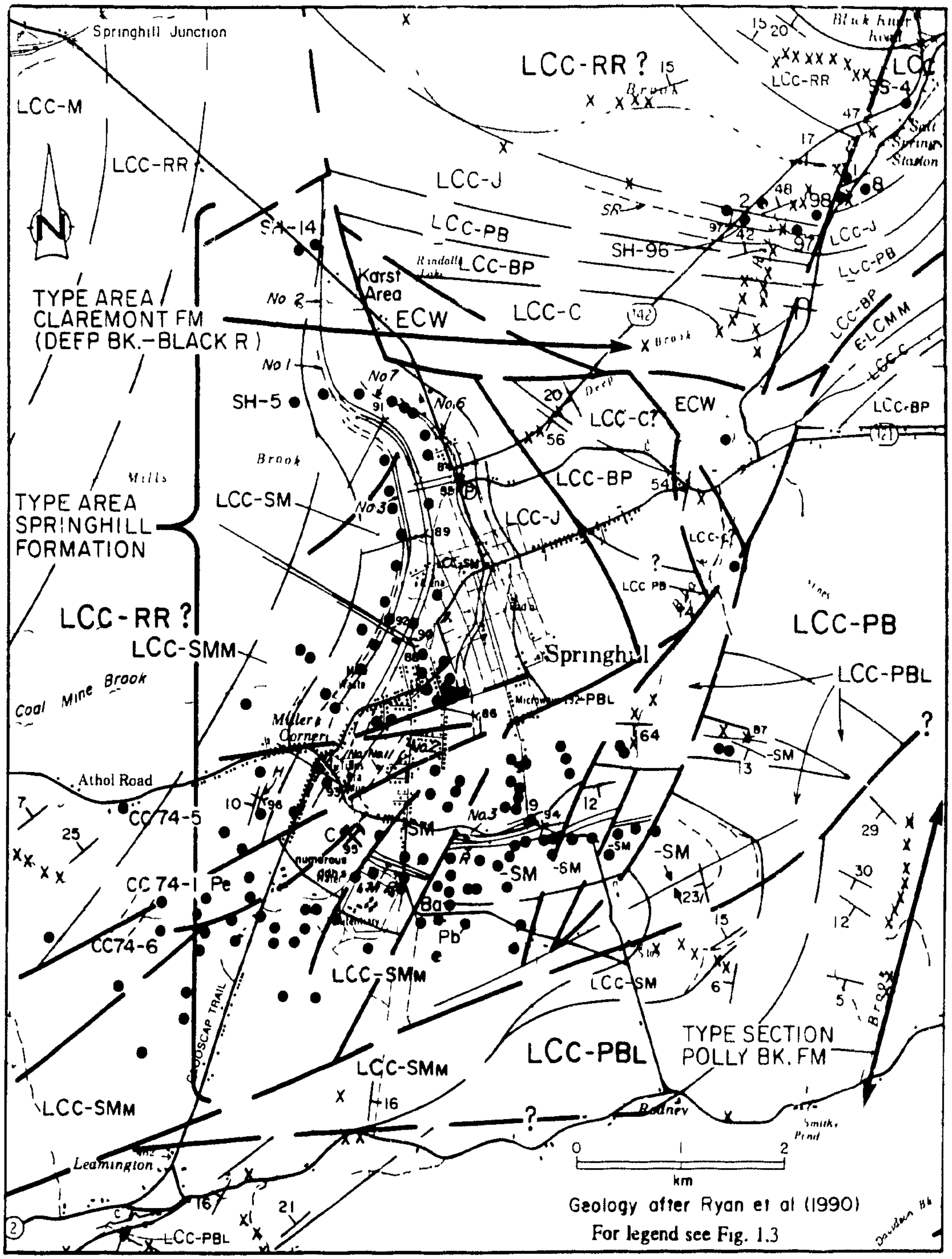


Figure 1.5: Location map and generalized geology map for the Springhill area. The map demonstrates the complex nature of the structure within the Springhill Mines Formation Type area. (After Ryan et al. 1991).

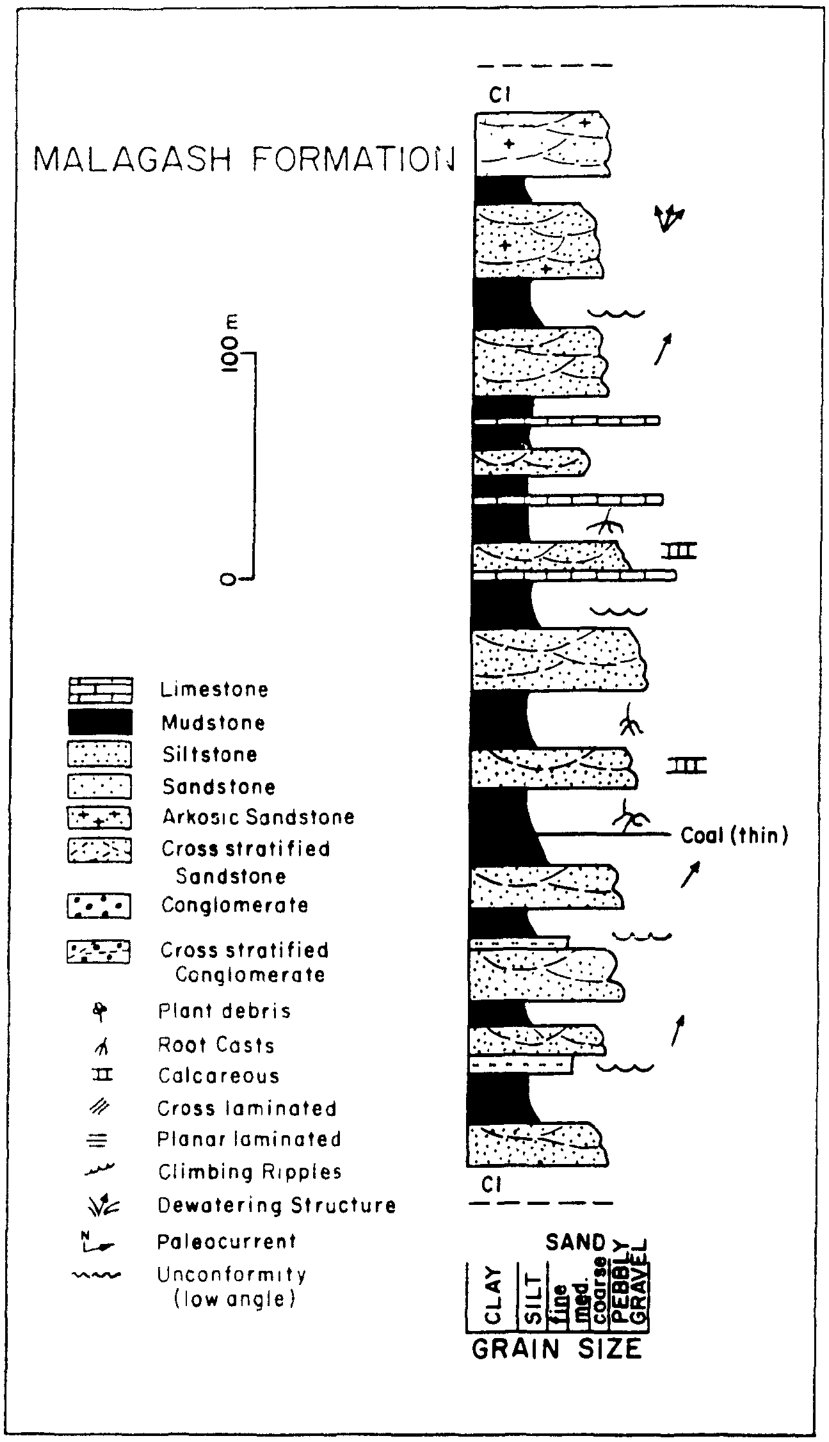


Figure I.6: Stratigraphic column of the Malagash Formation Type Section, Malagash Point (for location see Fig. I.7).

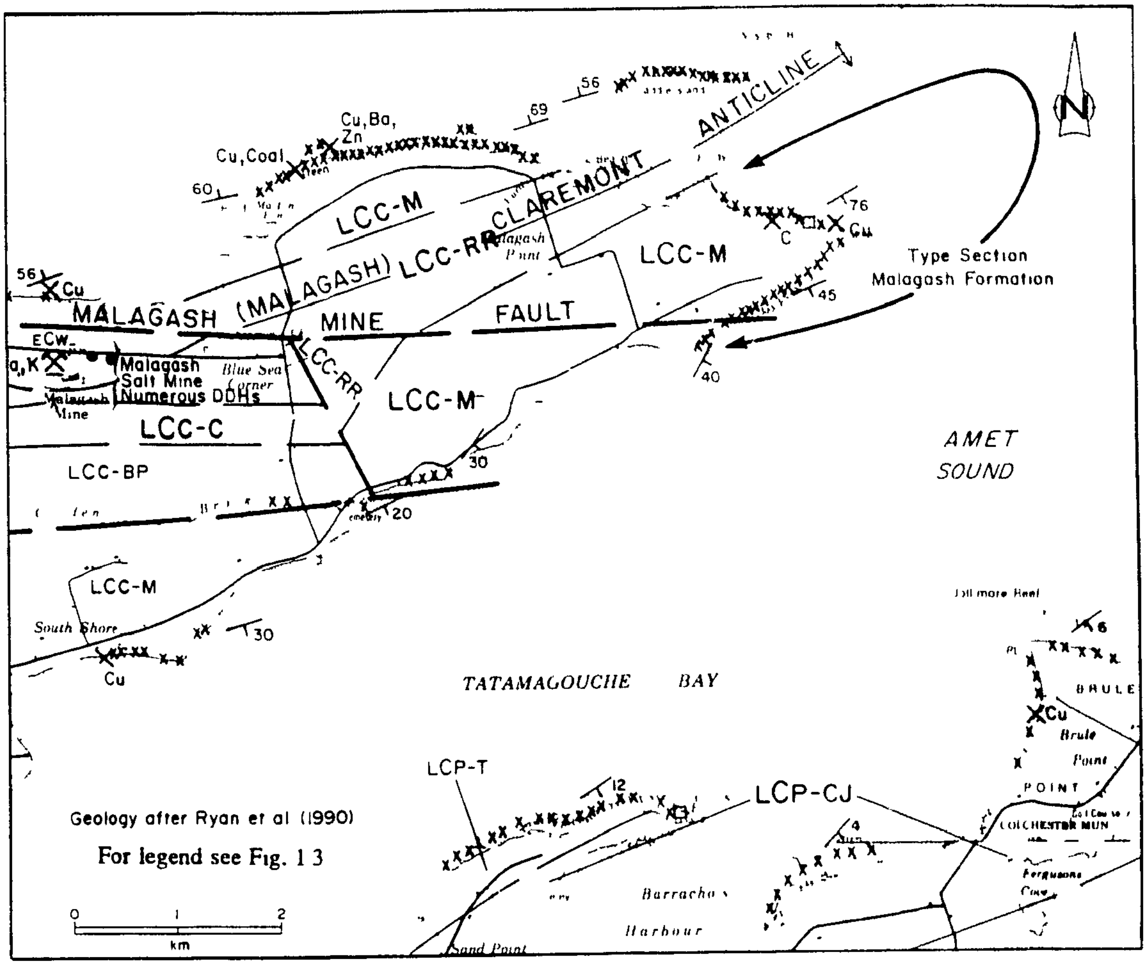


Figure I.7: Location map and generalized geology for the Malagash area. The type section of the Malagash Formation is exposed along the coast at Malagash Point near the axis of the Claremont Anticline.

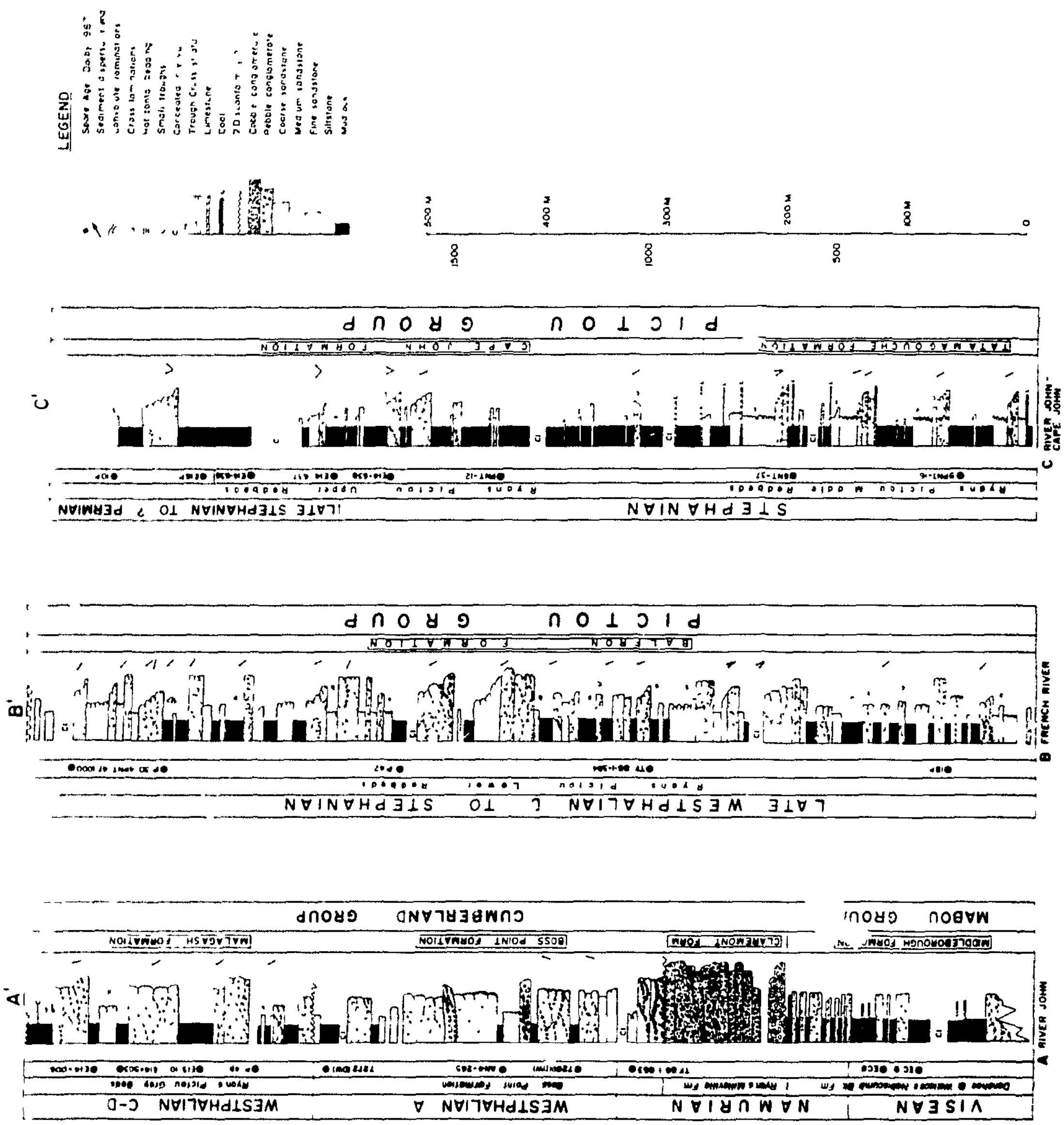


Figure I.8: Composite stratigraphic column of the River John and French River Sections, eastern Cumberland Basin. The two river sections both have well exposed sections of the Pictou Group strata both in the stream bed and on cliffs flanking the river edge.

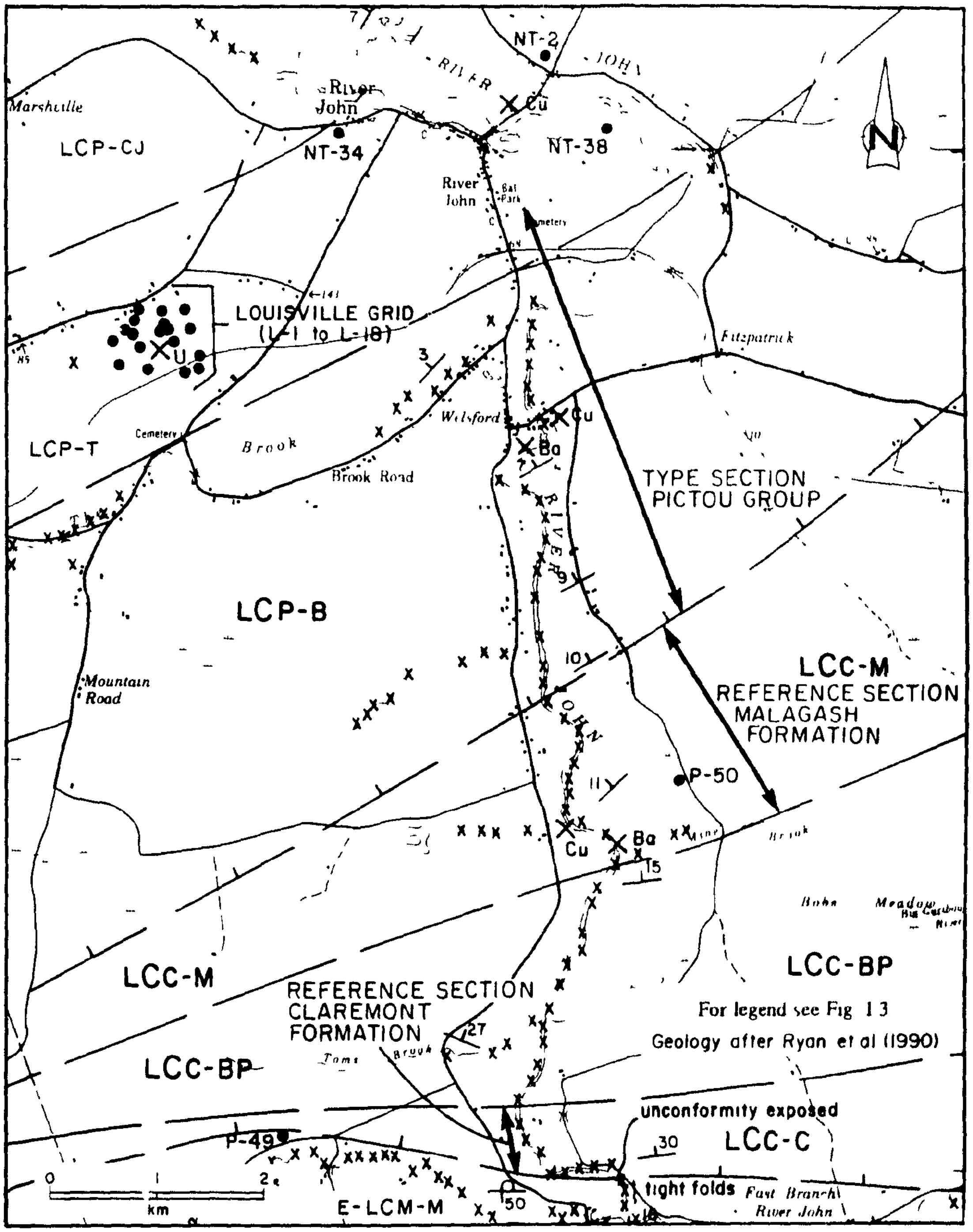


Figure I.9· Location map and generalized geology for the River John area of the eastern Cumberland Basin. The Pictou Group type section originally included the beds of the Malagash Formation which are now assigned to the top of the Cumberland Group(after Ryan et al., 1991)

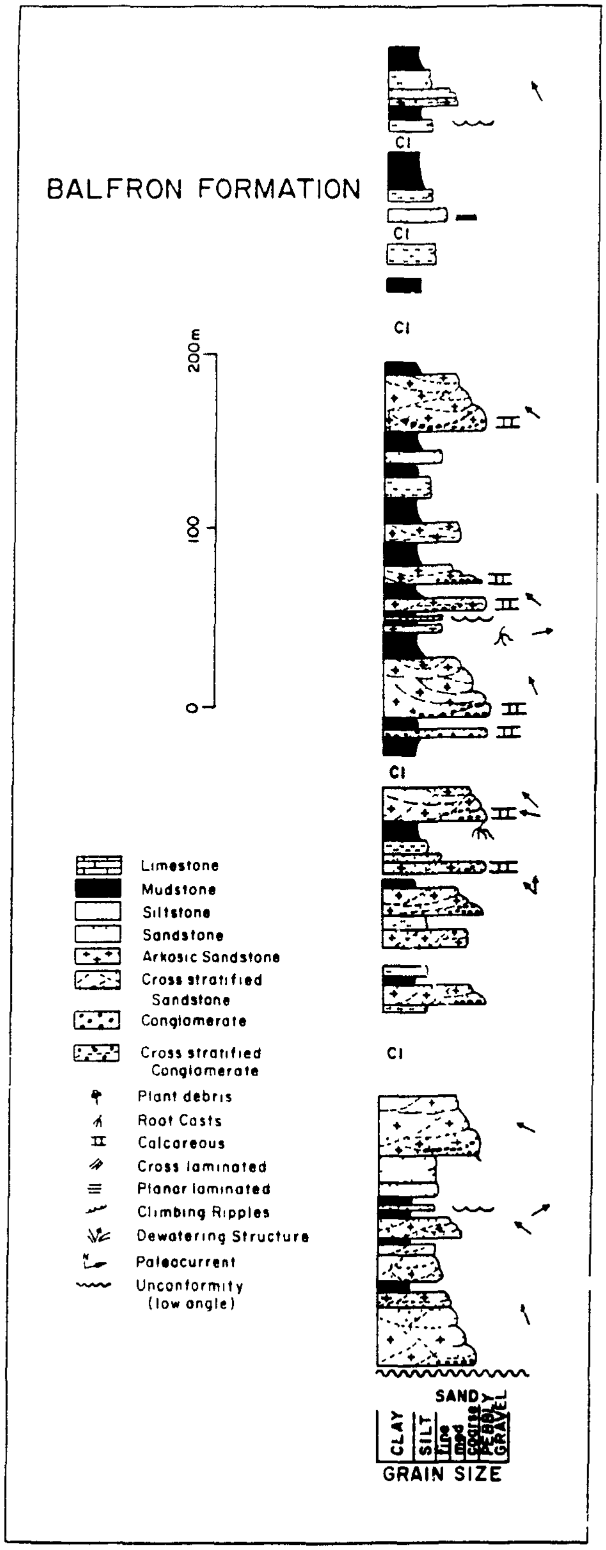


Figure 1 10: Stratigraphic column for the Balfron Formation of the type section, along the Waugh River south of Tatamagouche.

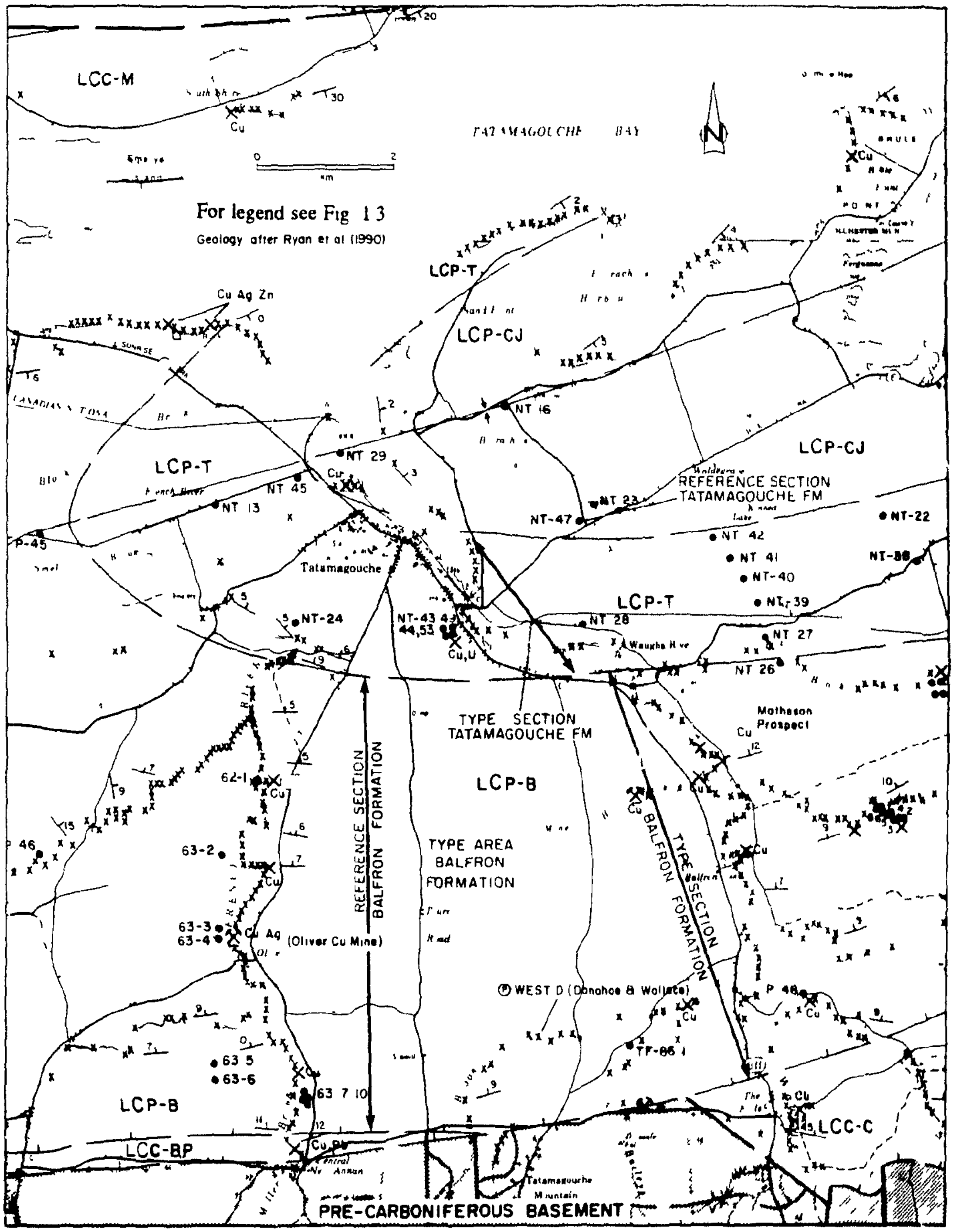


Figure I.11: Locatior . f ap and generalized geology for the Balfron Formation and Tatamagouche Formation type areas.

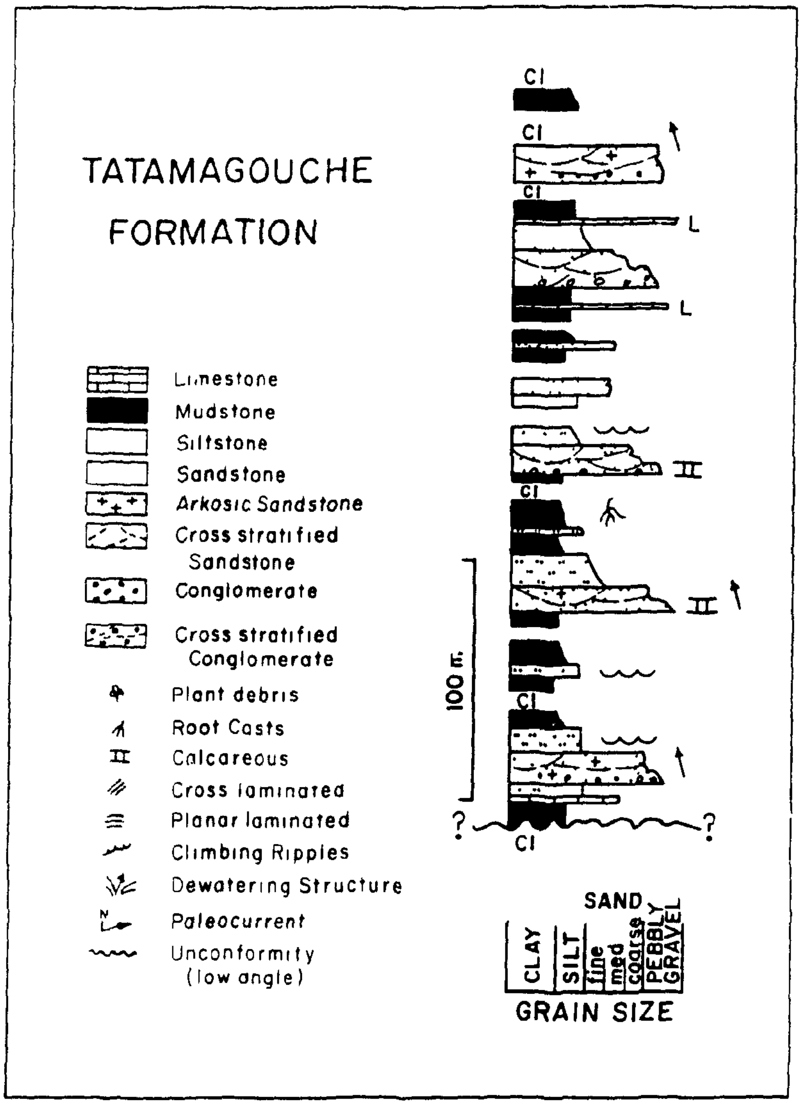


Figure I.12: Stratigraphic column of the Tatamagouche Formation, type section exposed along the Waugh River near Tatamagouche (see Fig. I.11 for location).

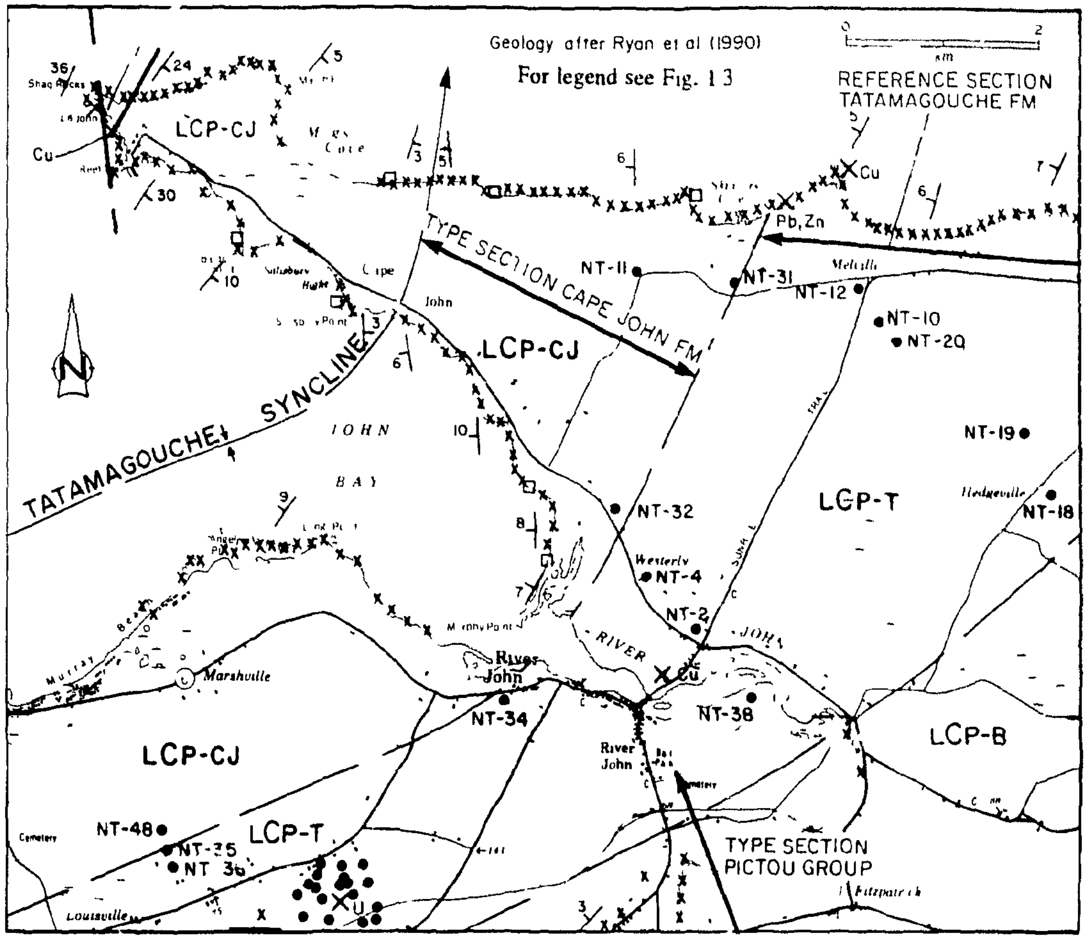


Figure I.13: Location map and generalized geology of the Cape John Formation type area. Excellent exposures of the formation occur both along the shore of John Bay and on the Melville shore. (see Fig. I.7 for the log of the section).

APPENDIX II STRUCTURAL FEATURES OF THE CUMBERLAND BASIN

INTRODUCTION

The Cumberland Basin was defined previously (see Chapter 1) as being the basin that lies between the Cobequid Highlands Massif and the Caledonia Highlands. The Basin has the general internal configuration of a synclinorium composed of a series of prominent synclines: the Athol, Tatamagouche, Wallace and Amherst synclines. There are two major diapiric anticlines, the Minudie and Claremont (Fig. 4.2). The structural features contained within the basin can be broadly related to: (1) the development of salt structures, including: diapirs, domes, diapiric anticlines, and folding and faulting related to salt flow; and (2) basin development (growth) features unrelated or indirectly related to evaporite tectonics, including: growth faults, strike slip faults, major synclines, and internal buried uplift blocks (e.g. Hastings Uplift), jointing and thrust faults.

SALT STRUCTURES

The Windsor Group evaporitic sequence varies in degree of deformation throughout the Maritimes Basin. Boehner (1986) classified the deformation of the evaporites in the Cumberland Basin as Type D (Fig.II.1). Type D is characterized by evaporitic sequences that exhibit an extreme intrusion-diapiric character, play an active tectonic role, have abundant salt deposits, and thick basin fill. The evaporites of the Cumberland Basin deformed to create diapiric anticlines, salt walls to salt stocks, or an aligned series of isolated diapiric salt stocks (domes). The terms used to describe the morphology of the diapiric structures within the basin conform to the classifications proposed by Trusheim (1960), and as modified by Talbot and Jackson (1987).

Diapiric Anticlines

The two major diapiric anticlines within the Cumberland Basin of northern Nova Scotia are: (1) the Claremont (Malagash) Anticline, and (2) the Minudie Anticline (Fig II 2). The Claremont Anticline is a 100 km in length east-west feature with outcrops of Windsor Group rocks exposed intermittently along the anticlinal axis at Springhill, Claremont, Oxford, Hansford, and Malagash (Fig. II.2). The Minudie Anticline is an east-west structure that extends for 60 km westward from southern New Brunswick through Minudie and Nappan to (at least) Beckwith on the east (Fig. II.2). The Pugwash diapir lying along the same trend, represents an extension of this structure.

The anticlines are evaporite cored, fault controlled, and formed by salt and anhydrite diapirism. Seismic and geological cross-sections through these features (Howie, 1988 and Boehner, 1986) indicate that the anticlines occur as salt walls or stocks which are aligned in an east-west direction parallel with, and genetically related to, the Cobequid-Chedabucto Fault System. These evaporite cored anticlines form by intrusion of evaporites up zones of weakness created by reactivation of deep basin faults.

Malagash

The internal structure of the Windsor Group diapiric evaporites was documented to a limited extent in the workings of the abandoned Malagash Salt Mine (1919-1959). The mine was located near the south dipping limb of the Claremont (Malagash) Anticline. To the north of the mine site the anticlinal structure is broken by faults, and is apparently asymmetric. Late Carboniferous Cumberland Group strata are in complex fault (intruded) contact with the Windsor Group evaporites and Mabou Group redbeds. The mine workings closely followed the moderately to steeply south dipping salt horizons which were only 2-5 m thick. The workings extended from approximately 30 m below surface to a vertical depth of approximately 350 m, and defined in detail a complex fold pattern over an east-west strike length of nearly 500 m. The fold pattern has the geometry of an asymmetric 'S' shaped fold (viewed from above), with hanging wall overhang-repeated by folding over a strike width of 100-200 m. The south dipping axial plane is parallel with the strike of the anticlinal axis.

Pugwash

Within the diapiric structure at Pugwash, the internal folding was described in detail by Evans (1972). Carter (1987) produced three dimensional reconstructions of the anhydrite units in the Pugwash Salt Mine (Canadian Salt Company Ltd.). He described these units as extremely deformed, vertical curtain folds, typical of piercement diapirs. Detailed documentation of the folding within the Pugwash Salt Deposit is currently in progress (Carter, 1990 and in prep.), and these observations should greatly enhance our understanding of diapir emplacement.

Carter (1987) concluded that the Pugwash salt deposit represents a true piercement diapir and that the present volume of salt may be only a remnant caused by migration-related thinning of the former deposit.

Isolated Domes

Isolated evaporite domes or salt stocks occur within the Wallace Syncline (including its extension, the Black River Syncline) of the Cumberland Basin. The most significant domes occur at: (1) Black River; (2) Roslin; (3) Canfield Creek; and (4) Wallace Bay (Fig. II.2). The evaporite domes in the complex Wallace Syncline are aligned east-west, parallel to the two major diapiric anticlines. This alignment strongly indicates a genetic link to intrusion along faults within the Wallace Syncline.

The Windsor Group (evaporite-bearing sequence) outcrops are limited, typically sub-circular in shape, and range from one to several kilometres in diameter. The Roslin structure is the only dome in which a salt core was confirmed by drilling, however gypsum occurs as outcrop and in shallow drillholes which have intersected highly disrupted karsted evaporite (solution collapse-residual caprock) in all of the domes.

Springhill Area

Calder (1984) and Boehner et al.(1986) described the structure in the axial area of the Claremont Anticline, in the Springhill area, based upon extensive diamond-drill information and detailed mapping in the Rodney Open Pit. The gently plunging axis of the anticline is complicated by block faulting in a series of major curvilinear faults which define a semi-radial pattern, itself complicated by cross faults. Several sets of faults were recognized, with early stage major normal faults (synthetic and antithetic-cross fault sets) and strike-slip (scissors) faults, succeeded by later bedding plane and thrust faults (Fig. II.3).

The Black River Syncline (southwestern extension of the Wallace Syncline) may be a block resulting from oblique strike-slip faulting, which has apparently repeated (perhaps by lateral telescoping) a portion of the southern limb of the Minudie Anticline. The western extension of these faults into the Athol Syncline is problematical in that there is no apparent evidence for major faults disrupting the syncline. The faults may, however, terminate and the inferred strike-slip movement may be accommodated by a complex reverse or overthrust diapiric structure along the western side of the Athol Syncline.

The western termination of the Claremont Anticline and related faults against the Athol Syncline near Springhill is similarly abrupt, structurally complex, and perhaps also related to the continuation of the reverse or overthrust structure. The faults related to the Claremont Anticline however, may continue to the southwest and converge with the splays of the North Fault near Leamington and Rodney. This type of complex splay fault diapiric evaporite structure is generally similar to the western termination of the Minudie Anticline in southern New Brunswick (Fig. II.4).

The extent and termination style of the east-west trending Minudie Anticline to the west is not well understood. The western extension of the Cumberland Basin is terminated in a complex faulted area on the southeast border of the Caledonia Highlands Massif in southern New Brunswick. The basin structure is reoriented from the prominent east-west trend to the regional trend of northeast-southwest. This is reflected not only in the basement highland blocks, but also in the parallel major faults including the Harvey-Hopewell and Locher Lake faults. The Minudie Anticline and related faults apparently terminate in the area of Shepody Bay into a complex of splays, thrusts (especially at or near convergent or restraining bends), and subordinate folds with evaporite tectonism, which includes diapirism (see Section 4.4.3.2). These structures may be analogous to the complex thrust flower structure at the termination-reorientation of the Cobequid-Chedabucto Fault System in the Bay of Fundy and in southern New Brunswick as described by Nance (1988).

Emplacement and Timing of Diapirism

Bell (1958) was the first to link the orientation of post Mabou Group faulting to the distribution of the diapiric structures. Howie and Cumming (1963) also suggested that fault zones may have controlled evaporite distribution in the Maritimes Basin. Bell (1958) suggested that diapirism began at these areas of weakness, and was subsequently driven by the confining pressures of the accumulating sediments, thus linking coal basin development in the western part of the basin with evaporite tectonics and diapirism. Based on seismic and gravity geophysical data the salt structures of the Claremont Anticline were interpreted as fault controlled (Bidgood, 1970). Bidgood (1970) and Howie (1985) indicate that basement faulting occurs beneath areas of diapirism, on the basis of seismic profiles. The mechanism of fault-controlled diapirism has been demonstrated experimentally by Lemon (1986). The model structures created by Lemon (1986), are very similar to the structures observed in the diapiric anticlines of the Cumberland Basin.

Two apparently conflicting theories have been proposed for the timing of diapirism within the Cumberland Basin. Van de Poll (1972) and Calder (1981) both suggested that the presence of brittle deformation adjacent to the diapirs, indicates a post-Pictou/Cumberland Group emplacement. Bell (1944) implied that the angular unconformities between the various Upper Carboniferous formations and groups, within the anticlines and domes of the basin, is evidence for syndepositional diapirism during the late Carboniferous. Ryan (1985) also favoured a syndepositional diapirism model, based on paleocurrent data that showed divergence away from the areas of domes and anticlines. Williams (1974) concluded, on the observed thinning of units adjacent to the diapirs in seismic profiles, that diapirism must have been syndepositional with the

Upper Carboniferous sedimentation The angular unconformity exposed at the Dewar Hill Quarry, near Pugwash, has flat-lying Malagash Formation strata, containing clasts of the underlying Windsor Group strata, overlying overturned Windsor Group carbonates and redbeds It is the most convincing evidence for syndepositional (mid-Westphalian) tectonism and evaporite diapirism found within the basin (Fig. II.5)

Halokinesis alone probably can not explain initiation of the diapirism in the basin A tectonically driven (halotectonic) mechanism for the initiation of the diapirism, rather than a gravity driven halokinetic mechanism (Trusheim, 1960) is favoured as, unlike these highly deformed evaporites, many other thick sequences of evaporites elsewhere in the world, with similar thicknesses of overlying strata, are undisturbed (Kingston et al 1983) It would seem that gravity alone is unlikely to have overcome the inertia, although only slight tectonic forces may have been necessary to initiate the salt flow (Talbot and Jackson, 1987)

These two theories (syn- and post-Westphalian) are not necessarily mutually exclusive Evaporite tectonics (including diapirism) in this complex setting was not a one-time event Although initiated and most intense during the Carboniferous, it may have continued periodically through the late Carboniferous, for some time after the Carboniferous (Permian?) and perhaps again in the Mesozoic. Progressive evaporite tectonics which evolved into a diapiric phase over an extended period of time is an appealing explanation for the dichotomy of structural and sedimentological features found within the Cumberland Basin In addition, post-Cumberland strike-slip offset and the possibility of high angle reverse to (?)thrust termination of the east-west trending faults near Springhill Junction may explain the juxtaposition of Windsor Group diapiric evaporites with the Springhill Mines Formation in a brittle deformation setting

EVAPORITE TECTONICS (DIAPIR) RELATED FOLDING AND FAULTING

Introduction

In the Malagash, Hansford, Minudie, Nappan, Wallace River, Beckwith, and Cape John areas there are numerous faults, commonly with less than 500 m displacement. These faults are restricted to the diapiric domes and anticlines, and are genetically related to extensional stresses caused by the evaporite emplacement. The most noteworthy of these faults are: (1) the Golden Brook Fault; (2) Malagash Mine Fault; (3) Hansford Fault; (4) Cape John Fault; (5) Lazy Bay Fault; (6) Beckwith Fault; (7) Fox Harbour Fault; (8) Little River Fault; (9) Black River Fault; (10) Mt. Pleasant Fault; (11) Glenville Fault; and (12) the Oxford Fault (Fig. 4.2). These faults commonly comprise a series of closely-spaced faults rather than a well defined single fault trace. Fault orientations are typically of two principal trends: a dominant east-west to northeast-southwest and a transverse subordinant trend of north-south.

The faults commonly exhibit normal dip-slip and minor strike-slip movement. Larger displacements are suspected, based on map unit boundary displacements, but are difficult to confirm. The sense of relative strike-slip movement is sinistral but locally appears to be dextral. This is in contrast to the dextral displacement (late Paleozoic) along the North and the Cobequid-Chedabucto Fault System. Although the relative displacement of the stratigraphic units by the faults appears to be sinistral (perhaps related to sinistral Mesozoic? movement), slickensided surfaces in some fault zones suggest that normal dip-slip or dextral strike-slip movements predominated. The dextral movement is supported by the seismic information across domal structures, where listric normal faulting radiates around the domes. Reidel shear sets are found in the Cape John Fault area. These conjugate fractures indicate extensional stress oriented northwest-southeast, which can be attributed to diapirism occurring north of the Cape John peninsula. This pattern is also reflected in the scattered transverse faults which offset the principal east-west structures.

On the basis of the structural data compiled from the field mapping, seismic interpretations, and geological cross-sections, it is apparent that many of the minor faults of the eastern Cumberland Basin are genetically related to the diapirism. The diapirism was triggered and controlled by earlier deep basin faulting. The zones of deep basin faulting, exposed at surface within the basin, may record a complex movement history involving reactivation zones which exhibit different displacements but similar orientations to the earlier basin- forming fault systems, (ie. pre- to syn-Carboniferous versus? Permian to Mesozoic).

Minudie: King Seaman Syncline

Fold structures, on the scale of hundreds of metres, are rarely as well exposed as in the King Seaman Syncline near Minudie. This overturned structure is located on the complex north limb of the Minudie Anticline along the western shoreline of River Hebert. Ryan and Boehner (1991) described in detail the folding of Shepody and Middleborough Formation strata of Visean to Namurian age, continuously exposed for approximately one kilometre in cliffs (3-10 m high) and in the intertidal shore face (Fig. II.6). The fold axis orientation is difficult to determine accurately, but commonly has a west southwest trend and plunges gently to the west.

The King Seaman Syncline is anomalous in that the north limb of the fold continues to be gently dipping and facing south to the north of the outcrop limits. It must, therefore be a subordinate fold and/or a faulted block on the northern limb of the Minudie Anticline, where north dips or facing would be appropriate. This asymmetry is consistent with the faulted nature of both the Minudie and the Claremont-Malagash anticlines which characteristically have nearly normal south limbs but faulted north limbs. The north limbs typically have complex, overturned fault blocks and high angle reverse to overthrust geometry. Examples of this type of structure are present in the Minudie Anticline east of Minudie near Limekiln Brook, as well as near Fenwick and Brookdale. These areas have complex structures comprising: (1) overturned fault blocks of Boss Point Formation forming a wedge in the axial region of the anticline near the termination of the Nappan Diapir outcrop, and (2) folded fault blocks of Windsor Group to Boss Point Formation near the north side of the faulted anticline. The overturned folding and complex fault blocks on the north side of the Minudie Anticline are consistent with a major overturned fold structure in the Sunoco No 1A borehole described by Howie (1988) The rocks at the bottom of this well were originally correlated with the Horton Group. Howie (1988) established them as Mabou Group, based upon palynology, overfolded beneath overthrust Windsor Group diapiric evaporites.

BASIN STRUCTURES

Introduction

Structures which may be related to the basin subsidence include: (1) faults within the basin away from the diapiric structures; (2) possible thrust faults; and (3) jointing. It is difficult in most instances to accurately determine the timing of the jointing or minor faulting within the strata of the area. Many of these structures may represent later events, such as Triassic rifting, and therefore do not reflect penecontemporaneous basin subsidence features. The presence of thick sequences of Triassic strata in the Chignecto Bay indicate that Triassic rifting occurred immediately adjacent to the basin. Some of the structures, such as the Athol Syncline, were Late Carboniferous features however the degree to which these structures have been changed by the Triassic rifting remains unclear. Detailed documentation and analysis of these features is beyond the scope of this study however, and only preliminary observations are presented here.

Basin Synclines

The Athol, Tatamagouche, Wallace and Amherst synclines are the most aerially extensive structural features in the Cumberland Basin. They are gently plunging to doubly plunging with curvilinear axis and oriented east-west. The Athol and Amherst synclines have axial planes trending northeast-southwest and perhaps may reflect their proximity to the major structural reorientation along the northwest border of the basin (Westmoreland Uplift, Sackville Sub-basin and Caledonia Highlands Massif). In addition, early Mesozoic to Cenozoic tectonism may also have resulted in minor faulting, folding, and deformation in the synclines as well as elsewhere in the basin. The Wallace Syncline, located between the Claremont and Minudie anticlines, is extensively disrupted by faults and evaporite diapirs. The other synclines in contrast are relatively unbroken, with the possible exception of the central parts of the Athol Syncline (Athol, Sand River and Sand Cove faults) and in proximity to its termination near Springhill, against the end of the Claremont Anticline (Fig. 4.5).

Hastings Uplift

The Hastings Uplift (Howie, 1988) is a buried uplift or fault block situated near the western apex of the Amherst Syncline and immediately north of the Minudie Anticline. The precise configuration of this block is not clearly defined however, Howie (1988) indicates an east-west trending extension to the north of the Minudie Anticline. The southern flank is inferred to be present in Gulf et al. Hastings No. 1 which intersected basement rocks at a depth of 2837.7 m. Early Carboniferous strata were apparently absent or only very thin and a major onlap-overstep relationship was inferred by Howie (1988). The area between the Minudie Anticline and the Sackville Sub-basin is structurally complex (Martel, 1987).

Intrabasinal Faults

Within the Basin proper there are several significant faults which are not apparently related to evaporite tectonics, although they locally may be conduits for saline brines (ie. in South Athol 88-1). The three most significant faults include: (1) the Sand Cove Fault, (2) the Athol Fault, and (3) the Apple River Fault (Fig 4.5). All three of these faults are in the western part of the Cumberland Basin and are oriented east-west. All the faults converge in the structurally disrupted area of Springhill and Rodney and are splays off of the North Fault (Spicers Cove Fault), which forms the southern boundary of the basin in the west. The faults are exposed in outcrop along the shores of Chignecto Bay as zones of high angle reverse faulting (Fig. II.6). Normal faults also occur within the fault zones, however the majority of the slickenside surfaces indicate sub-horizontal movement. Utilizing the seismic data for the western part of the Cumberland Basin, Calder and Bromley (1988) have interpreted these structures as high angle faults at depth. Chevron Standard seismic interpretations and those of Ryan and Boehner (1988) suggest that these structures are listric and are interpreted to shallow significantly at depth towards the south (Fig 4.5). The orientation, proximity to the North Fault, and the strike-slip nature of the displacement, suggests that these faults formed in response to movement along the North and Cobequid Faults during the Late Westphalian.

Jointing and Small Scale Faulting

The orientations of the joints and faults with minor displacements in the Cumberland Basin have a polymodal distribution. Three preferred orientations, north-south (015°), east-west (090°), and northwest-southeast (135°), were observed (Fig. II.7). Sea-Sat imagery for northern Nova Scotia (Fig. II.8) shows lineaments which correspond very well to the field observations. The dataset from the field observations can be divided into two subsets on the basis of the age of the rocks deformed: (1) the pre-Westphalian B strata; and (2) the post-Westphalian B strata. The two subsets are distinctive, with the older subset having east-west, north-south and northwest-southeast preferred orientations, whereas the younger strata only exhibit east-west and northwest-southeast joint and fault orientations (Fig. II.7). This may indicate that the north-south structures originated pre-Westphalian B, and therefore are contemporaneous with the basin subsidence. The timing of the joints and faults with the other orientations remains unclear, and perhaps are related to Permian to Mesozoic tectonics.

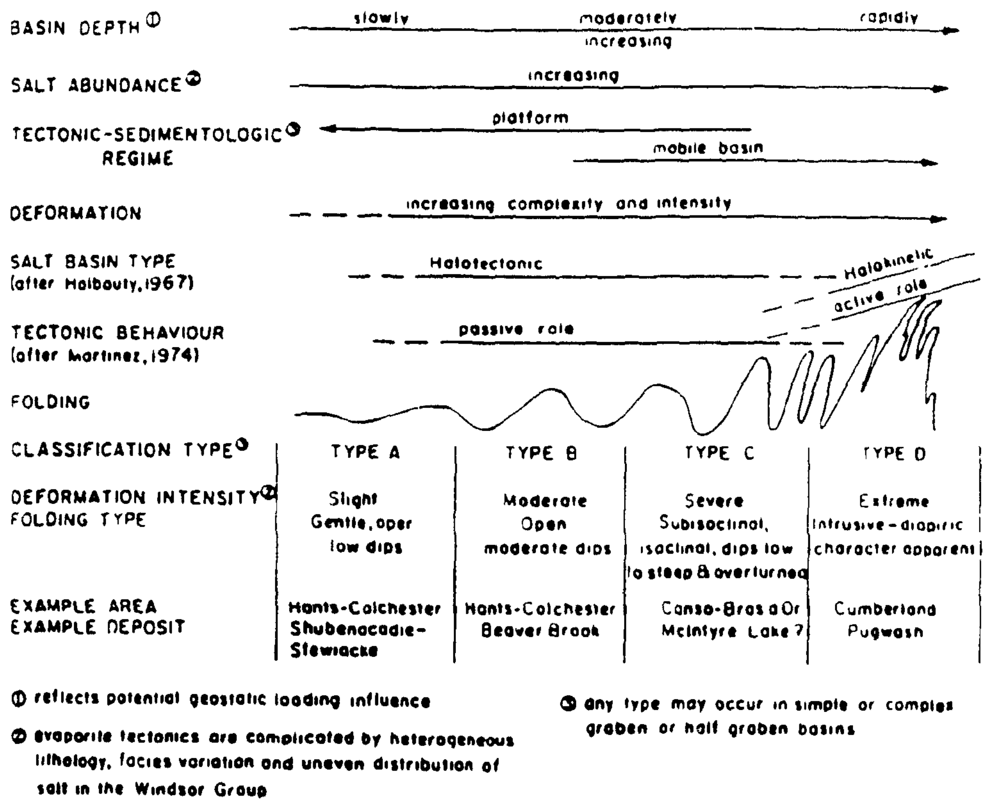


Figure II.1: Classification of the structural styles (intensity) of Windsor Group evaporites in Atlantic Canada (after Boehner, 1986). The Cumberland Basin evaporites fall into the Type D -Extreme intrusive-diapiric character.

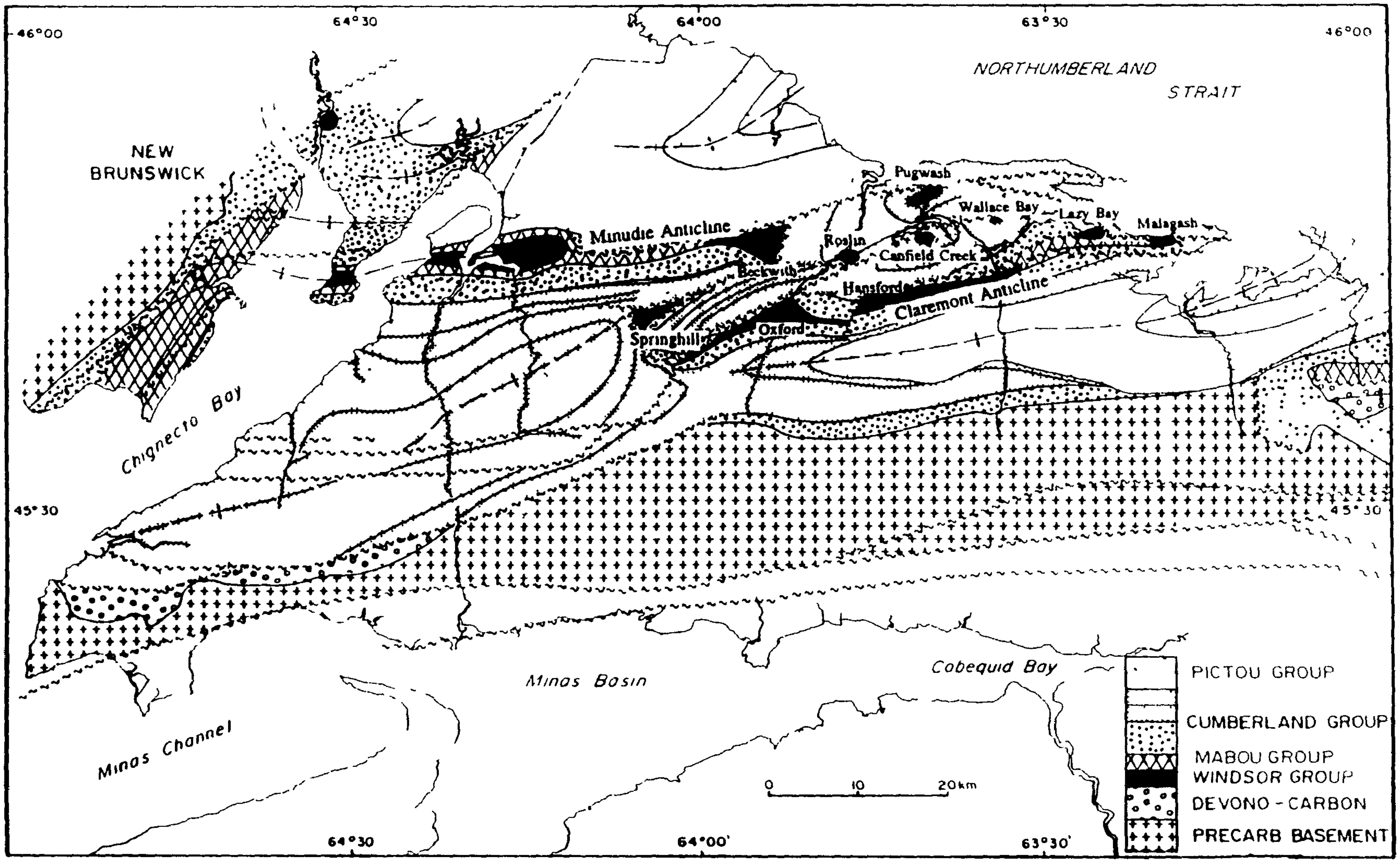


Figure II.2: Geology of the Cumberland Basin with special emphasis on the Claremont and the Minudie Anticlines and the isolated evaporite domes.

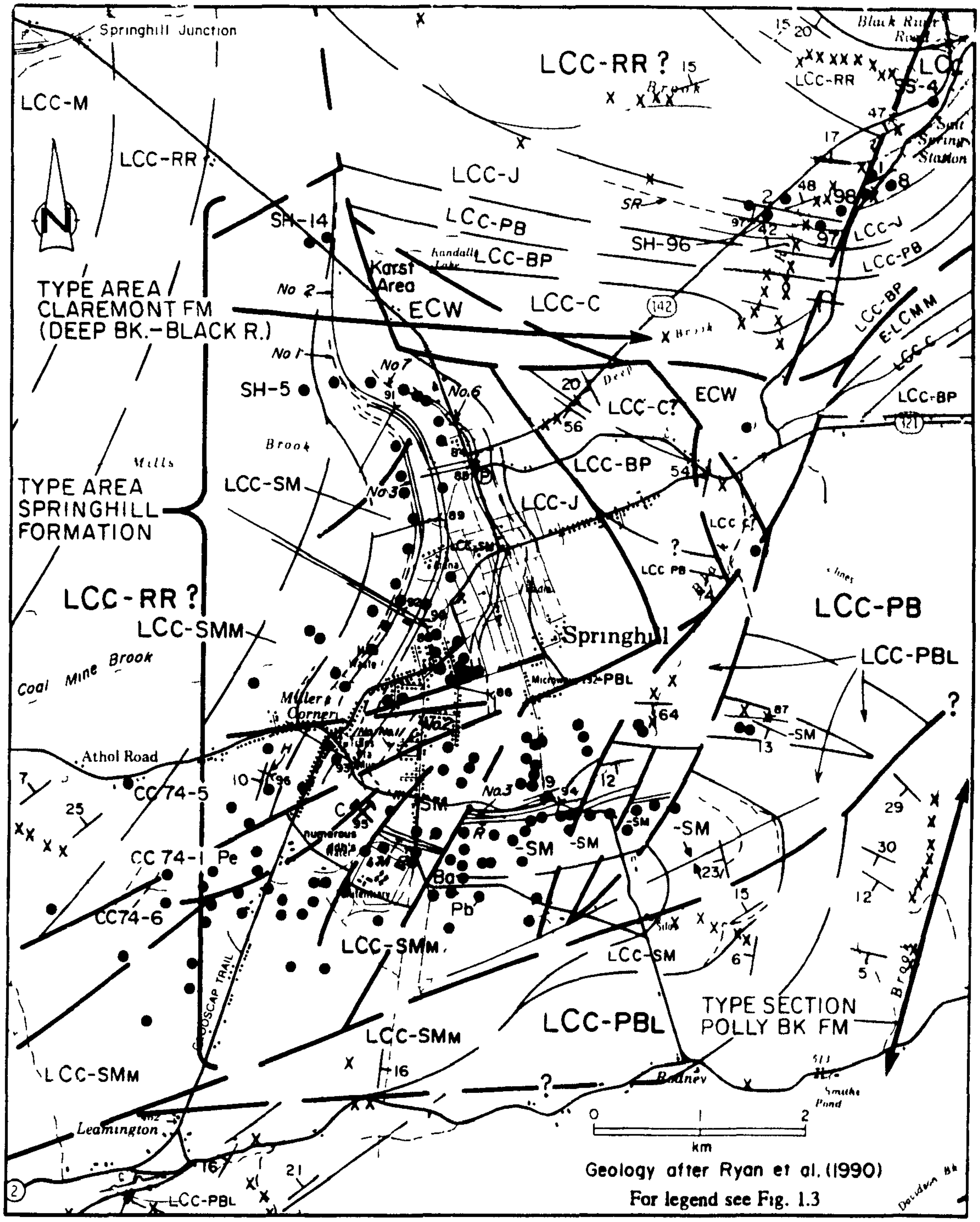


Figure II.3: Geology of the Springhill area, note the structural complexity of the coalfield.

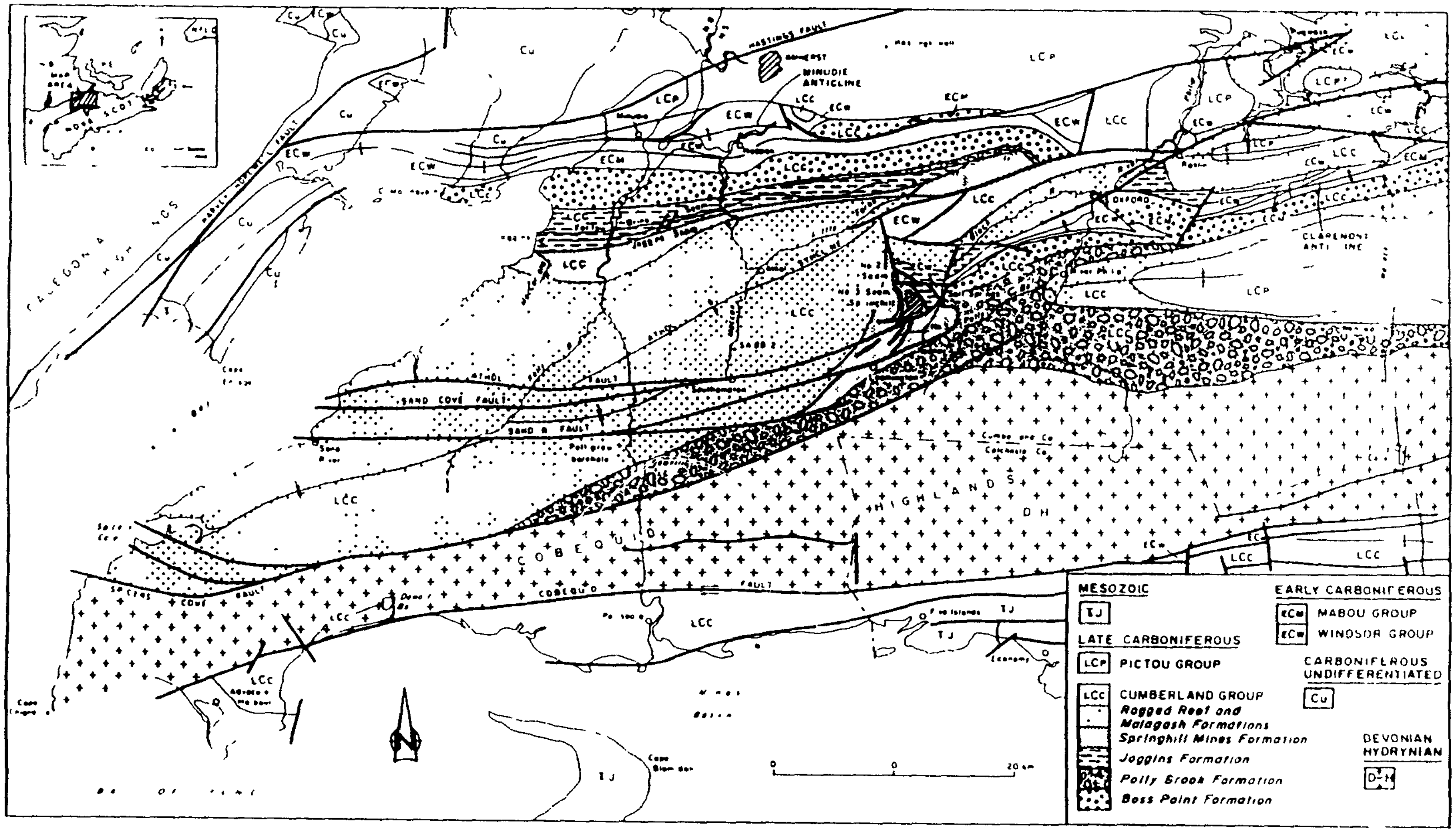


Figure II.4: Geology of the western Cumberland Basin.

Figure II.5: Photograph of the angular unconformity at Dewar's Hill Quarry, Pugwash. Flat lying Cumberland Group strata overlying overturned Windsor Group beds. This is clear evidence that in this area evaporite diapirism predates the deposition of the Cumberland Group strata (Malagash Formation - Westphalian C).

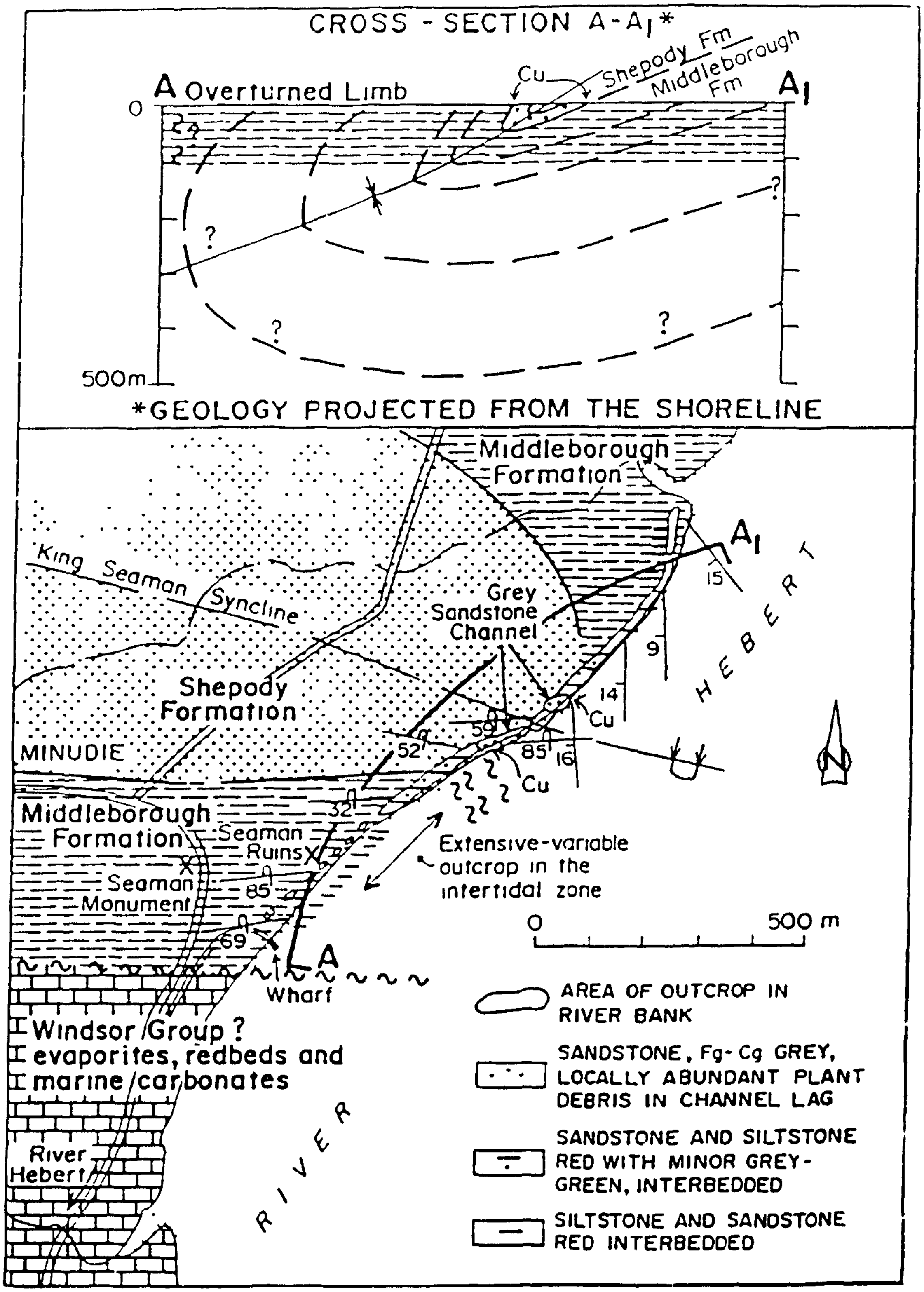
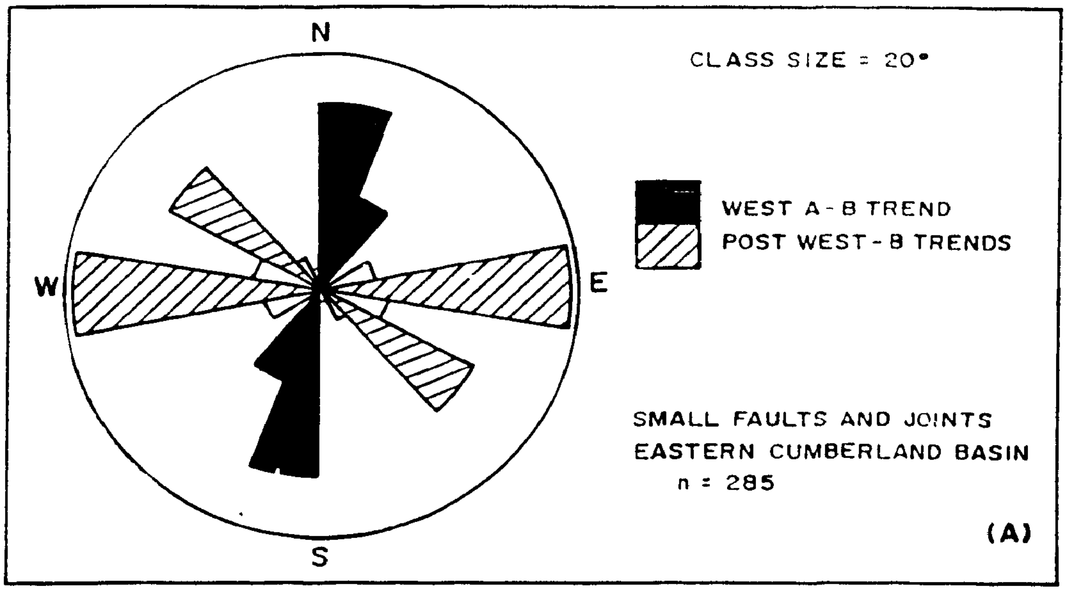


Figure II.6: Geology of the King Seaman Syncline, near Minudie, after Ryan and Boehner (1992). This is a rare exposure of a small scale anticline in the Cumberland Basin. The anticline is related to the larger scale evaporite diapirism which cores the Minudie Anticline in the north central part of the Cumberland Basin.



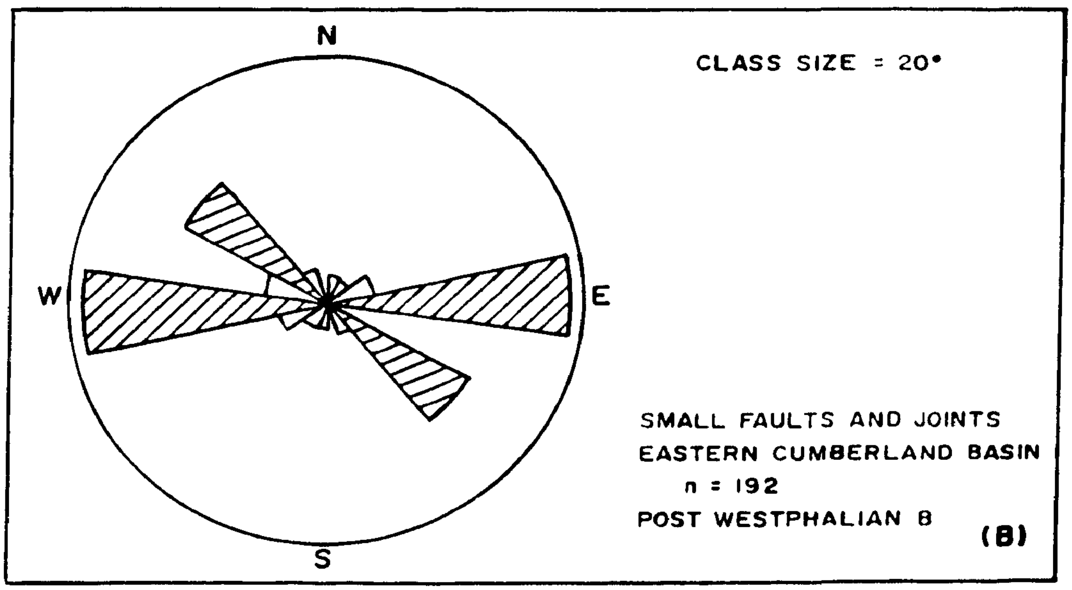


Figure II.7: Orientations of joints and small faults in the Cumberland Basin, (a) all strata, (b) only the post-Westphalian B strata and younger. This figure shows that in the eastern part of the Cumberland Basin there are north-south small fault and joint trends that appear to be contemporaneous with the Carboniferous as they occur within the Westphalian A-B strata but are absent in the younger strata.

Figure II.8: Sea satellite image of northern Nova Scotia, interpretation by Ryan (1986). These linear features correspond well to the major faults mapped in the Cumberland Basin (see Ryan et al., 1990).

CURRICULUM VITAE

Name: Robert James Ryan
Birthdate: July 11, 1953.
Birth Place: Annapolis Royal, Nova Scotia.
Address: 2119 Connaught Ave., Halifax, Nova Scotia.
Phone: (902) 420-8306

EDUCATION:

B.Sc. 1975 Geology - Acadia University, Wolfville, Nova Scotia

M.Sc. 1978 Geology - Acadia University, Wolfville, Nova Scotia
Thesis: Paleontology and Paleoecology of the Gays River Formation, Windsor Group of Nova Scotia.

Ph.D. 1993 Geology - Dalhousie University, Halifax, Nova Scotia
Thesis: Metallogenetic and thermal evolution of the Upper Paleozoic Maritimes Basin Evidence from the Cumberland Basin of Nova Scotia.

FELLOWSHIPS, AWARDS

1974 - Atlantic Undergraduate Geology Conference APICS Award for the best student paper
1975 - Harcourt Cameron Geology Award, Acadia University
1976/1977 - Graduate Fellowship, Acadia University.
1982 - Research Fellowship, University of New Brunswick
1991 - Research Fellowship, Dalhousie University.
1992 - Research Fellowship, Dalhousie University.

WORK EXPERIENCE:

May 1985 to present

Employer: Nova Scotia Dept.of Natural Resources

Position: Regional Geologist

Duties: Stratigraphy, mapping and economic geology in the Cumberland Basin, Guysborough Area, and in the Meguma Zone of Central Nova Scotia.

September 1984 to May 1986

Employer: St. Mary's University.

Position: Lecturer in Geology (Part time).

Duties: Teaching sedimentary petrology, stratigraphy and sedimentology, and introductory geology, economic ore petrology.

Summer of 1983 and 1984

Employer: Geological Survey of Canada

Position: Consultant Geologist.

Duties: Stratigraphy, sedimentology and economic geology and basin analysis in the Carboniferous strata of northern Nova Scotia.

September 1983 to May 1984

Employer: St. Mary's University.

Position: Lecturer in Geology.

Duties: Teaching Invertebrate Paleontology stratigraphy and sedimentology and Geology for Engineers.

June 79 to September 1982

Employer: Saarberg Interplan Canada Ltd.

Position: Project Geologist, Eastern Canada.

Duties: Supervision and initiation of uranium and base metal exploration programs in granitic, metamorphic, and sedimentary strata in New Brunswick, Nova Scotia, Newfoundland, and Northern Ontario

December 1978 to June 1979

Employer R J Ryan and Associates

Position Consultant Geologist.

Duties Consulting on stratigraphy and base metal and uranium exploration.

May 1978 to December 1978

Employer: PanCanadian Petroleum Ltd.

Position Geologist.

Duties. Oil Exploration in western USA

Summer 1977

Employer. Chevron Standard Ltd

Position Consultant Geologist

Duties· Consult on Pb-Zn exploration in Eastern Canada, carbonate and sandstone hosted deposits.

May 1975 to October 1976

Employer: Nova Scotia Department of Mines

Position Geologist.

Duties: Stratigraphy, sedimentology, subsurface correlation, mapping and paleontology in central N.S

September 1974 to May 1975

Employer· Nova Scotia Department of Mines

Position Paleontologist (Part time).

Duties: Paleontology of the Windsor Group in Atlantic Canada

Summer 1974

Employer: A C A. Howe International.

Position: Geologist.

Duties· Geochemical and geophysical exploration in central New Brunswick

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