Sedimentology and Depositional Environments of the Pennsylvanian Hub Cyclothem, Sydney Mines Formation, Cape Breton, Canada.

by

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DEPARTMENT OF EARTH SCIENCES

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ABSTRACT

The Late Carboniferous Sydney Mines Formation near Sydney, Nova Scotia comprises a succession of cyclothems, each 40 m thick on average, which show a basinwide alternation of red mudstones and grey coal-bearing strata. The Hub Cyclothem (Westphalian D - Stephanian) lies between the Hub coal seam and the Bonar (or Lloyd Cove) seam, and is intermittently exposed along 30 km of depositional strike.

Three facies assemblages constitute the Hub Cyclothem. Assemblage 1 contains coal-bearing floodplain deposits and meandering channel fills; it was deposited under the influence of a humid climate with a low degree of seasonality during a sea-level highstand. Assemblage 2 contains calcretes, vertisols, and fills from deep ephemeral channels; it was deposited under the influence of a seasonally semi-arid climate. The calcrete in Assemblage 2 may have formed following a relative fall in sea-level. Assemblage 3 contains calcite cemented floodplain deposits, and anastomosed channel fills; it was deposited under the influence of a strongly seasonal semi-arid climate, with an intense rainy season. Assemblage 3 may have been deposited while sea-level was rising.

In a sequence stratigraphic context, a sequence boundary lies at the top of the calcrete, near the base of Assemblage 2. A maximum flooding surface lies at the top of the thickest split of the Hub Coal seam. A highstand systems tract comprises all of the strata above the thickest split of the Hub seam, and below the top of the calcrete. The remainder of the cyclothem lies in a transgressive systems tract. There is no lowstand systems tract in the exposed part of the Hub Cyclothem; the transgressive surface, therefore, is near-coincident with the sequence boundary.

The Hub Cyclothem is a good source of coal. Petroleum exploration potential is poor in the exposed parts of the basin; offshore areas may be better if suitable source rocks can be

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CHAPTER 1

INTRODUCTION

1.0 Overview

The Pennsylvanian Hub Cyclothem is well exposed along 30 km of depositional strike in coastal exposures in the Sydney Basin of Nova Scotia. The excellent quality and extensive nature of the exposures make them an ideal setting in which to study floodplain and coastal sedimentary deposits laid down in response to climate change and, possibly, sea-level change.

The effects of relative changes in sea level and climate in sedimentary basins are currently receiving considerable attention. In particular, the widespread interest in sequence stratigraphy which began in the late 1970s, has focused attention on the importance of distinguishing climatic, tectonic, and eustatic events in the sedimentary record. Although extensive research into the nature of sequence-stratigraphic bounding surfaces and systems tracts has led to a much better understanding of coastal environments, the division between lowstand and transgressive deposits remains equivocal (see Van Wagoner *et al.*, 1988, and Galloway, 1989, for good reviews of sequence stratigraphic principles). Most research to date has employed deep seismic and borehole data, which are useful for determining large-scale features covering broad areas, but somewhat less appropriate for evaluating smaller-scale fills and units.

The purpose of this study is to use the excellent coastal exposures of the Hub Cyclothem to evaluate the nature of the cyclical sedimentary patterns in the Sydney Basin in terms of climate change, sea-level change and tectonism. This chapter provides background information on the Sydney Basin in general, and on the Hub Cyclothem in particular. Study locations and methods are also covered in this chapter. In Chapter 2, each of the sedimentary facies present in the Hub Cyclothem is described in detail and interpreted in terms of its depositional environment. The facies are gathered together into facies assemblages in Chapter 3; each assemblage represents a distinct set of climatic and eustatic conditions. Two depositional models for the Hub Cyclothem are developed and discussed in Chapter 4. Chapter 5 places the Hub Cyclothem in a sequence stratigraphic framework. The economic significance of the Hub Cyclothem is discussed in Chapter 6. The major conclusions of this thesis are summarized in Chapter 7. Appendix A contains a list of outcrops, with detailed maps and notes on access, as well as a map of drill hole locations. Appendix B contains stratigraphic columns for each outcrop.

1.1 Tectonic History and Basin Development

Most of the Sydney Basin lies under the present-day Laurentian Channel (Figure 1.1). The basin covers an area of more than 36 000 km^2 and trends roughly east-west; it is approximately 350 km long and 150 km wide, and contains a maximum of about 4 km of Carboniferous and Permian strata (King and MacLean, 1976). The onshore portion of the Sydney Basin is bounded on the northwestern side by the Mountain fault and on the southeastern side by the Mira River and Bateston faults (Gibling *et al.*, 1987). Very little is known about the offshore part of the basin. At least 50 km of marine seismic data have been collected and numerous holes drilled near the coastline; limited aeromagnetic data are available, covering most of the basin (Gibling *et al.*, 1987).

The sedimentary strata are juxtaposed against Precambrian and older Paleozoic rocks along faults and, locally, along unconformable contacts at the northern, western and southern basin margins. Mesozoic strata of the North American continental margin overlap the Sydney Basin strata on the southeastern margin (Gibling *et al.*, 1987).

Numerous faults were active during the Late Paleozoic Era in northeastern Nova Scotia (Figure 1.1). The Minas Geofracture (which includes the Cobequid and Chedabucto fault systems) was the most significant fault system; 165 km of dextral strike-slip motion may have occurred during the late Carboniferous and Permian (Keppie, 1982).

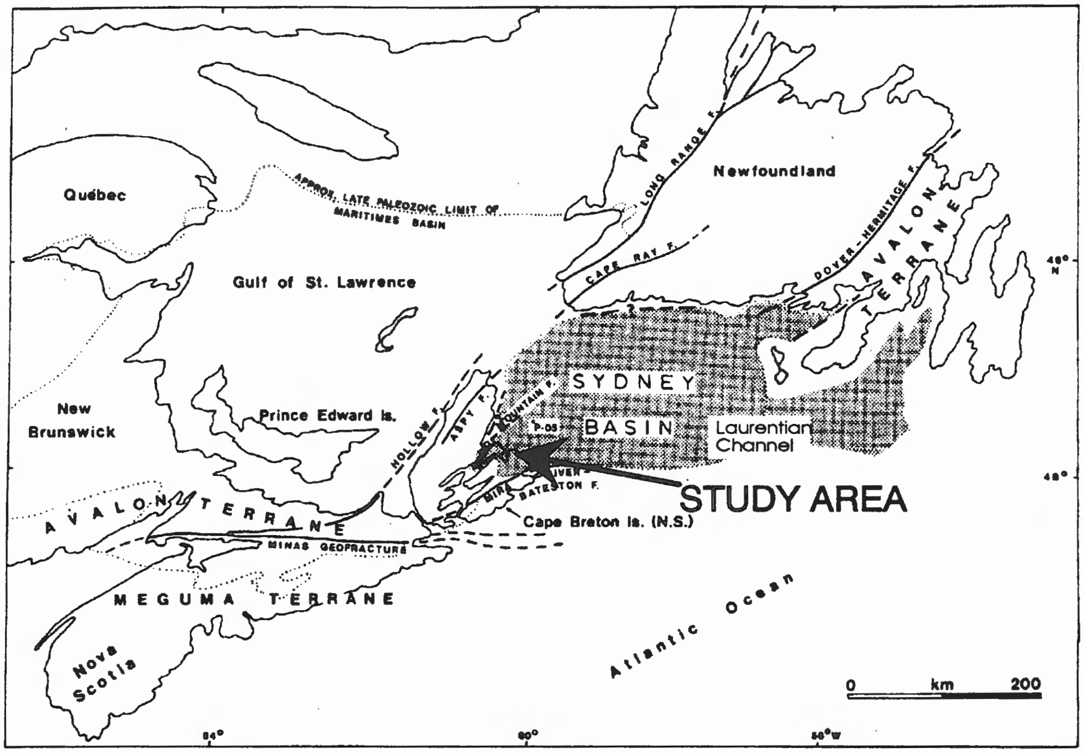


Figure 1.1. Location and extent of the major basins in the Maritimes Basin. Major structural features are also shown. (Modified from Gibling *et al.*, 1987)

Other late Paleozoic faults were probably splays off the Minas Geofracture. The faults in the Sydney Basin trend north-east, but some appear to curve eastward (parallel to the Minas Geofracture) in the offshore (Gibling *et al.*, 1987).

The Cape Breton faults were periodically active from the middle Devonian until the Permian. The majority of the activity within the Sydney Basin occurred in the late Devonian and early to mid Carboniferous (Gibling *et al.*, 1987). Lower Carboniferous strata, for instance, were displaced dextrally up to 18 km along the George River and Coxheath faults in the basin (Giles, 1983). Other faults near the basin (predominantly the Hollow fault, the Long Range fault, and the Minas Geofracture) were active during the Late Carboniferous (Gibling *et al.*, 1987; Langdon and Hall, 1994).

Aside from broad, gentle folds, and minor tilting (most beds dip less than 10°, although dips as steep as 45° are locally present), the late Paleozoic strata in the Sydney Basin are relatively undeformed. The nature of the folding differs between the Lower and Upper Carboniferous strata; this change probably reflects a change in the stress pattern and a difference in proximity to basement. The Lower Carboniferous strata lie in north-east trending folds (parallel to basement blocks); box folds are present near the Coxheath fault. The Upper Carboniferous strata are also folded along a north-east trend, but the folds have lower amplitudes and greater wavelengths (Gibling *et al.*, 1987).

1.2 Paleogeography and Paleoclimate

During the Westphalian and Stephanian, the Sydney Basin was located in an equatorial position (Figure 1.2), near a continental suture (Rowley *et al.*, 1985). Throughout the Carboniferous, the basin migrated north across the equator, from a humid climatic zone to an arid zone. The broad climatic change was influenced both by continental drift and by the collision of Laurussia and Gondwana (Hatcher *et al.*, 1989).

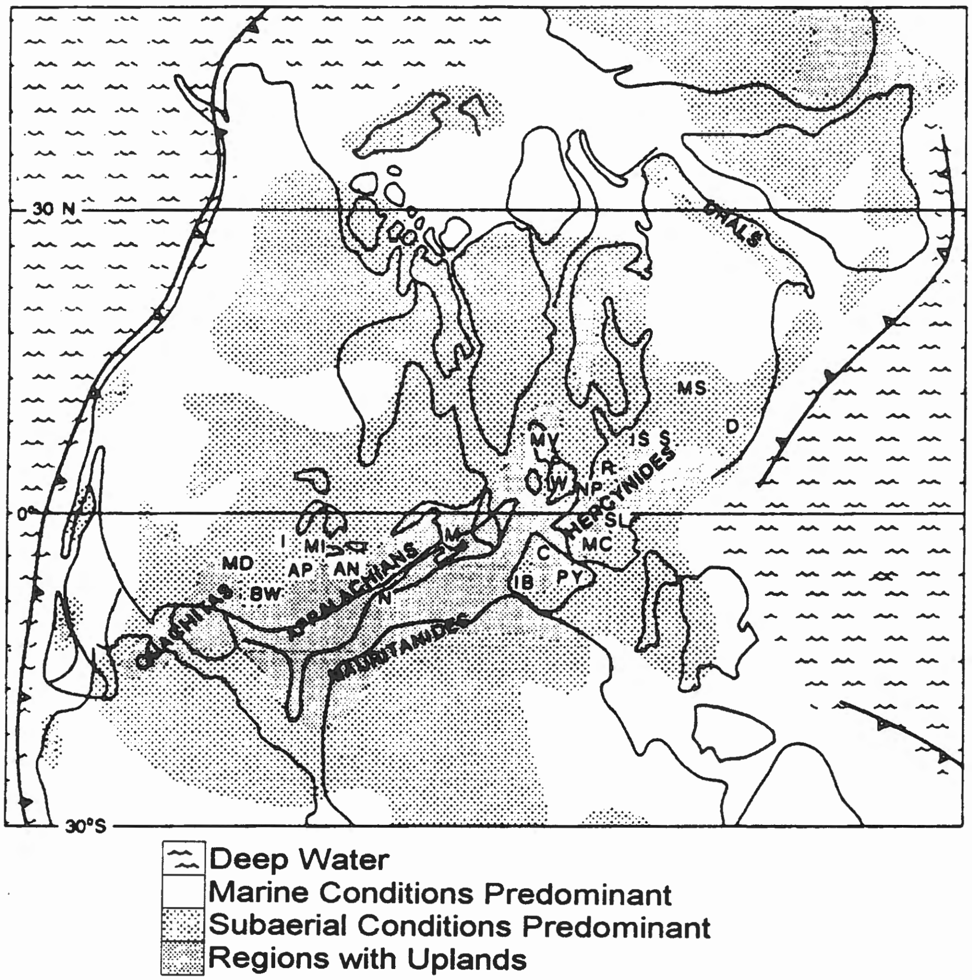


Figure 1.2. Generalized Late Carboniferous (306 Ma) paleogeographic reconstruction, showing the major Euramerican coal-bearing basins; AN: Anthracite Fields; AP: Appalachians; BW: Black Warrior; I: Illinois; M: Maritimes (which includes the Sydney Basin); MD: Midcontinental; MI: Michigan; N: Narragansett; C: Cantabrian Mountains; D: Donetz; IB: SW Iberia; IS: Intrasudetic; MC: Massif Central; MS: Moscow; MV: Midland Valley; NP: Nord-Pas de Calais; P: Pennine; PY: Pyrenees; R: Rhur; SL: Saar-Lorraine; S: Silesian; W: South Wales. (Modified from Calder and Gibling, 1994).

The Alleghanian Orogeny from the mid Carboniferous onward had a significant effect on the Westphalian and Stephanian paleoclimate. When Laurussia and Gondwana collided prior to the Westphalian, Himalayan scale mountains formed in an equatorial position, creating local rain shadow effects, and blocking cross-equatorial monsoonal winds (Rowley *et al.*, 1985).

During the Westphalian and Stephanian, Pangea was symmetrically oriented around the equator. The presence of large land masses on both sides of the equator created both summer and winter monsoonal winds. During the northern summer, a large low pressure system formed over the northern hemisphere and a large high pressure system formed over the southern hemisphere. The resulting wind patterns created a drier climate in the southern hemisphere and a more humid climate in the northern hemisphere. The patterns were reversed during the northern winter. The net effect was strong seasonality in both hemispheres (Schutter and Heckel, 1985).

As Pangea migrated north through the Late Paleozoic Era, the climate in the Maritimes Basin became increasingly seasonal and arid. This is reflected both in the upward increase in red strata in the Sydney Mines Formation, and in the upward transition from the coal-bearing Cumberland Group to the unnamed Permian redbeds in the Sydney Basin (Rust *et al.*, 1987).

1.3 Sedimentary History

In all cases throughout this thesis, absolute times and durations are based on the $^{40}Ar/^{39}Ar$ derived dates in Lippolt and Hess (1985) and Hess and Lippolt (1986). An older time scale (Harland *et al.*, 1982) is used in many of the older papers from the Sydney Basin (including Gibling *et al.*, 1987, which is referenced often throughout this section); all of the dates cited from these papers have been updated in order to remain consistent with Lippolt and Hess (1985). The duration of the Westphalian according to Harland *et al.* (1982) is 19 Ma, as opposed to the 10 Ma duration cited in Lippolt and Hess (1985).

The Sydney Basin is filled with 4 km of Lower Carboniferous to Permian strata in two megasequences (Figure 1.3) (Boehner and Giles, 1986; Gibling *et al.*, 1987). The lower megasequence, which represents about 35 million years of deposition, covers older basement rocks; the Horton, Windsor and Mabou Groups are the major divisions in the lower megasequence. The upper megasequence, which represents about 10.5 million years of sedimentation, covers basement highs; the Cumberland Group and overlying unnamed redbeds comprise the upper megasequence. A hiatus of about 9.5 million years created the post-Mabou unconformity which separates the two megasequences (Boehner and Giles, 1986).

1.3.1 Horton Group

The Horton Group, which rests unconformably on an older granitic and marble bedrock, is a succession of red conglomerates with associated sandstones, siltstones and pedogenic limestones (Boehner and Giles, 1986). The rocks range in age from late Tournaisian (Horton Group strata in other parts of the Maritimes are as old as Devonian) to early Visean and have a maximum thickness of 1000 m (Belt, 1965). The imbricate, clast-supported conglomerate fabric, and the presence of conglomeratic sheets with channel fills up to 1 m thick suggest that deposition occurred in shallow streams on alluvial fans (Hamblin, 1992). The clasts include granitic rocks and marbles similar to those in the surrounding basement rocks. The black shales common in the Horton Group elsewhere in Atlantic Canada are apparently absent in the Sydney Basin (Gibling *et al.*, 1987).

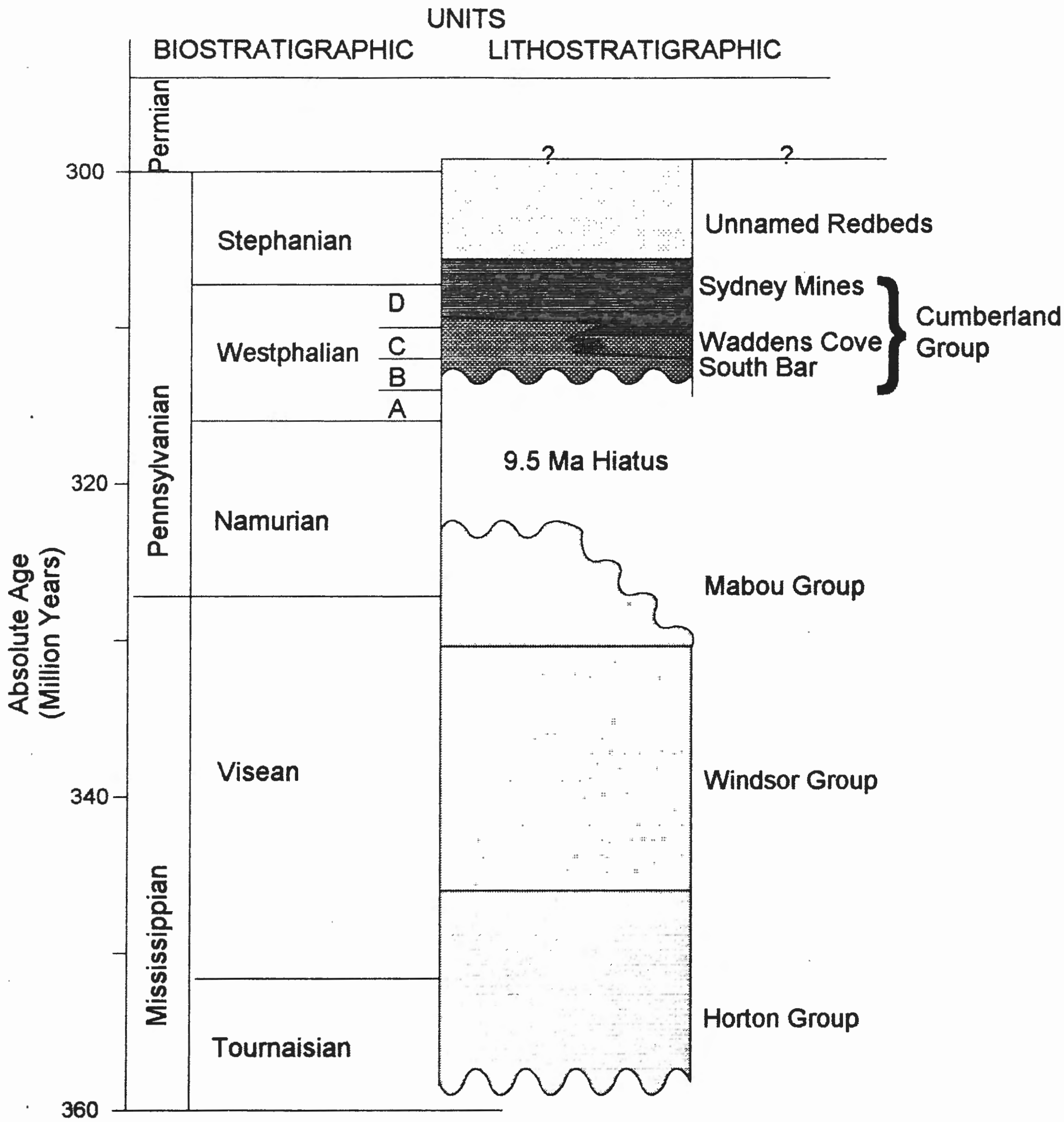


Figure 1.3. Generalized stratigraphy of the onshore part of the Sydney Basin. (Modified from Gibling *et al.*, 1987). Ages are based on the time scale of Lippolt and Hess (1985).

1.3.2 Windsor Group

The Windsor Group sediments, deposited between the early and late Visean, have a maximum thickness of 860 m in the Sydney Basin, and conformably overlie the Horton Group strata throughout the Sydney Basin (Bell, 1938; Boehner and Giles, 1986). Marine limestones, dolostones, anhydrite and shales dominate (Schenk, 1969), but red terrigenous conglomerates, sandstones and mudrocks are also common (Boehner and Giles, 1986). The Windsor Group consists of five shallowing-upward cycles, the thickest of which is 440 m thick (Boehner, 1985). The evaporites pass laterally into terrigenous sediments near basement blocks, suggesting that deposition took place in a periodically hypersaline marine embayment in which water depths were in excess of a few hundred metres during early periods of the transgressive phases (Geldsetzer, 1978).

1.3.3 Mabou Group

The late Visean to Namurian Mabou Group is predominantly composed of red and grey mudrocks, with calcareous sandstones, stromatolitic limestones and sulphate evaporites (Belt, 1965, 1968; Boehner and Giles, 1986). The strata conformably overlie the Windsor Group rocks and show an overall upward transition from predominantly grey strata into red strata with nodular calcretes. The top of the Mabou Group is truncated by a major unconformity in the Sydney basin; as preserved, it is locally more than 200 m thick (Gibling, *et al.*, 1987). The presence of nonmarine biota with carbonates and evaporites indicates a lacustrine depositional setting with minor fluvial influences (Belt, 1968).

1.3.4 Hiatus

In the parts of the Sydney Basin now exposed, the strata were eroded during approximately 9.5 million years following deposition. In some areas, as much as 250 m of Mabou and Windsor group strata were eroded (Gibling *et al.*, 1987); the remaining strata were tilted about 10°. Exposed Windsor Group limestones, such as those on Boularderie

Island, underwent extensive karstic weathering during the hiatus (Boehner, 1985). Sedimentation, however, continued in other parts of the Maritimes Basin. The basal Cumberland Group (previously called the Riversdale Group; Bell, 1944) was deposited during the latest Namurian and Westphalian A in western Cape Breton Island (Norman, 1935; Ryan *et al.*, 1991) and in Newfoundland (Knight, 1983). The Cumberland Group was deposited on mainland Nova Scotia during the Westphalian A to C (Ryan *et al.*, 1991).

1.3.5 Cumberland Group

The Pennsylvanian Cumberland Group in the Sydney Basin is a 2 km thick fining-upward sequence of strata (Hacquebard, 1983; Ryan *et al.*, 1991), deposited under tectonically quiescent conditions (Gibling *et al.*, 1987). The Cumberland Group sediments are the youngest rocks in the on-shore portion of the Sydney Basin; they range in age from Westphalian B-C to Stephanian (Figure 1.3) (Bell, 1938; Zodrow and McCandlish, 1978; Zodrow and Cleal, 1985).

In the Sydney Basin, the Cumberland Group strata historically have been called the Morien Group (Hacquebard, 1983; Boehner and Giles, 1986). The Morien Group was correlated with the Cumberland Group by Ryan *et al.* (1991) in a regional analysis of the Late Carboniferous rocks in Atlantic Canada. Because this thesis focuses on a cyclothem which may be correlatable beyond the Sydney Basin, the regional nomenclature is used.

The Cumberland Group comprises three formations in the Sydney Basin: the South Bar, Waddens Cove and Sydney Mines Formations (Boehner and Giles, 1986; Ryan *et al.*, 1991).

The South Bar Formation lies at the base of the Cumberland Group throughout most of the Sydney Basin (Figures 1.3 and 1.4). It is approximately 1 km thick and represents an upward gradation from a proximal braidplain with narrow confined channels to a distal

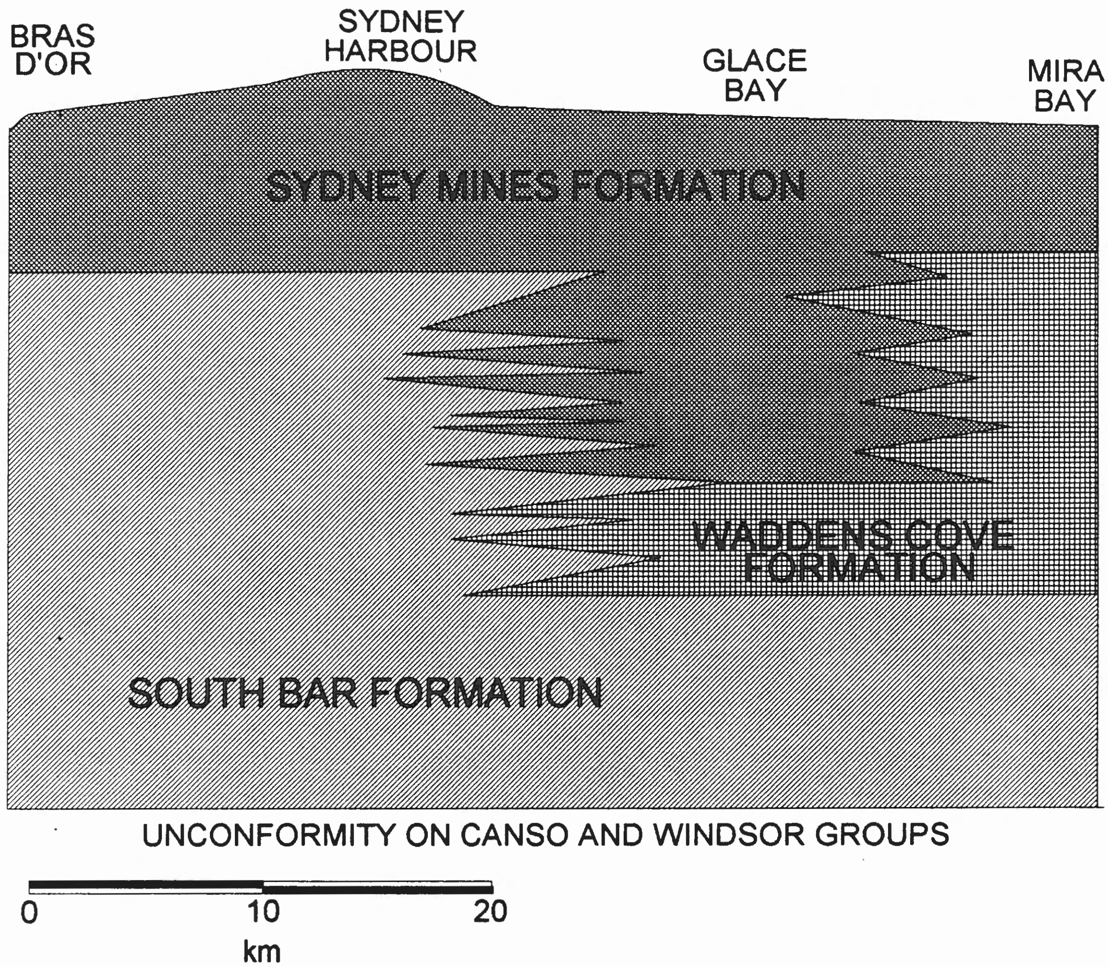


Figure 1.4. Generalized stratigraphic relationships of the three formations (South Bar, Waddens Cove and Sydney Mines) of the Cumberland Group in the Sydney Basin (Modified from Rust *et al*., 1987).

braidplain with broader channels (Rust and Gibling, 1990). Shale accounts for less than 10% of the formation, even at the highest levels. The South Bar braidplain deposits grade laterally and upward into the meander belt successions of the Sydney Mines and Waddens Cove Formations (Figure 1.4) (Rust *et al.*, 1987).

The Waddens Cove Formation (about 840 m thick; Boehner and Giles, 1986; Rust *et al.*, 1987) overlies the South Bar Formation in the southeastern portion of the Sydney Basin (Figures 1.3 and 1.4); it is overlain by the Sydney Mines Formation. It interfingers with the South Bar Formation to the southwest of Glace Bay and the Sydney Mines Formation to the southeast of Glace Bay. The Waddens Cove strata are predominantly red mudrocks and siltstones; duricrusts (very hard layers with silica cement) are common. The channel bodies have low width to thickness ratios (less than 15:1). Economic coal seams are not present in the Waddens Cove Formation (Rust *et al.*, 1987).

The Westphalian D and Stephanian (Bell, 1938; Barss and Hacquebard, 1967; Zodrow and McCandlish, 1978; Zodrow and Gastaldo, 1982) Sydney Mines Formation constitutes the upper 500 m of the Cumberland Group (Boehner and Giles, 1986) in the Sydney Basin (Figures 1.3 and 1.4). It conformably, but sharply, overlies the South Bar Formation throughout most of the basin, except in the southeast, where it overlies the Waddens Cove Formation (Figure 1.4) (Boehner and Giles, 1986). The Sydney Mines Formation is primarily composed of sandstone, red and grey mudrock, coal, and minor limestone. The contact with the underlying South Bar Formation is marked by the transition from sandstone to alternating sandstone and mudstone assemblages. This transition occurs 10 m below the lowest economic coal seam, the Emery Seam, over most of the basin; in the southeast, however, the transition is much lower (Rust *et al.*, 1987). The Sydney Mines Formation contains the major economic coal seams in the Sydney Basin (Hacquebard, 1983). Seam thicknesses range up to 4.3 m and some seams extend across the full 45 km width of the basin exposed onshore (Hacquebard and Donaldson, 1969).

Until recently, the depositional setting of the Sydney Mines Formation was interpreted as a broad fresh-water floodplain with peat mires and meandering channels, because of its sedimentological characteristics and the absence of diagnostic marine fossils (Rust *et al.*, 1987), although Hacquebard and Donaldson (1969) suggested that the Sydney coals were probably deposited in a paralic setting, inferring close proximity to the sea. More recent studies have cited sedimentological evidence for a paralic setting. The extensive limestones and carbonaceous shales resemble the "marine bands", bearing an open-marine biota, in European coalfields (Masson and Rust, 1990; Wightman *et al.*, 1994). The thin and extensive coal seams with low ash (5-9%) and high sulphur (2.5-6.2%) are more indicative of a paralic than a freshwater depositional setting (Hacquebard and Donaldson, 1969), although the high sulphur levels may be attributed either to sulphur recycling from the evaporites in the underlying Windsor Group (Gibling *et al.*, 1989), or to a rainwater source (Neuzil and Cecil, 1994). The presence of well-formed cyclothems is also suggestive of some degree of marine influence (Bird, 1987; Gibling and Bird, 1994).

The recent discovery of brackish-water agglutinated foraminifera and fresh water thecamoebians indicates that the Sydney Mines Formation was deposited in a coastal setting, with relative changes in sea-level (Thibaudeau and Medioli, 1986; Wightman *et al.*, 1993, 1994; Gibling and Bird, 1994).

1.3.6 Unnamed Redbeds

In the off-shore portion of the Sydney Basin, the Cumberland Group is overlain by at least 400 m of red mudrocks, siltstones and sandstones. Very little is known about these strata, because drill core data are very sparse in the basin (Hacquebard, 1983; Gibling *et al.*, 1987). Latest Carboniferous and Permian redbeds are present in the Pictou Group under the Gulf of St. Lawrence (van de Poll and Forbes, 1984; Gibling *et al.*, 1987), and may be equivalent to the redbeds in the Sydney Basin.

1.4 Cyclothems

The term cyclothem was originally used by Wanless and Weller (1932) to describe repeated stratal successions in the Pennsylvanian coalfields in the Illinois Basin (Udden, 1912; Weller, 1930; Wanless and Weller, 1932). They vaguely defined a cyclothem as "... a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period." (Wanless and Weller, 1932). Cyclothems in the American mid-continent are typically a few tens of metres thick, and contain limestone, shale, coal, and sandstone. The strata alternate between marine and non-marine assemblages; each cyclothem represents one cycle of regression and transgression (Udden, 1912; Heckel, 1986).

The Late Carboniferous Sydney Mines Formation comprises a succession of at least 12 cyclothems, about 40 m thick on average, which show a basinwide alternation of red mudstones and grey coal-bearing strata. The upper cyclothems are thicker (up to 70 m) and somewhat better developed than the lower cyclothems, which are as thin as 15 m. Cyclothem boundaries are placed at, or slightly above, thick coal seams; these units, in at least some instances, represent maximum flooding surfaces (Gibling and Bird, 1994).

They cyclothems in the Sydney Mines Formation do differ from the cyclothems originally described by Udden (1912) and defined by Wanless and Weller (1932). The midcontinental cyclothems are generally about 30 m thick, and are composed of coals, limestones and thick shale and sandstone bodies (Udden, 1912); red strata are often rare. Because they were deposited in a more landward setting, the Sydney cyclothems tend to be thicker (the Hub Cyclothem is about 70 m thick) and contain abundant red strata (Gibling and Bird, 1994).

The Sydney cyclothems are Westphalian D to Stephanian in age, which makes them broadly time-equivalent to cyclothems in the Illinois Basin (Gibling and Bird, 1994; Dolby, 1989). The average cyclothem duration in the Sydney basin has been broadly estimated at 200 ka (Gibling and Bird, 1994); this is similar to the average duration of cyclothems in the United States (235-400 ka, Heckel, 1986; 230-385 ka, Goldhammer *et al.*, 1991; 352 ka, Connolly and Stanton, 1992) and of transgressive-regressive cycles of similar age in Europe (Collier *et al.,* 1990). Comparisons of average cyclothem duration must be made with care, because many of the estimates are based on the time scale in Harland *et al.* (1982), which makes them about twice as long as they would be if the Lippolt and Hess (1985) time scale was used. Despite this uncertainty, however, the Sydney Mines Formation cyclothems have similar average durations.

The transgressive-regressive nature of cyclothems has been attributed to a variety of different causes including tectonism (Weller, 1930; Klein and Willard, 1989), climate change (Beerbower, 1961; Cecil, 1990), delta-lobe progradation (Ferm, 1970), and, most commonly, glacio-eustatic sea-level change in response to Gondwanan glaciation (Wanless and Shepard, 1936; Heckel, 1986; Veevers and Powell, 1987; Maynard and Leeder, 1992; Gibling and Wightman, 1994; Gibling and Bird, 1994).

The Hub Cyclothem lies near the top of the Sydney Mines Formation (Figure 1.5), and lies between the Hub and Lloyd Cove (also called the Bonar) coal seams. The Westphalian D to Stephanian stage boundary lies within the Hub Cyclothem (Zodrow and McCandlish, 1978; Zodrow and Cleal, 1985), about 25 m above the Hub seam (Dolby, 1989). The Hub Cyclothem is cyclothem 10 of Gibling and Bird (1994), and cyclothem 8 of Bird (1987). It is exposed in ten locations along the Sydney coastline, between Point Aconi and Glace Bay (Figures 1.6 and 1.7), and ranges in thickness from 50 to 70 m.

For the purposes of this study, the base of the Hub Cyclothem is defined as the base of

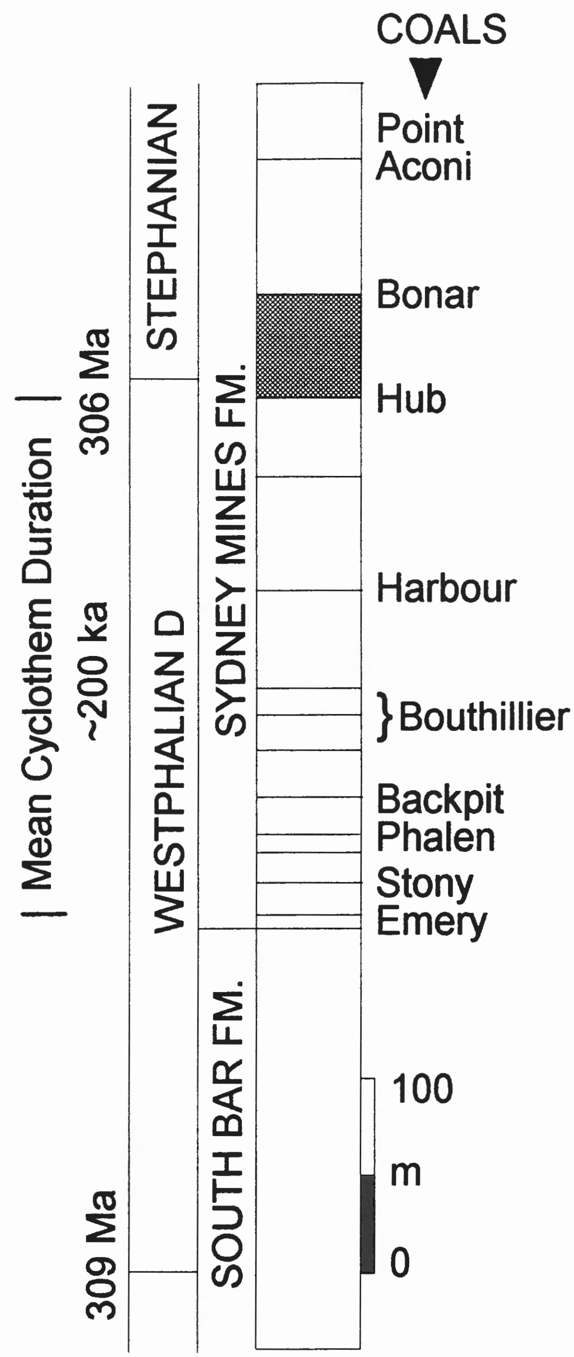


Figure 1.5. Generalized stratigraphic column of the Sydney Mines Formation, showing the major coal seams. The Hub Cyclothem (shaded) lies between the Hub and Bonar coal seams. (Modified from Tandon and Gibling, submitted). All absolute times are based on the timescale in Lippolt and Hess (1985).

the seat-earth underlying the lowest split of the Hub coal seam. This stratum overlies the redbeds and grey calcite cemented strata of the underlying Harbour Cyclothem. The top of the Hub Cyclothem is defined as the top of the uppermost occurrence of grey, calcite cemented siltstones and sandstones. This coincides with the base of the seat-earth below the lowest split of the Bonar coal seam. Gibling and Bird (1994) placed cyclothem boundaries at carbonaceous shales and limestones above the coals in the Sydney Mines Formation; their cyclothem boundaries are maximum flooding surfaces, which are used as sequence boundaries in Galloway's (1989) sequence stratigraphy models. There are, however, no limestones in the Hub Cyclothem, and the only major carbonaceous shales are at the Glace Bay exposure. The Hub Cyclothem boundaries used in this thesis (bases of the coal seams) were chosen for practical, rather than conceptual reasons: they are easy to identify in the field, and correlate well between outcrops. The tops of the coal seams are conceptually better boundaries (Calder and Gibling, 1994), but are confusing, because splits in the coal seams are common.

1.5 Economic Significance

The Sydney Basin has a long history of coal mining, beginning in 1720, when the French mined coal for use during the construction of their fortress at Louisbourg. The majority of mining took place over the past 160 years, with production peaking at 6 million short tons in 1940. Current annual production averages between 3 and 4 million short tons. Almost all of the production has occurred in sub-sea mines (Hacquebard, 1993).

Most of the economic coal seams in the Sydney Basin lie in the Sydney Mines Formation. They produce medium to high volatile A bituminous coal with relatively high sulphur (2.5-6.2%) and low ash (5-9%). Two underground mines are currently operating in the Sydney Basin: the Prince Mine near Point Aconi, and the Phalen Mine, near the New Waterford exposure.

The Hub seam is mined in the Prince Mine, which lies about 4 km offshore, near Point Aconi. The presence of sandstone channels which cut through the coal seam presents grave dangers to mining operations. When the automated longwall cutters strike a sandstone body, sparks are produced which can ignite any coalbed methane which may be present (Forgeron, 1980). Furthermore, mud-filled hollows are intermittently present in the top layers of the Hub coal seam in the Prince mine. Because the coal from the Prince Mine is not washed, the presence of these mud-filled hollows can dramatically increase the ash content of the produced coal. The adjustments to the longwall mining equipment, in order to avoid the hollows can take as much as a week; the predictions of these hollows is, therefore critical for both coal quality and production rates. It is important, therefore to develop a good understanding of the nature of the clastic facies, in order to better predict their presence and form.

Although only minor hydrocarbon shows have been found in the rocks of the Sydney Mines Formation (Murphy Oil Company, 1974), similar coal-bearing and estuarine sequences are important oil reservoirs in western Canada (Wood and Hopkins, 1992). The excellent exposures in the Sydney Coalfield, provide a useful workplace to develop depositional models to be used in other basins, where many economic units are known only in the sub-surface.

1.6 Location

The Hub Cyclothem is exposed in ten exposures along the Sydney coastline (Figures 1.6 and 1.7). Aside from the two exposures at Glace Bay, which are only partially

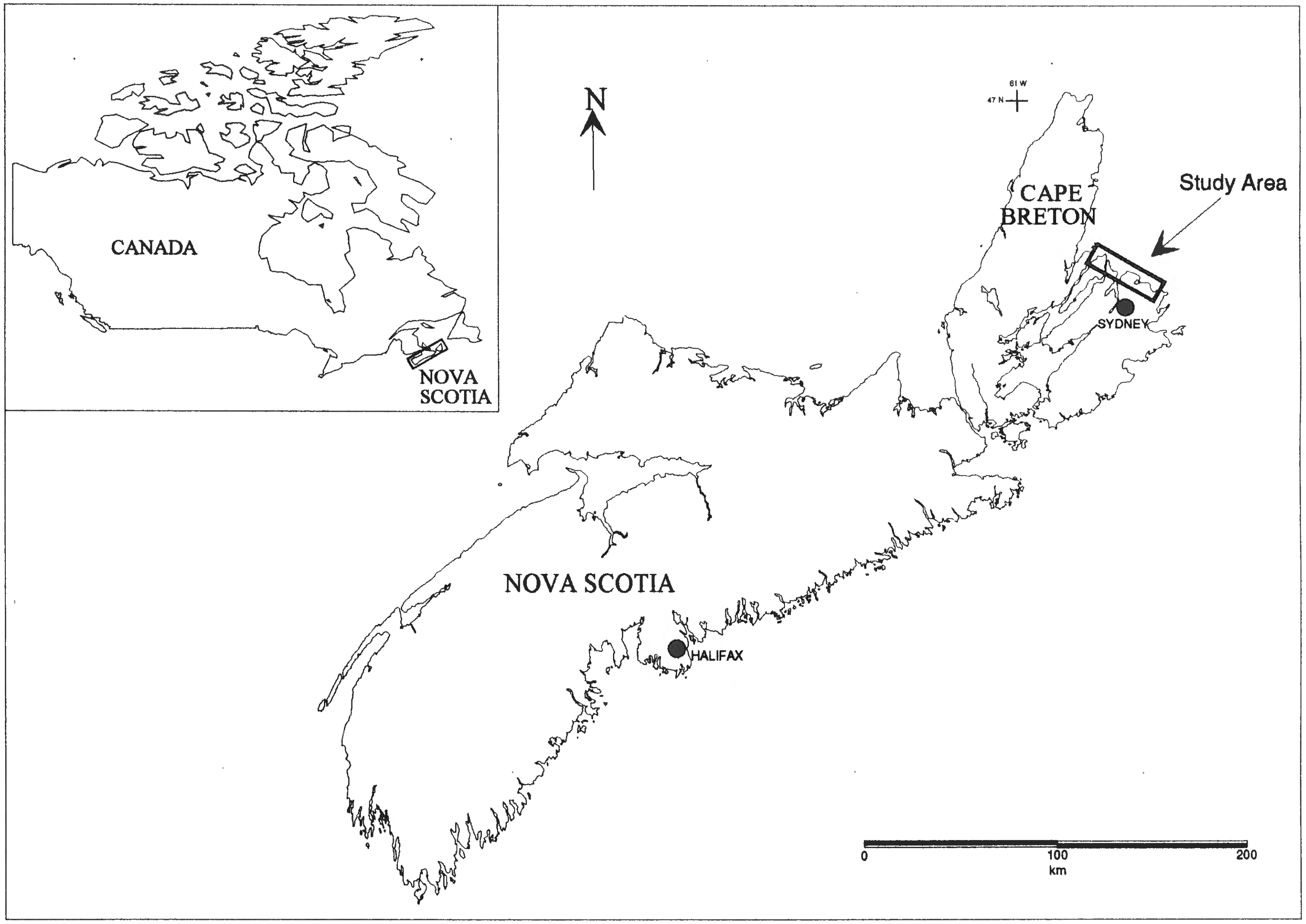


Figure 1.6. Location of the Hub Cyclothem study area.

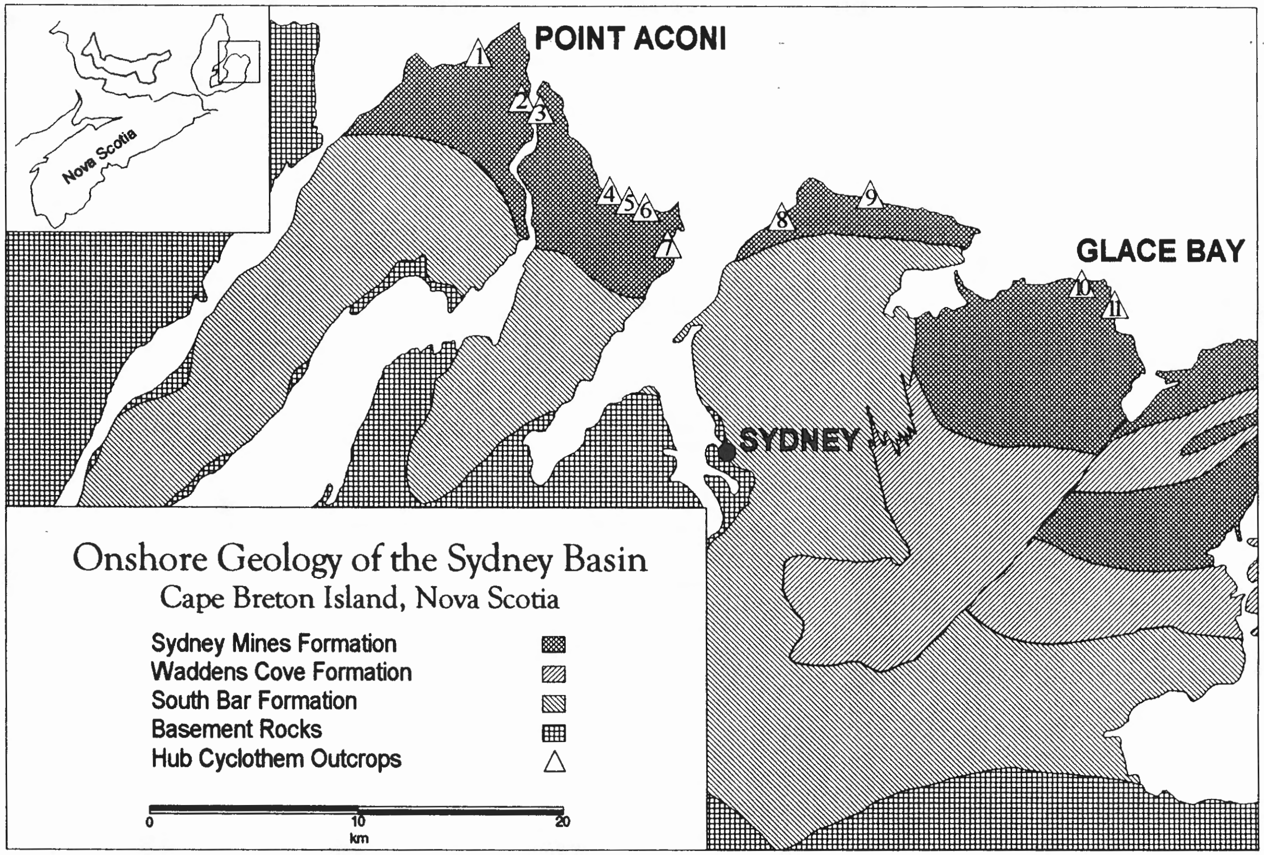


Figure 1.7. Onshore geology of the Cumberland Group in the Sydney Basin. Triangles mark exposures of the Hub Cyclothem. 1: Bras d'Or; 2: Point Aconi; 3: Alder Point; 4: Wetneck Point; 5: Black Point; 6: Oxford Point; 7: Chapel Point; 8: Victoria Mines; 9: New Waterford; 10: Glace Bay West; 11: Glace Bay East. (Modified from Boehner and Giles, 1986).

accessible, all the exposures can be visited at low tide. Notes on accessibility and detailed location maps are in Appendix A.

1.7 Goals

This study has six primary goals:

1) Produce detailed descriptions of all Hub Cyclothem exposures.

2) Evaluate the degree of marine influence during deposition of the Hub cyclothem, both in the channel fills and in mudrocks.

3) Identify and describe any paleovalley fills.

4) Develop a depositional model for the Hub Cyclothem.

5) Determine if vertical facies changes within the cyclothem were caused by allocyclic or autocyclic events.

6) Place the cyclothem in a sequence stratigraphic context. It is particularly important to determine whether paleovalleys were filled in response to increased sediment supply, or a relative rise in sea level. This question has important implications for sequence stratigraphic work, because sediments deposited in response to a relative rise in sea level belong to the transgressive systems tract, rather than the lowstand systems tract.

1.8 Data Collection

The bulk of the data collection for this project involved field work and photomosaic interpretation. Additional data were collected from logs of 14 drill cores (drilled and logged by Nova Scotia Department of Mines geologists), petrographic examination of thin sections, reviews of published and unpublished literature and discussions with geologists working on associated projects. The drill core logs are of only limited use: they generally list only grain size and colour (in many cases, only grain size is listed). The drill cores themselves are not available for examination. The locations of the drill holes are listed in Appendix A.

Field work was completed during June and July, 1993. During that period, all ten exposures of the Hub Cyclothem were visited, and described and measured in detail. The grain size, sediment type, sedimentary structures, fossils, overall shape, nature of the contacts with laterally and vertically adjacent units, and vertical position of each unit was documented. Stratigraphic columns for each outcrop were constructed and used in cross-basinal correlations in order to determine the lateral relationships among the various units in the cyclothem. Copies of the ten stratigraphic columns are in Appendix B. Most units were sampled; a total of 206 samples were collected. These samples currently reside with Dr. M.R. Gibling in the Department of Earth Sciences at Dalhousie University.

Photos were taken of all exposures from small chartered boats on two separate dates, in May and July, 1993. Photomosaics were constructed in order to document unit geometries on a scale too great for observation from shore.

Logs from drill cores were used to fill in gaps in the data provided from coastal exposures.

Petrographic examinations of seven thin sections were used to better document the nature of the different types of channel fills. Seven thin sections were deemed sufficient for this study, because they provide a general indication of the sandstone lithologies. Little variability exists among the thin sections for each location. However, point counting values for mineral abundances are not statistically significant for this small data set. All mineral abundances listed in Chapter two are, therefore, rough estimates.

Paleoflow directions were measured from ripple cross-lamination, rill marks, flute casts, and trough cross-strata on bedding surfaces. Because dips are low in the Hub Cyclothem exposures it was not necessary to correct the flow directions for tectonic tilt.

CHAPTER 2

SEDIMENTARY FACIES

2.0 Introduction

The fifteen facies described in this chapter form the basis for interpreting the depositional environment for each bed (this chapter), each facies assemblage (Chapter three) and for the cyclothem as a whole (Chapters four and five). The facies are distinguished on the basis of grain size, sedimentary structures and three-dimensional geometry. The primary characteristics of each facies are summarized in Table 2.1 and Table 2.2. Appendix B contains vertical columns for each of the measured sections used in this study. The relative proportions of each facies in each outcrop are shown in Figure 2.1. Each facies is described below; the depositional environment for each facies is described at the end of each section.

Throughout this chapter, the term mudrock is used to describe all rocks which formed from lithified clay with a minor amount of silt. Siltstones are rocks formed primarily from silt sized material, although clay and sand may be minor constituents. Sandstones are primarily derived from sand sized grains, although silt and clay may be relatively abundant; gravel may also be present.

Many of the facies descriptions include results from foraminiferal and thecamoebian analyses done by Dr. Winton Wightman (Dept. of Earth Sciences, Dalhousie University) in 1993 (Wightman, personal communication, 1994; Wightman *et al.*, 1993, 1994). The results from the Glace Bay region are summarized in Wightman *et al.* (1994); the Bras d'Or results are summarized in Figure 2.2 and Table 2.3.

Floral analyses of the Hub Cyclothem can be found in Dawson (1868), Bell (1938), Zodrow and McCandlish (1978), Zodrow and Cleal (1985) and Marchioni *et al.* (1994). The most current spore data are presented by Marchioni *et al.* (1994). Aside from foraminifera and thecamoebians, very little faunal material has been documented from the

Facies	Name	Grain Size	Colour	Sedimentary Structures	Fossils/Nodules	Thickness	Other	Depositional Environment
Ml	Laminated Grey Mudrock	Mud to silt	grey, green, black.	planar lamination ripple cross-lamination	- macerated plant leaves - coal stringers	<1 m	- local carbonate cement	Standing water bodies. eg. lakes or marine bays
Md	Disrupted Grey Mudrock	Mud	grey, green, black	massive	- siderite nodules - rooted zones - coal stringers -upright tree trunks	30 cm - 2 m		Very wet, frequently saturated sub-aerial conditions. (gleysols and protosols)
Mr	Red Mudrock	Mud to silt	red or mottled red and grey	concave-up fractures	none observed	5 - 80 cm	- local carbonate cement	Seasonally arid, sub-aerial conditions. (vertisols)
Mb	Black Shale	Mud	black	planar lamination	- coprolites - fish scales - disseminated pyrite	20 - 30 cm		Low energy environment eg. large bay or sub-basin, or large lake.
C	Calcrete	Silt to fine sand	light grey	nodular calcrete	none observed	50 cm - 1 m		Low sediment influx, seasonally arid climate, low precipitation .
SLg	Laminated Grey Siltstone	Silt	grey	- ripple marks - planar lamination - dessication cracks - tool marks - raindrop imprints	- tetrapod trackways	15 - 20 m	- carbonate cemented - no vegetation	Overbank sheet floods when CH4 channel capacity was exceeded (see Table 2.2).
SLr	Red Siltstone	Silt to gravel	red	none	none observed	< 30 cm	- no vegetation	Local erosion and deposition during floods.
Oc	Coal	Coal	black	none	none observed	< 1.5 m		Paralic peat mires.
Ob	Thin Carb. Shale Laminae	Mud	black	none	none observed	< 2 cm	- thin, but extensive	Floating or transported vegetation.
Gfu	Fining-Up Beds	Mud to medium sand	grey, black, red	- ripple lamination - planar lamination - disrupted bedding	- macerated plant debris - siderite nodules	50 cm - 4.5 m	- Fine upwards	Abandoned channel fills, splay deposits and sheet flood deposits.
Gcu	Coarsening-Up Beds	Mud to medium sand	grey, black, red	- disrupted bedding - ripple lamination - planar lamination	- macerated plant debris - siderite nodules - coal stringers - upright tree trunks	1.5 - 4.5 m	- Coarsen upwards	Filling of bays or lakes.

Table 2.1 Main features of the overbank facies in the Hub Cyclothem.

Facies	Name	Grain Size	Colour	Sedimentary Structures	Fossils/Nodules	Thickness	Other	Depositional Environment
CHp	Pebbly Meandering Channel Fill	Fine sand to gravel	light brown	- lateral accretion sets - trough cross bedding - ridge and swale topography - scroll bars - ripple lamination	- peat mats - tree and root fragments - siderite nodules	< 10 m (2 - 5 m per storey)	- multistoried - width:thickness > 50:1	Meandering channels in a major drainage system carrying both extra- and intra-basinal sediments to the sea.
CHs	Sandy Meandering Channel Fill	Fine to coarse sand	light brown	- trough cross bedding - lateral accretion sets - ridge and swale topography - scroll bars - ripple lamination	- siderite nodules - calcite nodules - macerated plant debris - tree and root fragments	< 15 m (2 - 5 m per storey)	width:thickness > 30:1	Meandering channels on a vegetated floodplain.
CHc	Large Complex Valley Fills	Mud to medium sand	grey, brown, red	- Mud/sand interbeds - planar lamination - ripple lamination - slickensides - slumps - trough cross bedding - flute casts - scour fills	- rip-up clasts of calcrete	> 5 m	- carbonate cement - no vegetation	Incized following a drop in base level. Filled under conditions of variable flow and seasonal climate.
CHu	U-Shaped Channel Fills	Fine to medium sand	grey	- planar lamination - climbing ripples	none	< 2.5 m	- "U" shaped cross-section - carbonate cement - width:thickness between 15:1 and 30:1	Anastomosed river complex on an unvegetated floodplain.

Table 2.2 Main features of the channel facies in the Hub Cyclothem.

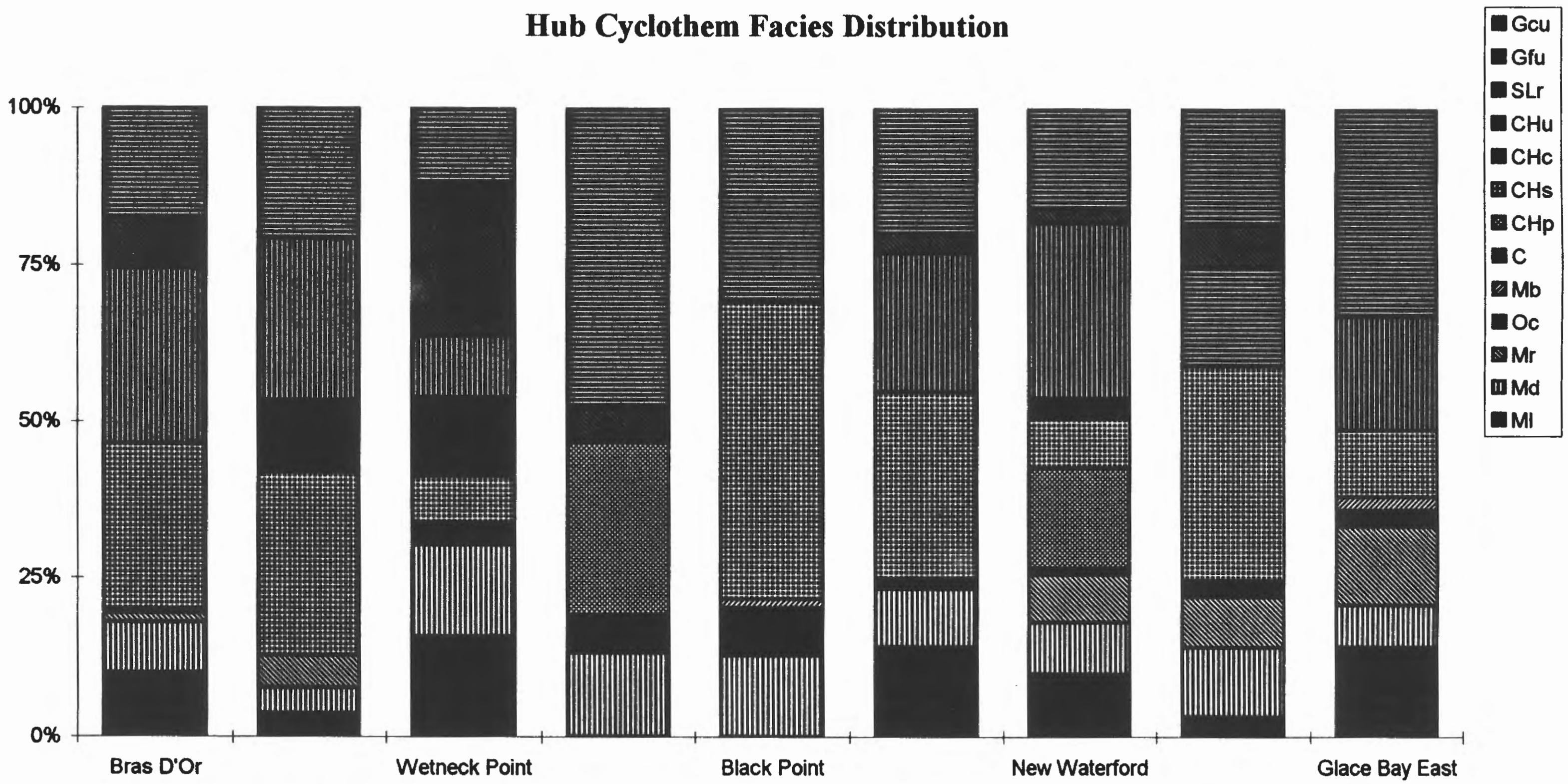


Figure 2.1 Facies proportions in the nine Hub Cyclothem exposures (see Figure 1.7 for locations). The cyclothem is fully exposed at Bras d'Or, Point Aconi and New Waterford; it is almost fully exposed at Wetneck Point and Chapel Point. Only the base of the cyclothem is exposed at the other locations. See Tables 2.1 and 2.2 for a summary of facies abbreviations.

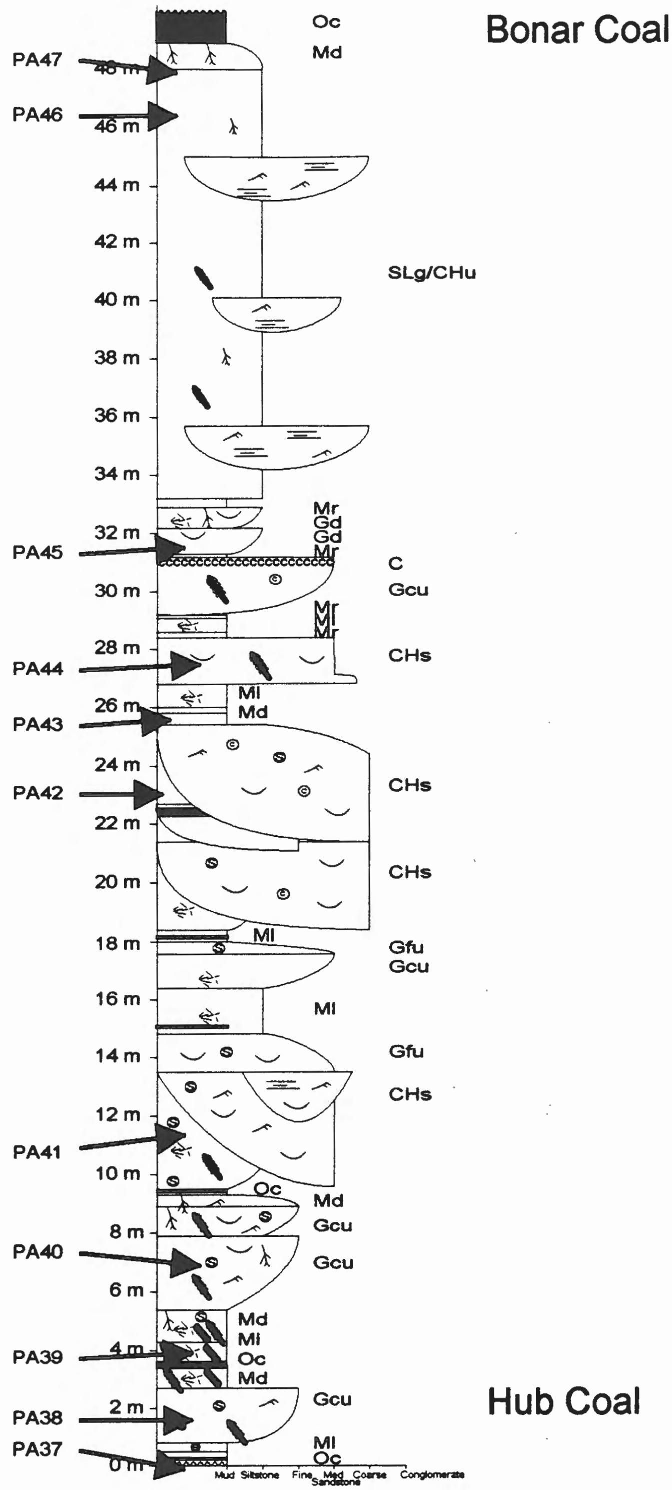


Figure 2.2. Measured section for the Bras d'Or outcrop, showing facies and sample numbers for microfossil analyses. All microfossil sample numbers begin with a PA prefix. The results of the analyses are shown in Table 2.3.

Sample	Microfossils present	Assemblage	Environment
PA37	Abundant *Trochammina*, few *Ammotium*	*Trochammina*	Upper salt-marsh
PA38	Abundant *Trochammina*, few *Ammobaculites*	*Trochammina*	Upper salt-marsh
PA39	Abundant Thecamoebians, very rare *Trochammina*	Thecamoebians	Fresh-water
PA40	Abundant Thecamoebians, rare *Trochammina*	Thecamoebians	Fresh-water
PA41	Common *Trochammina*, few Thecamoebians	*Trochammina*	Upper salt-marsh
PA42	Common *Trochammina*, few Thecamoebians	*Trochammina*	Upper salt-marsh
PA43	Common *Trochammina*, rare *Ammobaculites*	*Trochammina*	Upper salt-marsh
PA44	Barren		
PA45	Few *Trochammina*	*Trochammina*	Upper salt-marsh
PA46	Few *Trochammina*	*Trochammina*	Upper salt-marsh
PA47	Few *Trochammina*	*Trochammina*	Upper salt-marsh

Table 2.3 Results of microfossil analyses for samples from Bras d'Or; all samples were analysed by Dr. Winton Wightman (personal communication, 1994). The assemblages and environments used are described in Wightman *et al.* (1994). Relative numbers of each genera are indicated as abundant, common, few, or rare.

Hub Cyclothem. Gibling and Kalkreuth (1991) documented unspecified vertebrate remains in the black shales above the Hub seam at Glace Bay; these are presumably fish scales, which were identified from the same black shales in this study. Vertebrate trackways have been documented from a stratigraphic level close to the Hub Cyclothem (the location is not clearly specified) in Dawson (1868).

2.1 Ml: Laminated Grey Mudrock

These light grey, planar laminated mudrock beds (Figure 2.3) are rarely more than 1 m thick; ripple cross-lamination is locally present. Despite being relatively thin, they are laterally continuous at outcrop scale. Macerated plant debris is common. Upright tree trunks, rooted in disrupted grey mudrocks (facies Md) commonly extend up into Ml mudrocks. Thin (less than 2 mm thick) but extensive coal stringers are ubiquitous, and can be traced laterally for more than 100 m in some outcrops; they probably represent transported plant matter, or algal blooms, as they are not rooted. Where Ml mudrocks are interbedded with red mudrocks (facies Mr), they are usually carbonate-cemented; calcite and siderite nodules were not observed in Ml beds.

Individual laminae are distinguished on the basis of grain size and colour variations. The laminae range in thickness from about 2 mm to 10 mm, and extend laterally at least 10 m, often beyond outcrop scale.

Of the three Ml beds at Bras d'Or sampled for foraminifera and thecamoebians, one contained abundant thecamoebians, and the remaining two samples contained abundant *Trochammina* and a few thecamoebians (Winton Wightman, personal communication, 1994). These analyses suggest that laminated grey mudrocks (facies Ml) were deposited in conditions ranging from slightly brackish to fresh-water.

The Ml mudrocks in the Hub Cyclothem were deposited in standing water bodies with little or no flow. None of the upright tree trunks observed were rooted in the Ml

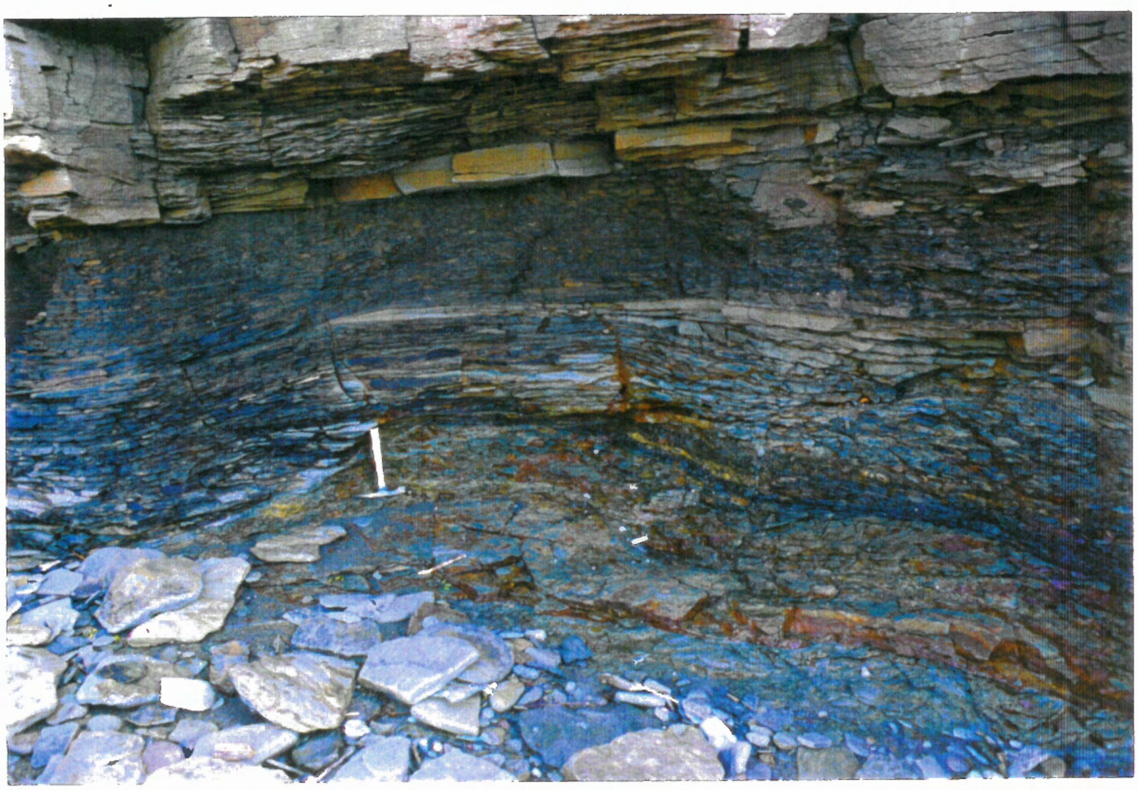


Figure 2.3. Ml laminated mudrock bed (above the hammer) overlying a Gfu fining-up sequence and underlying a CHs channel fill. Photo taken at the Wetneck Point exposure (between 26 and 28 metres on the vertical column in appendix B). The hammer is 30 cm long.

mudrocks. Floating plant matter occasionally sank to the base of these water bodies and developed into thin coal stringers. Fresh-water lakes and marine bays are the most likely depositional settings for Ml beds.

2.2 Md: Disrupted Grey Mudrock

This group encompasses all mudrocks which lack clear lamination, appearing massive or highly disrupted. Md beds are either light grey, dark grey or light green; they generally darken upwards. Very dark grey and black mudrocks are locally common. In outcrop, they are usually deeply weathered to reddish, friable mud. Bed thickness ranges from about 30 cm to 2 m; thickness is consistent at outcrop scale, except where the muds were deposited over an irregular surface. Md mudrocks commonly grade up from laminated grey mudrocks (facies Ml), and underlie coals. Pancake-shaped siderite nodules, up to 2 cm thick and 10 cm in diameter, are abundant throughout these mudrocks. Although siderite nodules have been documented from marine environments, they are most common in fresh and brackish-water environments (Pye *et al.*, 1990). They commonly form around root traces, which are areas of high productivity and nutrient supply; bedding planes are, likewise, common sites for siderite nodule growth, as nutrient rich pore waters are concentrated along bedding planes (Pye *et al.*, 1990). Extensively rooted zones (Figure 2.4) are very common, and often underlie and are interbedded with coals (Figure 2.5), upright tree trunks, and bituminous laminae. Numerous rooted zones are present in each Md bed, indicating that periodic sediment influx inhibited mature paleosol development. Macerated plant debris is also common.

Of two disrupted grey mudrock (facies Md) beds sampled for foraminifera and thecamoebians, one contained abundant *Trochammina* and a few *Ammotium*, while the other contained abundant *Trochammina* and a few *Ammobaculites* (Winton Wightman, personal communication, 1994); this suggests that brackish water infiltrated the beds

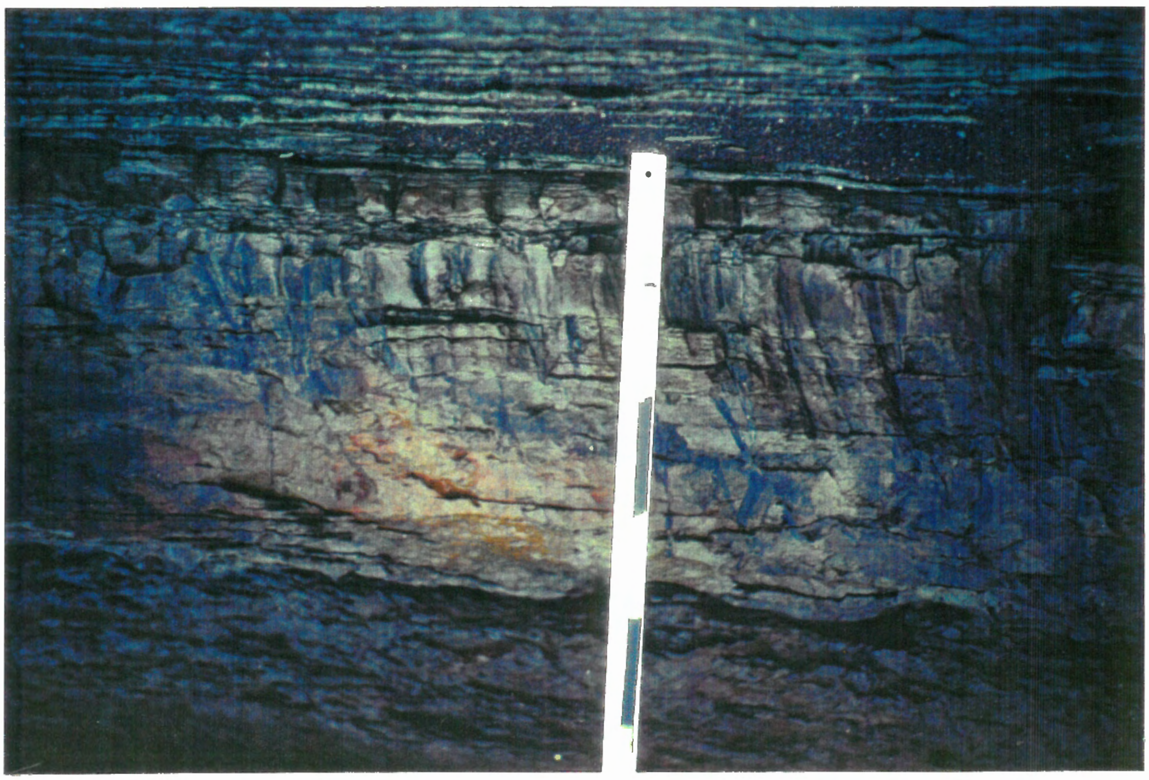


Figure 2.4. Rooted Md mudrock bed underlying a laminated grey mudrock (Ml) bed at the Glace Bay East exposure (about 8 metres on the measured section in appendix B). The rooted zone extends down from the top of the ruler (55 cm of the ruler is exposed in the photo).

Figure 2.5. Interbedded thin coals and Md mudrock beds near the base of the Chapel Point exposure (between 7 and 10 metres on the column in appendix B). The lowest coal lies below Neil Tibert's feet; the uppermost coal lies at the top of the ruler.

during deposition, although the foraminifera may have been introduced through bioturbation related to the extensive rooting.

Md mudrocks were deposited in very wet, frequently saturated fresh to brackish-water conditions. The presence of siderite nodules, rooted zones, and disrupted lamination indicates that Md mudrocks are either gleysols or gleyed protosols (Mack *et al.*, 1993), depending on the degree of paleosol development. Occasional major flood events covered rooted zones and buried trees in muddy sediment. These intermittent floods hindered the development of more mature paleosols.

2.3 Mr: Red Mudrock

Red and mottled red and grey mudrocks are present near the middle of the Hub Cyclothem at all complete exposures across the basin. Most Mr beds grade up from grey mudrock into mottled red and grey mudrock (Figure 2.6), although some are red throughout. All Mr beds have gradational bases and sharp tops. The beds have relatively consistent thicknesses at outcrop scale, but thickness varies widely between exposures. The thinnest redbeds are only 5 cm thick; thicker beds exceed 80 cm. Very few of the Mr beds effervesce when they come in contact with acid, indicating that calcite cements and nodules are rare. Although they contain little calcite, Mr redbeds are usually interbedded with calcite-cemented laminated grey mudrocks (facies Ml). Concave-up fractures are common. They are generally less than 50 cm wide and 20 cm deep; they rarely intersect other fractures. No roots or transported plant debris were observed; lamination is not apparent.

The distinctive concave-up fractures, gradational bases and red/grey mottling indicate that Mr redbeds are vertisols: paleosols which formed under the influence of a seasonally arid climate, in a tropical or warm-temperate area. The concave-up fractures,

Figure 2.6. Mottled red and grey Mr bed (top third of the photo) overlying a calcrete (centre of photo) at the New Waterford exposure (29 metres on the measured section in appendix B).

in particular, are indicative of internal deformation resulting from seasonal wetting and drying of smectite-containing soils (Mack *et al*, 1993).

2.4 Mb: Black Shale

Black shales are present only in the Glace Bay exposures (Figure 1.7). They are planar laminated and range in thickness from 20 to 30 cm; thickness of individual units does not vary at outcrop scale. Coprolites, fish scales and disseminated pyrite grains are all common.

Gibling and Kalkreuth (1991) analyzed four black shale samples at Glace Bay (between 18 and 20 m on the vertical section in Appendix B) using thin sections and Rock Eval techniques. The shales have between 6 and 23% organic matter, about half of which (3-14%) is sporinite; vitrinite and inertinite constitute the remainder. Fish remains (scales), clay minerals (illite, kaolinite and chlorite), quartz silt, pyrite and phosphatic grains are all common constituents of the Mb black shales. The shales have between 6.85 and 25.69 % total organic carbon (TOC) and plot as either type I or type II kerogen on a plot of hydrogen and oxygen indexes. Measured oil and gas potential ranges from 29.9 to 172.11 kg of hydrocarbon per tonne of rock.

The presence of extensive, thin beds, with abundant pyrite and coprolites, but no bioturbation, suggests that the black shales were deposited in a low energy anoxic environment, such as a large bay, or deeper sub-basin in the Glace Bay area. The pyrite is probably early diagenetic: it is absent in overlying and underlying beds which contain abundant siderite nodules. On the basis of the chemical data and thin section analysis, Gibling and Kalkreuth (1991) interpreted the black shales as the products of deposition in anaerobic waters.

2.5 C: Calcrete

A single nodular pedogenic calcrete is present in each full exposure of the Hub Cyclothem (Figures 2.6 and 2.7). It ranges in thickness from 50 cm to 1 m across the basin, but remains constant at each exposure. The calcrete formed within the topmost layers of laminated siltstone and fine sandstone units. The calcrete is always associated with red mudrocks (facies Mr). The top of the calcrete horizon has irregular topography.

The nodules in the calcrete range from about 2 cm to 10 cm in diameter and tend to be flattened and elongated parallel to bedding. *In situ* brecciation of the nodules is common; this indicates concomitant shrinkage and cementation (Freytet, 1973). They become more spherical near the top of the calcrete. Although the nodules are commonly vertically stacked, the vertical fabric is not as pronounced as it is in other calcrete horizons in the Sydney Mines Formation (Tandon and Gibling, 1994). They correspond to stage 2 to 3 calcretes of Gile *et al.* (1966).

There are no distinctive macroscopic biogenic features in the Hub Cyclothem calcretes. Tandon and Gibling (submitted), however, studied calcretes from four other Sydney Mines Formation calcretes and found that almost all of them are alpha-type (Wright, 1990) calcretes, with fabrics indicative of desiccation and shrinkage effects, and lacking any microscopic biogenic features.

The calcrete at the Bras d'Or section is less mature than other calcretes in the basin. The nodules have not developed to the point where they obscure the depositional lamination. This is a stage 1 or 2 calcrete of Gile *et al.* (1966).

The vertical fabrics, *in situ* brecciation of the nodules and the irregular surface topography on the calcretes indicate that the Hub Cyclothem calcretes are pedogenic. Modern pedogenic calcretes form in areas with between 400 and 600 mm of rain annually, and a net moisture deficit; the climates are usually seasonal (Goudie, 1983; Tandon and

Figure 2.7. Eighty centimetre thick nodular calcrete (beside ruler) at the New Waterford exposure (29 metres on the measured section in appendix B). Ruler is 100 cm long.

Gibling, 1994). The association of the calcrete with red paleosols suggests that a similar depositional setting was responsible for calcrete formation.

2.6 SLg: Laminated Grey Siltstone

These planar laminated siltstones (Figure 2.8) are primarily composed of silt and clay, with about 5% very fine sand grains (70% quartz, 10% potassium feldspar, 5% white mica, 10% brown and green biotite and minor amounts of chlorite, plagioclase and opaques). The grains are angular and poorly sorted. Elongate grains (mostly micas) are aligned parallel to lamination.

Ripple marks, desiccation cracks (Figure 2.9), tool marks, primary current lineations and raindrop imprints are all common on bedding surfaces of SLg rocks. Ripple-drift cross-lamination is present in a few SLg beds. At New Waterford and at Point Aconi, tetrapod trackways are present in the siltstones (Figure 2.10). In the best examples, both tail drag marks and footprints are apparent. Tetrapod remains have been previously noted in the Sydney Mines Formation. Dawson (1868, pp. 356-358) described trackways in the Sydney Basin; Carrol (1967) described fossilized tetrapod remains from strata over the Bonar coal seam (the seam at the top of the Hub Cyclothem) near Florence (about 25 km west of Sydney)

Two samples analyzed for agglutinated foraminifera and thecamoebians in SLg beds at Bras d'Or contained rare *Trochammina* specimens (W.G. Wightman, personal communication, 1994), suggesting that there was a degree of brackish water influence.

All of the SLg siltstones are calcite cemented. Although no geochemical data are available for the cements, they are assumed to be calcite because they effervesce dramatically in acid. The cements are very fine grained. Most of the cement shows extinction parallel to bedding in thin section under crossed polars, suggesting a common alignment; the thin sections were cut perpendicular to bedding. Pedogenic calcite cements

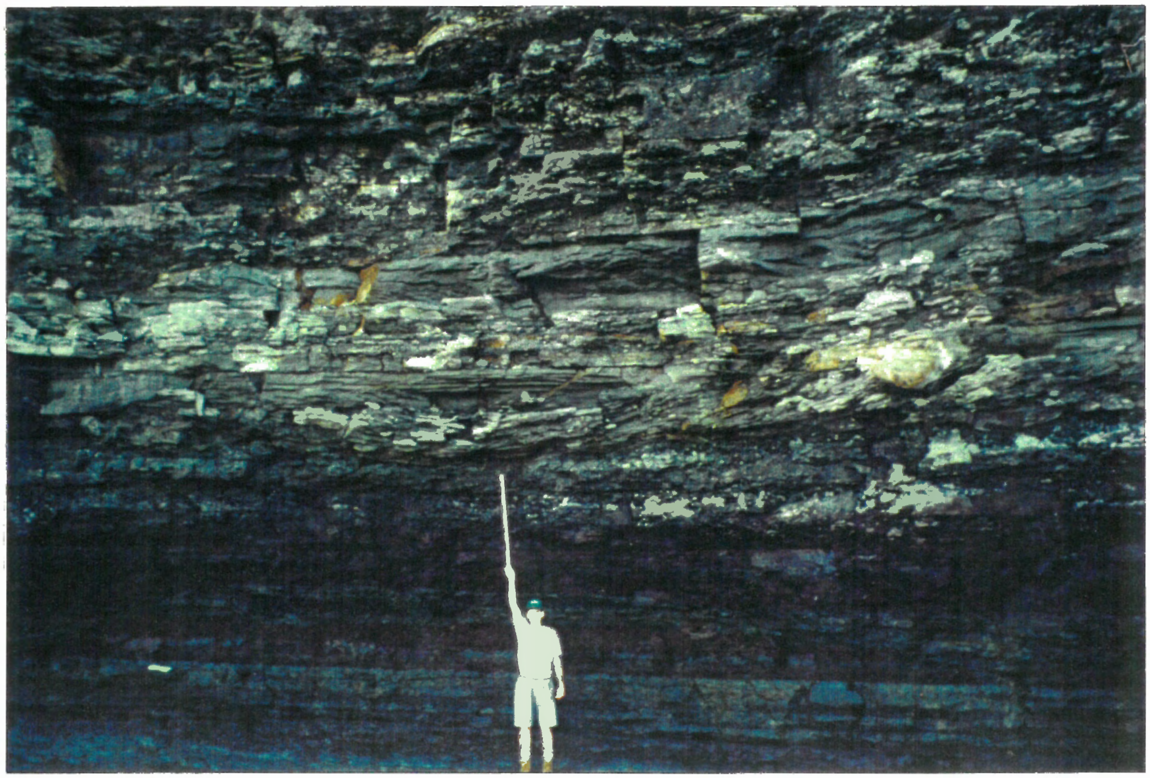


Figure 2.8. A series of SLr beds are visible at the bottom of the photo, up to the top of the ruler; note the distinctive sharp based redbeds. A CHu channel fill occupies about 2 m near the centre of the photo. Above and below the channel fill are indistinct SLg carbonate cemented siltstones. Photo taken between 36 and 40 metres at the Point Aconi section.

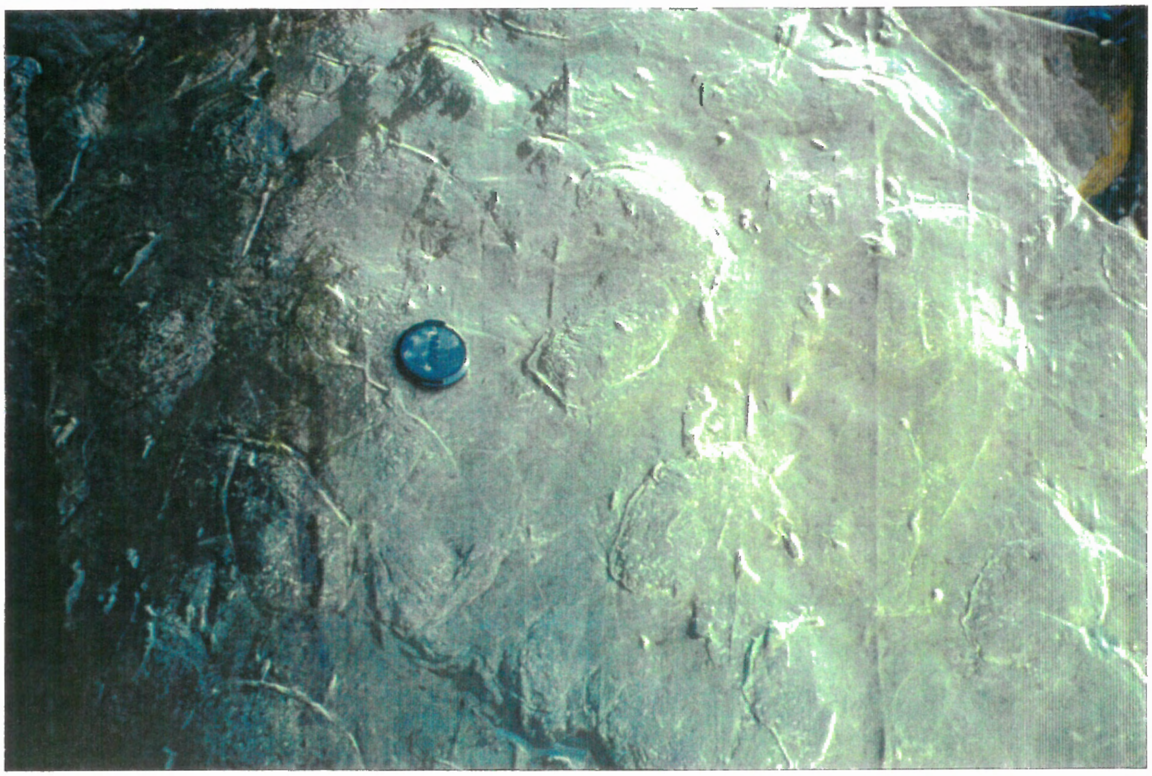


Figure 2.9. Faint desiccation cracks and tool marks on an SLg bed surface at 42 metres at the Point Aconi exposure. Lens cap is 7 cm wide.

Figure 2.10. Tetrapod trackways at 44 metres at the New Waterford exposure. Lens cap is 7 centimetres wide.

are often very fine grained and difficult to view in thin section in contrast to burial carbonate cements which tend to occur either as large poikilotopic calcite grains which enclose other grains, or as drusy calcite spar which fills voids with sparite crystals (Tucker, 1991). The SLg cements, therefore, probably formed shortly following deposition of the SLg strata. Because the SLg beds show no evidence of rooting, it is likely that the mechanism which led to the precipitation of the carbonate cements is related to evaporation at the ground surface.

SLg siltstones occur only in conjunction with facies interpreted as anastomosed channel fills (facies CHu). The SLg sediments, therefore, were probably deposited as levees and alluvial ridges during sheet flood events, when the anastomosed channels overflowed and dumped their suspended sediment load. At least some of the flooding was upper flow regime, indicated by the presence of primary current lineation and tool marks. The absence of any plant material or root traces, and the presence of desiccation cracks and abundant calcite cement (precipitated in response to evaporation at the ground surface) indicates that the climate was dry during much of the year.

2.7 SLr: Red Siltstone

These siltstones are present in the New Waterford section, where they are a minor constituent (they are very thin and discontinuous), and in the Glace Bay West section, where they form a moderate proportion of the section (Figure 2.1). They occur only in association with laminated grey siltstones (facies SLg) (Figure 2.8), and beds rarely exceed 30 cm in thickness; they are laterally discontinuous, even at outcrop scale. SLr beds have sharp bases and tops, and unlike the red mudrocks (facies Mr), lack mottling. The beds are predominantly composed of siltstone, although gravel-sized clasts of red mudrock and coarse sand-sized clasts of quartz are locally abundant (Figure 2.11). They contain weak planar stratification. Despite their close association with laminated grey

Figure 2.11 Close view of an SLr bed at about 46 metres at the New Waterford exposure. Two gravelly bands, each about 5 cm thick are visible near the top of the photo. The lens cap is 7 cm wide.

siltstones (facies SLg) and anastomosed channel fills (facies CHu), both of which are carbonate cemented, SLr siltstones contain no apparent carbonate.

Unlike the red mudrocks (Mr), the red siltstones (facies SLr) do not appear to have reddened *in situ*. SLr beds were deposited by the local erosion of redbeds during floods with subsequent deposition of red sediment layers. The abundance of SLr beds decreases to the west. The SLr redbeds may have been sourced locally: erosion of underlying red mudrocks (facies Mr) in upstream areas could have sourced the SLr beds. This source, however, does not explain the westward decrease in SLr abundance. A more distant source may also have been available for the red sediments; Forchu Group and Cambrian volcanic rocks are present along the eastern margin of the Sydney Basin (Giles, 1983), and may have been exposed during the deposition of the Hub Cyclothem. If the Mabou or Windsor Groups were exposed on highlands surrounding the Sydney Basin during the deposition of the Hub Cyclothem, they could have acted as sources for the red sediments as well. This would suggest that subsidence in the Sydney Basin was controlled by basin-bounding faults during the Westphalian. This is discussed in greater detail in Chapter 5.

2.8 Oc: Coal

The Hub Cyclothem contains one major coal seam and is bounded by another: the Hub seam lies in the lower half of the cyclothem, and the Lloyd Cove (locally called the Bonar) seam bounds the top (Figure 2.12). These major coals can be as thick as 1.5 m in outcrop, and extend across the entire exposed part of the basin (about 30 km). Numerous smaller coals are present in the lower half of the cyclothem; these range in thickness from a few cm to 50 cm. Lateral thickness variations are common; the smaller coals cannot be correlated between outcrops. Hacquebard (1993) reports average ash contents of 5-9% and sulphur contents of 2.5-6.2%; locally, however, the values can be much higher.

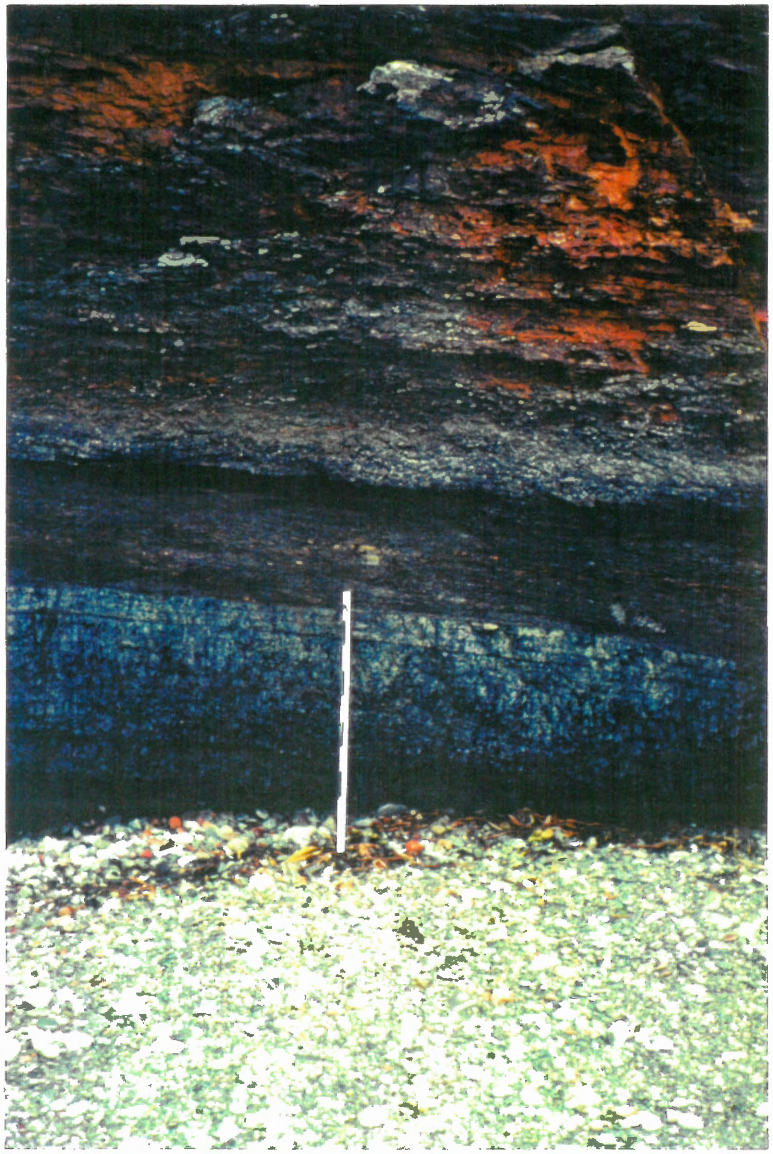


Figure 2.12 An exposure of the Bonar coal seam at 62 metres at the New Waterford exposure. It is overlain by an Ml mudrock and a CHp pebbly channel fill. Ruler is 100 cm long.

Reported analyses of the Hub and Bonar seams (Birk and White, 1991; Gibling *et al.*, 1989) show marked variations in ash (2.1% to 25.5% in the Hub seam and 3.4% to 14.6% in the Bonar seam) and sulphur (1% to 4.5% in the Hub seam and 2.9% to 9.8% in the Bonar seam). The coals are all high volatile bituminous A (Hacquebard, 1993). Marchioni *et al.* (1994) studied the petrology of the Hub coal seam at the Prince Mine, near Point Aconi; their results are summarized below. The Hub seam is predominantly composed of vitrinite (about 80%), with minor inertinite (about 10%) and liptinite (about 10%); mineral content is about 3%, most of which is pyrite. About 50% of the coal is bright coal. The Hub Seam plots in the lower delta plain field on a cross plot of gelification and tissue preservation indices of Diessel (1986). More specific data are in Gibling and Kalkreuth (1991), Birk and White (1991), and Marchioni *et al.* (1994).

Palynological analyses of the Hub seam in the Prince Mine (Marchioni *et al.*, 1994) provide good evidence for the depositional environment of the coal. The spores found in the Hub coal are listed in Table 2.4. On the same table, the producing plant (derived from a list in Calder (1993), and the paleoenvironmental conditions (from DiMichele and Phillips, 1994) for growth are also listed. All of the spores preserved in the Hub seam were produced by plants which grew predominantly in planar mires, with intermittent floods and clastic input events. Many of the plants grew under the influence of a slightly seasonal climate. Spores from plants which are indicative of everwet conditions and domes peats are not present (Marchioni *et al.*, 1994).

The thin, extensive nature of the coals, the high sulphur values and the presence of brackish water foraminifera in associated strata (W.G. Wightman, personal communication, 1994) indicate that the coal in the Hub Cyclothem was deposited in a coastal paralic setting, as suggested by Hacquebard and Donaldson (1969). The most likely setting is slightly landward of a coastline, in coastal mires. The palynological

Spore Genus (from analyses in Marchioni *et al*., 1994)	Paleobotanical Affinity (from a summary in Calder, 1993)	Ecological Implications (from a summary in DiMichele and Phillips, 1994)
Apiculatisporis	*Diaphorodendron*	Saturated, occasionally flooded peats with occasional mineral enrichments.
Calamospora	Calamites or Sphenophyll	Areas with clastic input and substrate aggradation or instability.
Crassispora	*Sigillaria*	Rheotrophic mires and seasonal climates.
Cyclogranisporites	Various ferns	Prefer substrates with periodic or full subaerial exposure.
Endosporites	*Chaloneria*	Clastic swamps/ fluctuating, ephemeral shallow-water habitats.
Granulatisporites	Pteridosperm	Clastic swamps
Leiotriletes	Fern (Filicales)	Variable
Lophotriletes	Fern	Variable
Lycospora orbicula	*Paralycopodites*	Intermittent flooding, clastic input and peat exposure.
Lycospora pusilla	*Lepidodendron hickii*	Clastic swamp/ reotrophic mires.
Raistrickia	Fern (Filicales)	Variable
Vestispora	Sphenopsids (eg. Calamites)	Areas with clastic input and substrate aggradation or instability.
Laevigatosporites	Calamites	Areas with clastic input and substrate aggradation or instability.
Punctatosporites	Tree fern (Marattiales)	Prefer substrates with periodic or full subaerial exposure.
Florinites	Cordaites	Planar swamps with seasonally or periodically high water tables.

Table 2.4. Fossil spores present in the Hub coal seam in the Prince Mine (Marchioni *et al*., 1994), the producing plants (Calder, 1993), and the paleoenvironmental conditions indicated by the spores (DiMichele and Phillips, 1994)

evidence demonstrates that the mires were probably either swamps or marshes (following the definitions of Moore, 1987)

2.9 Ob: Thin Carbonaceous Shale Laminae

These thin, black bands are common throughout the Sydney Basin. They are never thicker than 5 mm and are usually weathered to black mud in outcrop. Unweathered laminae are black shaley coals or coaly shales. Although very thin, these laminae commonly extend across entire exposures (a few hundreds of metres). They are usually associated with laminated grey mudrock (facies Ml) beds.

Because they are not rooted, the carbonaceous shale laminae are inferred to have been deposited from detrital plant debris, or thin floating peat mats in a standing water body. When the detritus, or peat mats sank to the bottom, an Ob bed formed. It is not clear whether they formed in a lacustrine, or paralic setting. Because they are very thin, Ob laminae are not shown on the vertical columns or the facies distribution chart (Figure 2.1).

2.10 CHp: Pebbly Meandering Channel fills

This distinctive facies contains the coarsest sediments in the Hub Cyclothem (Figure 2.13). The channel fills have width to thickness ratios in excess of 50:1. The lateral extents of the CHp channel fills are difficult to estimate because the channel margins are rarely exposed. At the Oxford Point section, for instance, the channel body (between 10 and 16 m on the measured section in Appendix B) is exposed along approximately 500 m perpendicular to current direction. Likewise, the CHp channel fill at the New Waterford exposure (11 to 20 m on the measured section in Appendix B) is exposed along at least 600 m perpendicular to paleoflow.

Figure 2.13 Trough cross-bedded pebbly sandstone at 39 metres at the Chapel Point exposure. The bright white spots are extrabasinal quartz clasts. The lens cap is 7 cm wide.

The CHp channel bases are relatively planar, although concave-up scours are present in some exposures. Lags containing sandstone clasts, tree and root fragments and peat mats are common at the channel bases. These lags are generally less than 40 cm thick.

The channel fills are multi-storeyed, with three or four vertically stacked storeys as thick as 10 m in aggregate; individual storeys are between 2 m and 5 m thick. Peat mats are common at storey boundaries, which have slightly less planar topography than the channel body bases.

All of the channel storeys are predominantly filled with pebbly sandstone in the form of lateral accretion sets and trough cross-beds; scroll bar deposits (fining-updip bar deposits with interfingering muddy and sandy components) are locally common at storey tops. Ridge and swale topography is present on some bedding surfaces. Lateral accretion sets can be as thick as 3 m, measured vertically; individual sandstone beds range from 15 cm to 35 cm thick. Sheets of trough cross-bed sets range in thickness from 50 cm to 2 m. At upper levels in each storey, the largest particles are fine sand sized, in trough cross-beds and ripple cross-laminated planar beds. Both grain size and set thickness decrease upwards through each CHp channel storey.

Grains range from 0.05 mm to 12 mm in diameter; most gravel-sized grains are between 2 and 6 mm in diameter. The sandstones are moderately well sorted, with sub-angular, moderate sphericity grains. The following mineral abundances are based on visual estimates on two thin sections. 50% of the gravel, sand and silt sized grains are quartz; sutured boundaries and undulose extinction are common in most grains. Potassium feldspars make up 15% of the grains; plagioclase accounts for 5%. About 10% of the grains are fragments of metamorphic rocks with abundant mica; these were probably derived from schists and gneisses in the surrounding highlands. Sandstone fragments, mostly composed of fine grained quartz with minor feldspar and mica make up 15% of the grains; these are usually the largest grains in the channel fills. Clays, macerated plant material, hornblende, chlorite, opaques, and brown, green and white micas account for the remaining 5%. According to the classification scheme in both McBride (1963) and Folk (1974), these are feldspathic litharenites. The grains are silica cemented. Based on a visual estimate, the CHp sandstones have about 15% porosity. The cements are mostly quartz overgrowths, although clays appear to bind some of the grains. The cements do not appear to have been strained, indicating that the undulose extinction and sutured boundaries in many of the quartz grains are relict features, formed prior to erosion from basement rocks. Small *in situ* siderite nodules, up to 20 cm in diameter, are abundant in all CHp channel fills. They are either pancake shaped, parallel to bedding, or tube shaped, perpendicular to bedding.

CHp channels were part of a major drainage system which carried sediment from extra-basinal areas to the sea. They were incised more deeply than other channels in the basin, and carried grains which clearly came from the surrounding basement rocks. The presence of peat mats in channel bases clearly indicates that the channels incised through peat at times. Abundant lateral accretion sets indicate that CHp channel fills were deposited in meandering channels. The ridge-and-swale topography and scroll bar deposits (which form on curved bars in modern meandering rivers, Allen, 1965) are also diagnostic of meandering channel fills (Gibling and Rust, 1993). Rough estimates of original channel depth can be gleaned from lateral accretion set thicknesses which must be less than the channel depth. The thickest lateral accretion sets are about 3 m thick, indicating that in at least some cases, channel depth was greater than 3 m. The thickest storeys are about 5 m thick, suggesting that some channels were at least 5 m deep.

2.11 CHs: Sandy Meandering Channel fills

These are volumetrically the most abundant channel fills in the Hub Cyclothem. They are usually multi-storeyed, and up to 15 m thick; individual storeys are no thicker than 5 m. Because CHs channels extend laterally beyond outcrop extents, their width to thickness ratios are difficult to measure; they do, however, clearly exceed 30:1.

Most CHs fills are fine and medium grained sandstones; coarse sandstone is common above some channel bases. Both grain size and the scale of sedimentary structures decrease upward through the channel fills. At the channel bases, grain sizes range from fine to coarse sand. Lateral accretion sets (inclined perpendicular to current direction) containing planar-laminated and trough cross-stratified beds (Figure 2.14) are the most common sedimentary feature near the channel bases. Trough cross-bed sets are generally less than 1.5 m thick, and composed of beds less than 20 cm thick. Higher in the fills, the average grain size decreases to fine sand or silt. Muddy interbeds are locally common. A greater variety of sedimentary features, such as scroll bar deposits (Figure 2.15), and ripple cross-laminated planar beds, is apparent at upper levels in the channels. The beds which comprise the scroll bars are generally between 15 and 40 cm thick.

The sandstones are broadly similar to those found in the pebbly meandering channel fills (facies CHp), but more mature. They are moderately well sorted, with sub-rounded, moderate sphericity silt and sand sized grains. Based on visual estimates from two thin sections, about 65% of the grains are quartz; sutured boundaries and intense straining are common in most grains. Potassium feldspars make up 10% of the grains; plagioclase accounts for 5%. About 5% of the grains are fragments of schists and gneisses. Sandstone fragments, mostly composed of fine grained quartz and minor feldspars and mica, make up 5% of the grains; these are usually the largest grains in the CHs channel fills. Clays, macerated plant material, hornblende, chlorite, opaques, and brown, green and white micas account for the remaining 10%. According to the

Figure 2.14 Thick trough cross-bedded sandstones in a CHs channel fill between 10 and 14 metres at the Black Point exposure. The ruler is 100 cm long.

Figure 2.15 Scroll bars (centre of photo) in a CHs channel fill at 24 metres at the Bras d'Or exposure. Note the interfingering of sandy beds (light grey) and muddy beds (dark grey). About 5 metres of cliff is visible in the photo.

classification schemes in McBride (1963) and Folk (1974), these are feldspathic litharenites. The sandstones are silica cemented. Based on a rough visual estimate, these sandstones have about 10% porosity. The cements are similar to those found in pebbly meandering channel fills (facies CHp): mostly quartz overgrowths, with some clay cementation.

Small siderite nodules (up to 5 cm diameter) are ubiquitous throughout the CHs channel fills; they are disseminated throughout the channel fills, and appear to have formed early: the surrounding laminae are distorted. At Bras d'Or, very large, columnar carbonate nodules are common in one of the channel fills (Figure 2.16). Macerated plant debris and coalified tree trunk and root fragments (Figure 2.17) are very common. A single sample analyzed for foraminifera and thecamoebians was barren (Winton Wightman, personal communication, 1994).

Scroll bars (fining updip bar deposits with interfingering muddy and sandy components) form on curved bars in meandering rivers (Allen, 1965). Lateral accretion sets are also indicative of a meandering river setting. CHs channel fills were, therefore, deposited in large meandering channels on a vegetated floodplain. Unlike the CHp channel fills, the sources of the CHs channel fills were probably in the basin. Original channel depths were probably greater than 1.5 m (thickness of trough cross-bed sets), but probably less than five metres (the maximum storey thickness).

Peat mats (Figure 2.18) are rare in CHs channels, although the channel fills almost always rest directly on top of a coal seam (Figure 2.19). Because they have relatively high cohesion soon after deposition, the peat layers may have acted as barriers to vertical incision during channel formation (McCabe, 1984). The channels incised down to the peats, and then began to migrate laterally, because the floodplain was more easily erodable. Pebbly meandering channel fills (facies CHp) more commonly contain peat

Figure 2.16 Large columnar calcite nodule (top view) in a CHs channel fill at 23 metres at the Bras d'Or exposure. Lens cap is 7 cm wide.

Figure 2.17 Large dichotomizing *Stigmaria* fragment in a CHs channel fill at 16 metres at the Glace Bay exposure. Lens cap is 7 cm wide.

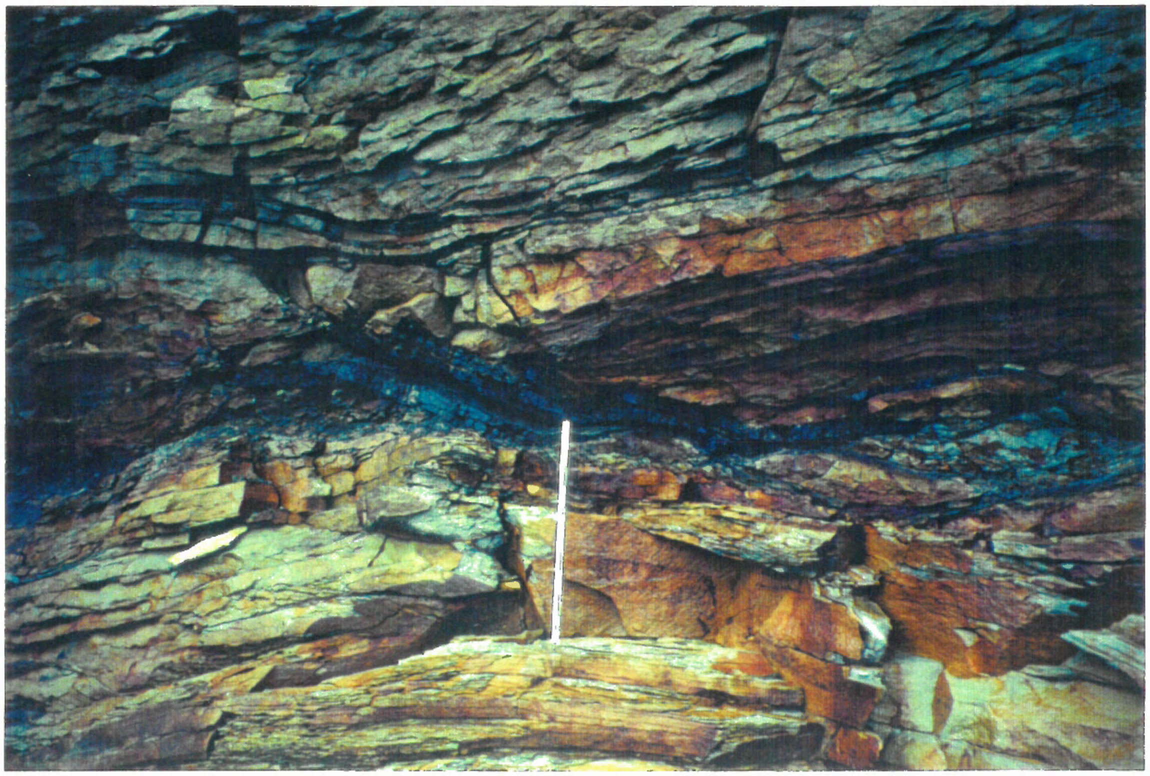


Figure 2.18 Peat mat (top of the ruler) at a storey boundary in a large CHs channel fill at 12 metres at the Black Point exposure. The ruler is 100 cm long.

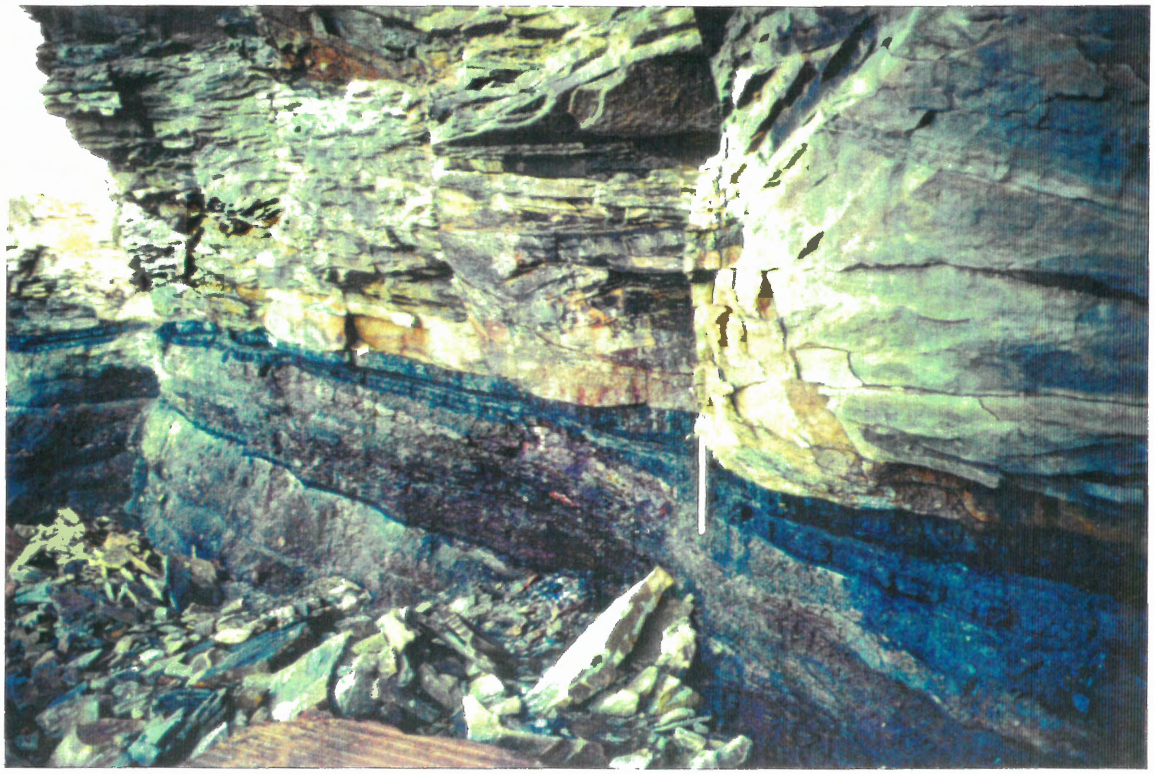


Figure 2.19 CHs channel fill sitting directly on a thin coal seam at 36 metres at the Chapel Point exposure. The ruler is 100 cm long.

mats, because flow was faster in CHp channels than in CHs channels, and the coarser bedload clasts in the CHp channels may have been more abrasive than the bedloads in CHs channels.

2.12 CHc: Large, Complex Valley Fills

These large valleys incised through both red and grey strata, many of which are carbonate cemented. The valley at Point Aconi incised through at least 7 m of strata (its base is located below the beach); the Wetneck Point valley incised at least 5 m. The widths of these valleys are uncertain, because they are not completely exposed. Three distinct fill types (described below as subfacies) are present in each CHc fill: trough cross-bedded sandstone; inclined, interbedded mudrock and sandstone (IHS sets of Thomas *et al.*, 1987); and massive carbonate-cemented siltstone. The trough cross-bedded sandstone (CHc1) and interbedded mudrock and sandstone (CHc2) are both channel fill facies; they are always found in separate channel cuts.

2.12.1 CHc1 - Trough cross-bedded sandstone

These channel fills occur largely near the bases of CHc valleys, particularly at Wetneck Point, where they occupy the basal 2 m of the valley fill. The sandstones are medium grained and locally carbonate cemented. Near the base of the channel, large rip-up clasts of calcrete are abundant. Trough cross-bed sets range in thickness from 15 cm to 30 cm, in cosets up to 1.5 m thick. No plant debris is preserved in the sandstones.

These channels were probably cut by upper regime flow during major flood events on a poorly vegetated floodplain; they were subsequently filled under lower flow regime conditions. Much of the CHc1 sandstone lies directly on the CHc valley base and contains rip-up clasts of calcrete, indicating that it was deposited during the same event which initiated the CHc incision. CHc1 channel fills at higher levels formed during brief, but intense flood events.

2.12.2 CHc2 - Interbedded mudrocks and sandstones.

These fills occupy long, flat-based channels. In the Wetneck Point section, they are consistently about 2 m thick and about 40 m wide. In the Point Aconi section, the channels are poorly exposed, but one of them is clearly at least 3.5 m deep and more than 60 m wide; they commonly scoured laterally into older CHc2 fills. At both exposures, the interbedded strata are inclined by about 20° relative to the other strata. The sandy and muddy beds have similar thicknesses: 10-30 cm, although the muddy beds thin updip along their bounding surfaces. The sandy beds are fine grained, carbonate-cemented sandstones, with planar or ripple cross-lamination. Trough cross-bedding is locally common. The muddy beds are massive clay with minor silt. In some scours, all the mudrock is grey; in other scours, all the mudrock is red.

These channels were incised following minor drops in base level, or in response to flood events. Inclined heterolithic beds in which the red muds wedge out updip are found in modern, highly ephemeral channels, such as those of the Kosi Fan in India (Wells, 1987), as well as other settings where stage flow fluctuates (Thomas *et al.*, 1987).

The CHc1 and CHc2 channel fills are very similar to fills in the modern Barwon River in Australia (Taylor and Woodyer, 1978). The Barwon River flows under the influence of a seasonally arid climate. It is deep and narrow, and has not migrated significantly in more than 100 years. Most of the sedimentation occurs on three types of bank-attached benches. Sedimentation on the low benches consist of cross-bedded sands with thin mud laminae; sedimentation on the middle and high benches consists of mud and sand interbeds (Taylor and Woodyer, 1978). The cross-bedded sands on the low benches are analogous to the CHc1 channel fills in the Hub Cyclothem; the mud and sand interbeds on the middle and upper benches are very similar to the CHc2 channel fills. This suggests that the CHc1 and CHc2 fills represent deposition under fluctuating conditions as generated under a seasonal climate in a stable channel. This conclusion is supported by the presence of IHS beds in both the Barwon River and the CHc2 channel fills and by the lack of scroll bar deposits in both settings.

2.12.3 CHc3 - Carbonate-cemented siltstone

The CHc valleys are filled with massive carbonate-cemented siltstone (facies CHc3), along with the CHc1 and CHc2 channel fills. No bedding is apparent in the CHc3 strata and lamination is very weakly developed; there is no evidence of plant material or rooting. Most of the siltstones are grey, although red strata are locally abundant. Slumps and slickensides are common at the Point Aconi section.

This sub-facies was deposited when CHc1 and CHc2 channels overflowed and dumped fine sediments. The climate may have been seasonally or intermittently semi-arid; otherwise there would have been abundant vegetation and little carbonate cement.

This subfacies is very similar to the laminated grey siltstones (facies SLg), except that desiccation cracks, raindrop imprints and flute casts were not observed. The depositional conditions were, however, quite similar; the setting for the CHc3 subfacies was probably slightly wetter (probably because it was deposited in a channel) than the laminated grey siltstones (facies SLg).

2.12.4 Cause of Incision

The cause of the incision event is not clear, but it must have involved a drop in base level which led to significant erosion (more than 8 m) along channel systems. Causes of this incision are discussed in Chapter 4. The fills, which are described above, were deposited under conditions of variable flow.

2.13 CHu: U-Shaped Channel fills

These channels have "U" shaped cross-sections with rounded bases; their width to thickness ratios are less than 15:1 (Figure 2.20). The fills are all fine to medium grained, carbonate-cemented grey sandstone. They incise through laminated grey, carbonate-cemented siltstones (facies SLg). With the exception of those in the Point Aconi section, the CHu channel fills are all single storeyed, with maximum thicknesses of 2.5 m, and widths ranging up to 30 m. Two larger channel fills at the Point Aconi section are discussed at the end of this section. Paleoflow directions for the U-shaped channel fills (facies CHu) have relatively low variability, indicating that the CHu channels were probably of low sinuosity.

The sand grains are angular, low sphericity grains up to 0.2 mm long. The following mineral abundances are based on rough visual estimates on three thin sections. Grains represent approximately 70% of the total rock volume: 35% are quartz, 15% are potassium feldspar, 5% are plagioclase, 10% are brown biotite, and 5% are green and white mica. Chlorite and opaque grains are also present, but do not represent a significant rock volume. The elongate mica grains are aligned parallel to bedding. Of the remaining 30%, most is carbonate cement (25%), with minor clay (5%); less than 1% of the rock volume is pore space. These rocks are lithic arkoses in the classifications of McBride (1963) and Folk (1974); in Gilbert's classification (Williams *et al*., 1982) they are feldspathic wackes. The CHu sandstones are, therefore, more arkosic than those in the meandering channel fills (facies CHp and CHs); this suggests that the source rocks were subjected to less humid weathering.

The channel fills are planar bedded, with both planar lamination and abundant ripple-drift cross-lamination (Figure 2.21). Rip-up clasts of siltstone, sandstone and very limited plant debris are present at some channel bases. Unlike the meandering channel fills (facies CHp and CHs), these channel sands do not fine up, and the channels are not

Figure 2.20 A "U" shaped CHu channel fill (arrow)at 36 metres at the Point Aconi section.
The channel fill is about 2.5 metres thick and sits above Mr redbeds.

Figure 2.21 Ripple-drift cross-lamination in a CHu channel fill at 44 metres at the New Waterford exposure. Lens cap is 7 cm wide.

capped with paleosols. Splay, levee, or lateral migration indicators (e.g. lateral accretion sets, scroll bar deposits) are not present. CHu channels appear to have been incised and filled rapidly, and then spilled over onto the floodplain, depositing the laminated grey siltstones (facies SLg).

These channel fills represent deposition in anastomosing channels on a broad floodplain. The identification of anastomosed channel systems is usually based on plan view geometry (Miall, 1992), which is not known for the CHu channels in the Hub Cyclothem. However, the channels clearly aggraded vertically and did not migrate laterally; the fills have low width to thickness ratios and their paleoflow directions are unidirectional. All of these features suggest that they are anastomosed channel fills, although they could also be termed "stably positioned, ephemeral rivers".

Two CHu channels in the Point Aconi exposure are multistoreyed and larger than the other "U" shaped channels. The largest one is 5 m thick and 40 m wide, with 4 storeys, each less than 1.5 m thick. The other channel fill is only 3 m thick and about 25 m wide, with two storeys. Their depositional setting may have been related to a more significant drop in base level, or the development of a more resistant floodplain, which inhibited channel avulsion. The floodplain material is all carbonate-cemented grey laminated siltstone (facies SLg). If base level dropped in response to a drier climate, the channels would incise deeper into the floodplain; at the same time, the floodplain would become more intensely cemented. Under these conditions, deeper and multistoreyed channel fills could have formed.

2.14 Composite Facies

These two facies are composites of other facies listed in this chapter. The facies in the Gfu and Gcu beds are always thin and grade from one into the next. In order to facilitate mapping and interpretations, they are listed as distinct facies.

2.14.1 Gfu: Fining-Up Beds

These beds range in thickness from 50 cm to 4.5 m (usually thicker than 2 m) and grade up from fine or medium grained sandstone (or siltstone) to mudrock or very fine sandstone. The coarser sediments are always grey, but the mudrocks are locally red. Gfu bed bases locally scour 5 to 25 cm into underlying strata.

The coarse sediments at the bases of these beds are usually ripple or planar laminated, although trough cross-bedding and lateral accretion sets are present in some of the coarser beds. Successive beds with an upward trend from planar lamination, to ripple cross-lamination, to massive fine sandstone or siltstone are common; these rarely exceed 30 cm in thickness. Macerated plant debris is common, as are pancake-shaped siderite nodules, which are locally up to 30 cm long.

Lamination in the finer sediments is poorly developed, probably due to dewatering effects. Small pieces of macerated plant debris and coal stringers are common. Fining-up sequences are usually capped by a disrupted grey mudrock (facies Ml), or a coal (facies Oc).

Some of the fining-up sequences contain small scour-and-fill features (generally less than 1.5 m deep and 2 m wide), containing fine sandstone with ripple or planar lamination.

These fining-up beds can be attributed to a variety of different depositional settings. The beds which fine up from trough cross-bedded sandstone or lateral accretion sets are probably fills of abandoned meandering channels; this interpretation is difficult to draw, however, because the sides of the channels are not exposed. Beds which scour down into underlying strata are probably either splay-channel deposits or fills from small tributary channels.

2.14.2 Gcu: Coarsening-Up Beds

Gcu beds grade up from mudrock or fine siltstone to fine or medium sandstone. Beds range in thickness from 1.5 m to 4.5 m. Macerated plant debris, siderite nodules, and coal stringers are all common. *In situ* tree trunks (Figure 2.22) are also common in this facies, suggesting that these beds were deposited rapidly, before the trees had time to rot or fall over. The number of erect trees at Black Point (four were observed in a cliff face less than 50 m wide) indicates that entire forest stands of lepiododendrids were engulfed in some cases.

The basal sediments are usually grey or black mudrock, although mottled red and grey mudrock is locally common. The beds often overlie disrupted grey mudrocks (facies Md), or coals (facies Oc). Of three Gcu beds sampled at Bras d'Or, one contained thecamoebians, while the other two contained *Trochammina* (W.G. Wightman, personal communication, 1994); this suggests that they were deposited under both brackish and fresh-water conditions.

Upper sediments are fine to medium grained sandstones with ripple or planar lamination. 30 cm thick upward gradations from planar lamination to ripple cross-lamination to massive sandstone are common, indicating successive pulses of waning flow. Irregular and wavy topography (up to 1.5 m high) is locally common. Small scours, up to 1 m wide and 30 cm deep, are also locally common. Gcu beds are generally capped with hydromorphic paleosols (facies Md).

Gcu sequences were deposited when vegetated areas flooded, forming bays and lakes. Deltas then prograded across these standing water bodies, and deposited increasingly coarse sediments. Eventually, the lake or bay was filled and vegetation grew on the delta sediments. A second delta sequence often followed. This repeated pattern of flooding and filling is probably related to compaction. As lake, bay and delta deposits compacted and dewatered, increased subsidence occurred locally and a new bay or lake

Figure 2.22 A large in-situ tree trunk (above ruler) in a Gcu coarsening-up sequence at 6 metres at the Black Point exposure. Numerous other tree trunks also rise up from the same coaly layer visible at the base of the cliff. Ruler is 100 cm long.

formed. It is unlikely that external effects were responsible for the subsidence, because the Gcu sequences are rarely correlatable between outcrops, except where they are in close proximity. This topic is discussed in greater detail in Chapter 4.

2.15 Summary

Fifteen facies comprise the Hub Cyclothem. Laminated grey mudrocks (facies Ml) were deposited in standing water bodies, such as lakes or bays. Disrupted grey mudrocks (facies Md) are paleosols, commonly formed beneath lycopsid forests. Reddened mudrocks (facies Mr) are vertisols, deposited in subaerial conditions under the influence of a seasonally semiarid climate. Black shales (facies Mb) are present only in the Glace Bay exposure; they were deposited in deeper water settings. A single calcrete (facies C) is present in each full exposure of the Hub Cyclothem; it was deposited during a long (a few thousand years), relatively dry period with very limited sediment supply. Laminated grey siltstones (facies SLg) are calcite cemented and were deposited when anastomosed river channels (facies CHu) flooded over their banks; both of these facies were deposited in a seasonally dry climate. Red siltstones (facies SLr) differ from the Mr redbeds in that they formed from transported red sediments. The coals (facies Oc) accumulated as histosols in peat forming wetlands (mires). The thin carbonaceous shale laminae (facies Ob) are less than 2 cm thick, but are often laterally extensive; they may have been deposited either as transported plant matter, or from algal blooms. The pebbly channel fills (facies CHp) were deposited in meandering rivers, as were the sandy channel fills (facies CHs). The deep CHc valley fills contain three subfacies: trough cross-bedded sandstone channel fills (facies CHc1), interbedded mudrock and sandstone channel fills (IHS sets; facies CHc2), and carbonate-cemented siltstones (facies CHc3). The CHc2 channels were ephemeral and witnessed fluctuating stage flow. The CHu channel fills were deposited in ephemeral anastomosing channels. Two composite facies are also present: fining-up beds (facies Gfu) were deposited as abandoned channel fills and splay deposits; coarsening-up beds (facies Gcu) were deposited by deltas prograding into lakes and bays.

CHAPTER 3

FACIES ASSEMBLAGES

3.0 Introduction

Three facies assemblages, each interpreted to be representative of a distinct depositional setting, comprise the Hub Cyclothem across the exposed part of the Sydney Basin (Figure 3.1): the basal assemblage represents deposition on a near-coastal floodplain with meandering rivers; the middle assemblage represents a desiccated landscape with major drainage channels carrying seasonal flow; the uppermost assemblage was deposited on an anastomosed river floodplain. Although the three assemblages can be correlated across the exposed part of the basin, correlation of units within each assemblage is not possible, except where the outcrops are very close together (this happens only at Black Point, Chapel Point and Oxford Point, see Figure 3.2).

All of the paleocurrent rose diagrams in Figures 3.4 through 3.8 were plotted with Rose for Macintosh (written by Dr. John Waldron at Saint Mary's University, Halifax, Nova Scotia). The rose diagrams are plotted such that it is the area (rather than the radius) of each segment which is proportional to the number of measurements in that range of values. All of the diagrams use a class range of 15°.

In this chapter, each of the facies assemblages is described with regard to facies, interrelationships among the facies, paleoflow directions, and interpretations of climate, relative changes in sea-level, and tectonics.

3.1 Assemblage 1: Near Coastal Floodplain with Meandering Rivers

The basal facies assemblage in the Hub Cyclothem extends from the lowest basal split of the Hub Coal seam (including the Hub seam and seat-earth) and extends to the base of the either the lowest occurrence of red strata, or the calcrete, whichever is lower.

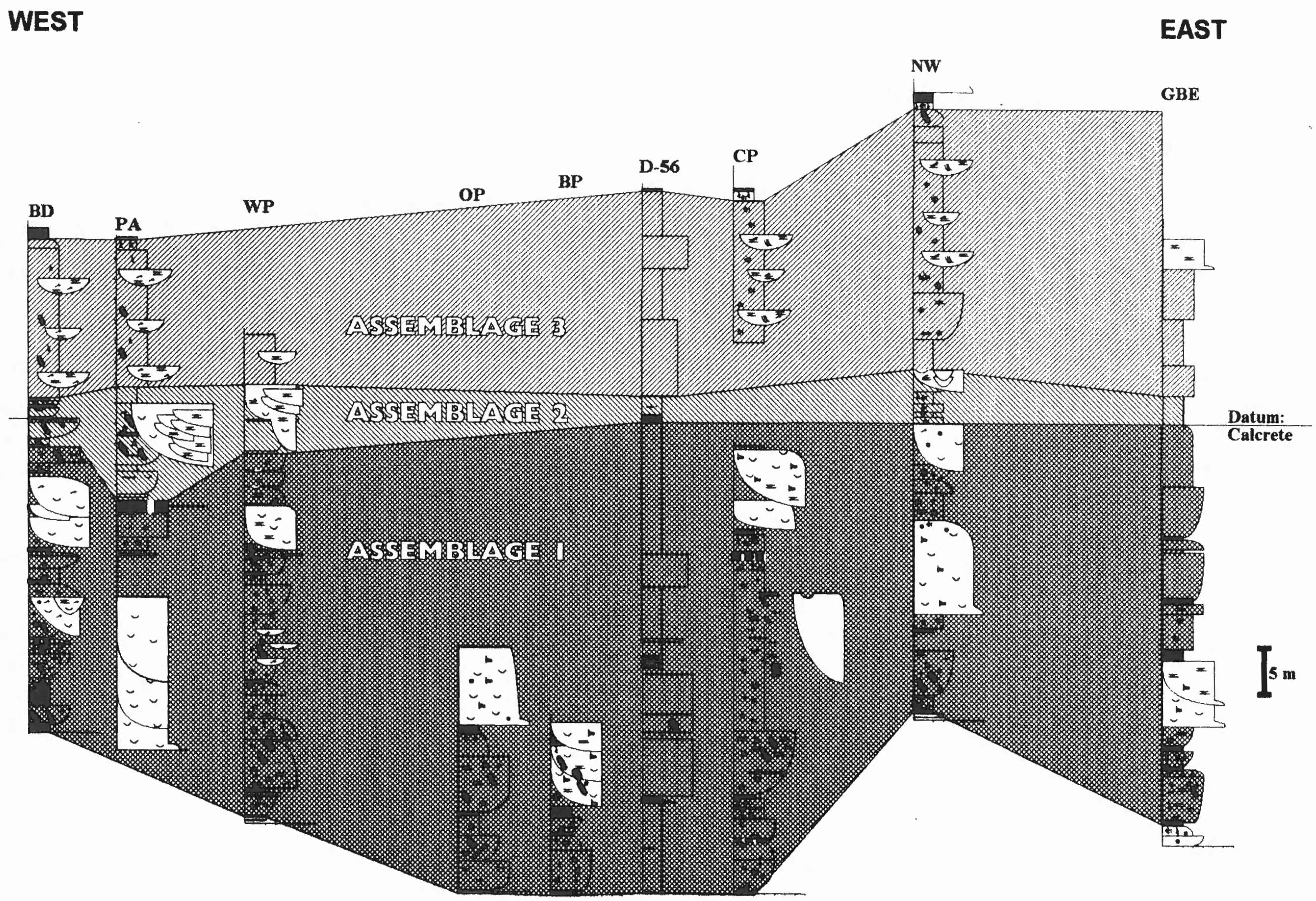


Figure 3.1. Simplified cross-section through the onshore part of the Sydney Basin. The calcrete was used as a datum. Because the calcrete is not exposed at the Black Point, Oxford Point or Chapel Point exposures, they were tied to borehole D-56 along the base of the Hub Coal Seam. The three facies assemblages are shaded; the channel fills (facies CHp, CHs, CHc and CHu) are white. Section locations are shown on Figure 1.6. BD: Bras d'Or; PA: Point Aconi; WP: Wetneck Point; OP: Oxford Point; BP: Black Point; CP: Chapel Point; NW: New Waterford; GBE: Glace Bay East. A legend of the symbols used is included in Appendix B.

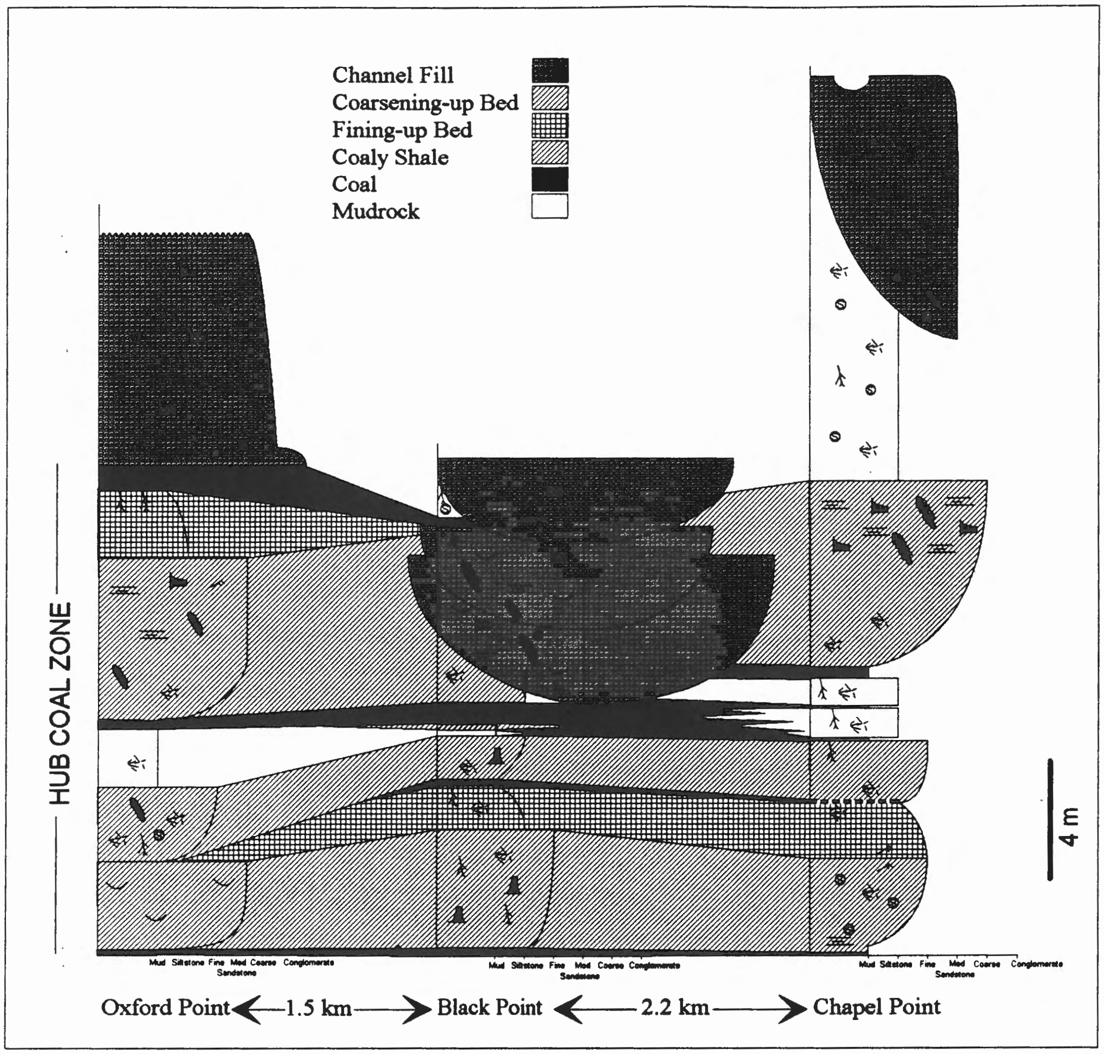


Figure 3.2. Cross-section through the Black Point, Oxford Point, and Chapel Point exposures (locations shown on Figure 1.6). Note that the coal, and some of the coarsening-up and fining-up beds are the only facies which are easily correlatable at this scale. Some of the channel bodies may be correlatable. The symbols used are identified in Appendix B.

Assemblage 1 ranges in thickness from 28 m at Bras d'Or to 45 m in drill hole D-56 near Oxford Point.

3.1.1 Facies

Nine of the facies described in Chapter two comprise Assemblage 1; they are listed below:

Overbank Facies:	Ml	Laminated Grey Mudrock
	Md	Disrupted Grey Mudrock
	Mb	Black Shale
	Oc	Coal
	Ob	Bituminous Laminae
	Gfu	Fining-Up Beds
	Gcu	Coarsening-Up Beds
Channel Facies:	CHp	Pebbly Meandering Channel fills
	CHs	Sandy Meandering Channel fills

As a group, these facies represent a broad, low-relief floodplain intersected by meandering river channels. Broad, extensive peat mires intermittently covered most of the floodplain.

Correlations within Assemblage 1 are difficult, even where the outcrops are close together. Figure 3.2 is a cross-section through Black Point, Oxford Point and Chapel Point, all of which are close together (see Figure 1.7). At both Black Point and Chapel Point, the redbeds of the underlying Harbour Cyclothem are visible; the lowest exposed split of the Hub seam at each of those outcrops is, therefore, the base of the Hub Cyclothem, and can be correlated. The only units which can be correlated directly from outcrop to outcrop, even at that close scale, are the coals (facies Oc) and coarsening-up beds (facies Gcu). The channel bodies appear to correlate either with other channel bodies or with coarsening-up beds (probably representing splays and flood events which breached the channel banks). Other units do not appear to have any clear correlations even at the inter-outcrop scale.

Aside from channel incisions, few lateral facies transitions are visible at outcrop scale. Vertical facies transitions are quite common in outcrop, however, and clear trends are visible. Typical facies transitions for each facies in Assemblage 1 are discussed following a short section on Markov chain analysis.

Markov Chain Analysis

Assemblage 1 is extensively exposed across the basin, and numerous facies transitions can be documented. A Markov chain analysis is used to determine which of the various vertical facies transitions are statistically significant; these are the transitions in which one facies preferentially leads into another facies. For example, a seat-earth usually passes preferentially into coal. Markov chain analysis has been in common use in vertical stratigraphic successions since the 1960s (e.g. Potter and Blakey, 1968; Gingerich, 1969; Miall, 1973; Walker, 1979; Harper, 1984). In a Markov analysis, the frequency of each type of facies succession in a stratigraphic succession is tabulated (transition count matrix, Table 3.1a); transitions from a facies into the same facies are not permitted. Two matrices are then tabulated. The first contains the probabilities of each facies occurring over each other facies, assuming that all facies transitions are random (independent trials matrix, Table 3.1b). The second contains the probabilities for each transition (proportional difference matrix, Table 3.1c), based on the actual data. In most methods, the difference between the two matrices is calculated in order to determine which transitions occur significantly more often than random. In this thesis, a method proposed by LeRoux

Table 3.1a. Transition Count Matrix

Facies	Ml	Md	Mb	Oc	Gfu	Gcu	CHp	CHs	Totals
Ml		3	0	0	5	6	0	3	17
Md	2		1	25	1	1	1	1	32
Mb	1	2		0	0	1	0	0	4
Oc	3	9	2		0	10	1	4	29
Gfu	3	2	0	0		5	0	0	10
Gcu	5	11	1	0	3		0	2	22
CHp	1	0	0	0	0	0		0	1
CHs	3	4	0	0	1	0	1		9
Totals	18	31	4	25	10	23	3	10	124

Table 3.1b Independent Trials Matrix

Facies	Ml	Md	Mb	Oc	Gfu	Gcu	CHp	CHs	Row Total
Ml		5.55	0.51	4.77	1.34	4.89	0.13	1.19	18.37
Md	5.48		1.16	10.82	3.03	11.10	0.28	2.71	34.58
Mb	0.51	1.18		1.02	0.28	1.04	0.03	0.25	4.32
Oc	4.73	10.85	1.00		2.61	9.57	0.24	2.33	31.34
Gfu	1.34	3.08	0.28	2.65		2.72	0.07	0.66	10.81
Gcu	3.61	8.30	0.76	7.13	2.00		0.19	1.78	23.77
CHp	0.13	0.29	0.03	0.25	0.07	0.26		0.06	1.08
CHs	1.20	2.75	0.25	2.37	0.66	2.43	0.06		9.73

Table 3.1c Proportional Difference Matrix

Facies	Ml	Md	Mb	Oc	Gfu	Gcu	CHp	CHs
Ml		-0.062	0.000	0.000	0.148	0.054	0.000	0.044
Md	-0.056		-0.001	2.859	-0.016	-0.081	0.006	-0.014
Mb	0.004	0.013		0.000	0.000	0.000	0.000	0.000
Oc	-0.042	-0.134	0.016		0.000	0.035	0.006	0.054
Gfu	0.040	-0.017	0.000	0.000		0.092	0.000	0.000
Gcu	0.056	0.240	0.002	0.000	0.024		0.000	0.003
CHp	0.007	0.000	0.000	0.000	0.000	0.000		0.000
CHs	0.044	0.040	0.000	0.000	0.003	0.000	0.008	

Table 3.1d Chi-Square Matrix

Facies	Ml	Md	Mb	Oc	Gfu	Gcu	CHp	CHs
Ml		1.17	0.51	4.77	10.04	0.25	0.13	2.74
Md	2.21		0.02	18.59	1.36	9.19	1.80	1.08
Mb	0.46	0.57		1.02	0.28	0.00	0.03	0.25
Oc	0.63	0.32	1.00		2.61	0.02	2.33	1.19
Gfu	2.05	0.38	0.28	2.65		1.92	0.07	0.66
Gcu	0.53	0.88	0.07	7.13	0.50		0.19	0.03
CHp	6.04	0.29	0.03	0.25	0.07	0.26		0.06
CHs	2.71	0.56	0.25	2.37	0.17	2.43	14.15	

Table 3.1. Data tables from a Markov chain analysis on facies transitions in Assemblage 1 strata in the Hub Cyclothem. Please see the text for a description of each table. The values were calculated following the method of LeRoux (1994). Note that the number of transitions to and from each facies are rarely equal, because eleven different stratigraphic sections were used, rather than one continuous section.

(1994) is employed. It uses an iterative chi-square method to separate the non-random transitions from the random ones. Transitions are removed from the proportional difference matrix (Table 3.1c) and the chi-square matrix (Table 3.1d) until the sum of all elements in the chi-square matrix is less than the critical chi-square value at the appropriate number of degrees of freedom, and the chosen level of confidence. The transitions removed from the matrices are considered to be non-random.

A Markov chain analysis of all transitions from Assemblage 1 strata in the Hub Cyclothem (Table 3.1 and Figure 3.3) indicates that the transition from disrupted grey mudrock (facies Md) to coal (Facies Oc) is the only non-random transition at the 99.5% confidence level (the critical chi-square values are from Bethea *et al.*, 1985). At the 95% confidence level, the transition from coarsening-up beds (facies Gcu) to disrupted grey mudrock (Md) and the transition from laminated grey mudrock (facies Ml) to fining-up beds (facies Gfu) are both non-random. Non-random transitions at the 90% and 10% confidence levels are shown in Figure 3.3. The depositional conditions responsible for each of these transitions are discussed in the following paragraphs.

Ml - Laminated Grey Mudrock

There is no clear precursor to the Ml mudrocks; they overlie all of the different facies. A transition to the Ml mudrock generally represents a shift to higher water table conditions and the development of a lake or bay. This may have been caused by a relative rise in base-level, or differential compaction over a peat. In any case, the presence of a Ml mudrock represents the development of a standing water body.

The laminated grey mudrocks most commonly grade up into coarsening-upward beds (facies Gcu), indicating that a delta prograded into the lake or bay in which the Ml sediments were deposited. Other Ml beds are sharply overlain by fining-up beds (facies

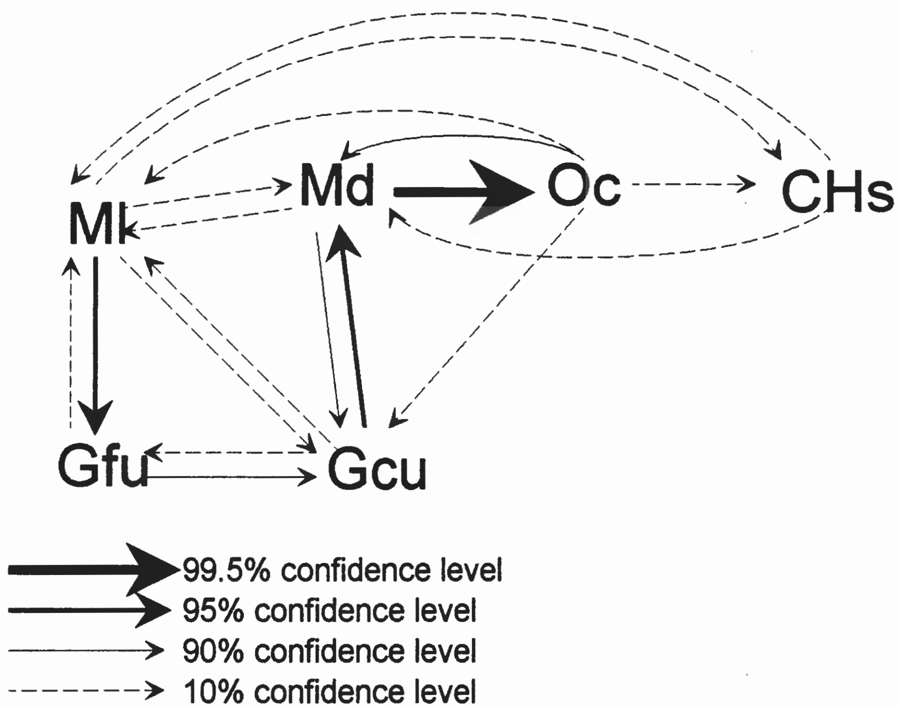


Figure 3.3. Facies relationship diagram for Assemblage 1 transitions in the Hub Cyclothem. Statistically significant facies transitions (those which occur statistically more often than random processes would allow) are shown at four levels of confidence (the critical chi-square values are listed in Bethea *et al.*, 1985). The significance of each transition was calculated using a Markov chain analysis method developed by LeRoux (1994).

Gfu) with relatively coarse ripple cross-lamination, or planar laminated sediments at the base; these were probably deposited as crevasse-splays during flood events; these transitions are statistically more significant than all other Ml transitions (Figure 3.3). Other standing water bodies either drained or filled with sediment, initiating the development of a disrupted grey mudrock (facies Md).

Md - Disrupted Grey Mudrock

The vast majority of Md beds overlie either coal or coarsening-up beds; both of these transitions are statistically significant (Figure 3.3). In the case of coal, the upward transition to Md mudrocks occurred when the formation of peat in a wetland ceased, either as a response to burial by an influx of sediment, or to other allogenic change. After a delta prograded across a lake or bay (generating a Gcu coarsening-up body), a paleosol developed on top of it, and an Md bed formed. Md beds also overlie fining-up beds (facies Gfu) and channel bodies; in both cases, the transition to Md represents a cessation of flow and the development of a soil.

Almost all Md beds are overlain by coals (Figure 3.3); the Md paleosols may have been the seat-earths for the coals. In a few cases, they are overlain by laminated grey mudrocks (facies Ml), or black shales (facies Mb), indicating that the Md paleosols were flooded. The Md paleosols were substrates for lycopsid trees; the Md beds which are overlain by other facies may have been incipient histosols which had too much clastic input for peat formation.

Mb - Black Shale

The black shales are exposed only at Glace Bay, where they sharply overlie coals (facies Oc), disrupted grey mudrocks (facies Md) and coarsening-up beds (facies Gcu). In all cases, they represent a rapid transition to deeper water conditions, or a cessation of sediment supply and oxygenated water.

The shales grade up into laminated grey mudrocks (facies Ml), disrupted grey mudrocks (facies Md), and coarsening-up beds (facies Gcu). Both mudrock facies represent shallowing conditions. The coarsening-up beds (facies (Gcu) were deposited as deltas prograded over the deeper water bodies in which the shales were deposited.

Oc - Coal

The coals in the Hub Cyclothem consistently overlie disrupted grey mudrocks (facies Md), which are hydromorphic paleosols. The transition from disrupted grey mudrocks (facies Md) to coal represents the time at which peat began to develop.

Three facies commonly lie above the coals: laminated grey mudrocks (facies Ml), which commonly form the base of a coarsening-up bed (facies Gcu); meandering channel bodies (facies CHp or CHs); disrupted grey mudrocks (facies Md). The laminated grey mudrock (facies Ml) transitions occurred when the peat mires flooded (possibly in response to increased compaction over the peats) and peat formation ceased. The disrupted grey mudrock (facies Md) transitions represent a shift to better drained conditions and the development of a gleysol or protosol horizon; this is commonly followed, once again, by a coal. The transition to Md beds is the most statistically significant transition above the coal beds (Figure 3.3). Channel bodies generally overlie, but rarely cut the coals; as the channels incised, they met little resistance to vertical cutting in the floodplain deposits, but the peats were difficult to cut due to their fibrous nature. As a result, the channels rarely incised through the peats. Coalified peat fragments are present, however, in some channel fills, indicating that the channels occasionally did cut through the peats.

The coals in the Hub Cyclothem are commonly split. The Hub seam, in particular, is extensively split and occurs as a thick zone of coal and clastics (Figure 3.2) in all exposures. The peat formation was clearly interrupted intermittently by clastic input from channels and lakes which intersected the peat mires. Coaly shales are relatively rare in the Hub Cyclothem, suggesting that the coals rarely pass laterally into clastic facies. Rather, the coals are interconnected, and the clastic facies form large pods and lenses in the coal, reflecting areally extensive peatlands with local ponds, lakes and streams.

CHp and CHs - Meandering Channel fills

The channel-fill facies sharply and erosionally overlie both channel and overbank facies. Because the channel fills are multi-storied, most of the channel bases lie within other channel-fill bodies. Many channel bodies directly overlie coal seams, as described in Chapter 2.

The upper boundaries of the channel-fill facies tend to be gradational; most channel bodies are capped with either laminated or disrupted grey mudrocks (facies Ml or Md), both of which represent cessation of flow. In the first case (facies Ml), the channel became flooded when flow ceased, possibly as an ox-bow meander or abandoned channel branch. In the second case, the channel dried and a paleosol formed on top of it; a coal may overlie the paleosol.

Gfu and Gcu - Gradational Beds

These facies do not show any clear trends, and tend to overlie and underlie the other facies types with relatively equal frequency. Because the bases of coarsening-up beds are often similar to the laminated or disrupted grey mudrocks (facies Ml or Md), they tend to overlie the same facies types as the mudrocks. Likewise, the tops of fining-up beds are similar to the laminated or disrupted grey mudrocks (facies Ml or Md); they are usually overlain by the same facies types as those facies (most commonly coal or other gradational beds).

The Markov chain analysis, however, emphasizes some transitions which are more significant than others. The upward transitions from coarsening-up beds (facies Gcu) to disrupted grey mudrocks (Md) and from laminated grey mudrocks (facies Ml) to fining-up beds (Gfu) are among the most significant transitions in Assemblage 1. The former transition type (Gcu to Md) represents the development of a paleosol over a delta deposit. The latter transition type (Ml to Gfu) may represent deposition from a splay flowing into a standing water body.

3.1.2 Paleoflow Directions

The paleoflow directions measured in Assemblage 1 channel fills are summarized on Figures 3.4, 3.5 and 3.6. The indicated current directions range from about 320° to 190°, with a circular mean of 087°. Observed paleoflow directions vary by 150° to 200° within each outcrop, and over the basin as a whole. The broad spread of current directions (about 200°) is consistent with a meandering river setting (Miall, 1992). In all cases where there are enough indicators to be significant, the mean paleoflow direction is northeasterly or easterly. The mean paleocurrent direction at Bras d'Or is east-southeast, suggesting that these channels at the western margin of the basin tended to flow in towards the basin to the east.

The Hub Cyclothem paleoflow directions are consistent with others measured throughout the Sydney Mines Formation. Gibling *et al.* (1992) measured paleoflow directions for twenty-eight channel-sandstone bodies in the Sydney Mines Formation; the current directions are highly variable (through about 200°) and trend to the northeast.

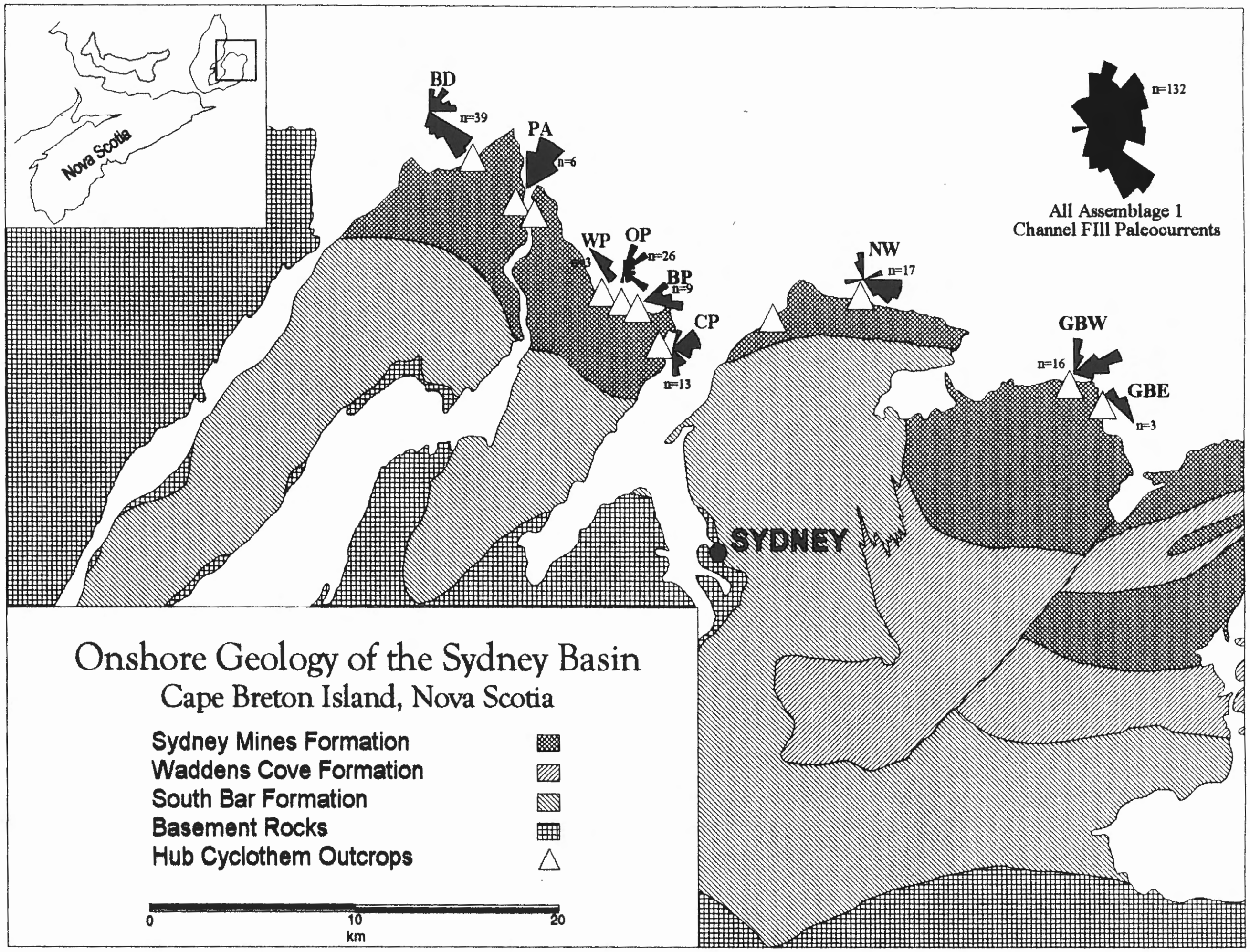


Figure 3.4. Map of the Sydney Basin summarizing the paleocurrents in Assemblage 1 meandering channel fills (facies CHp and CHs). Trough cross-bed crest intersections and ripple cross-lamination on bedding surfaces were used as paleocurrent indicators. The rose diagrams were plotted such that the area of each segment (rather than the radius) is proportional to the number of readings. The abbreviations used for outcrop names are the same as in Figure 3.1.

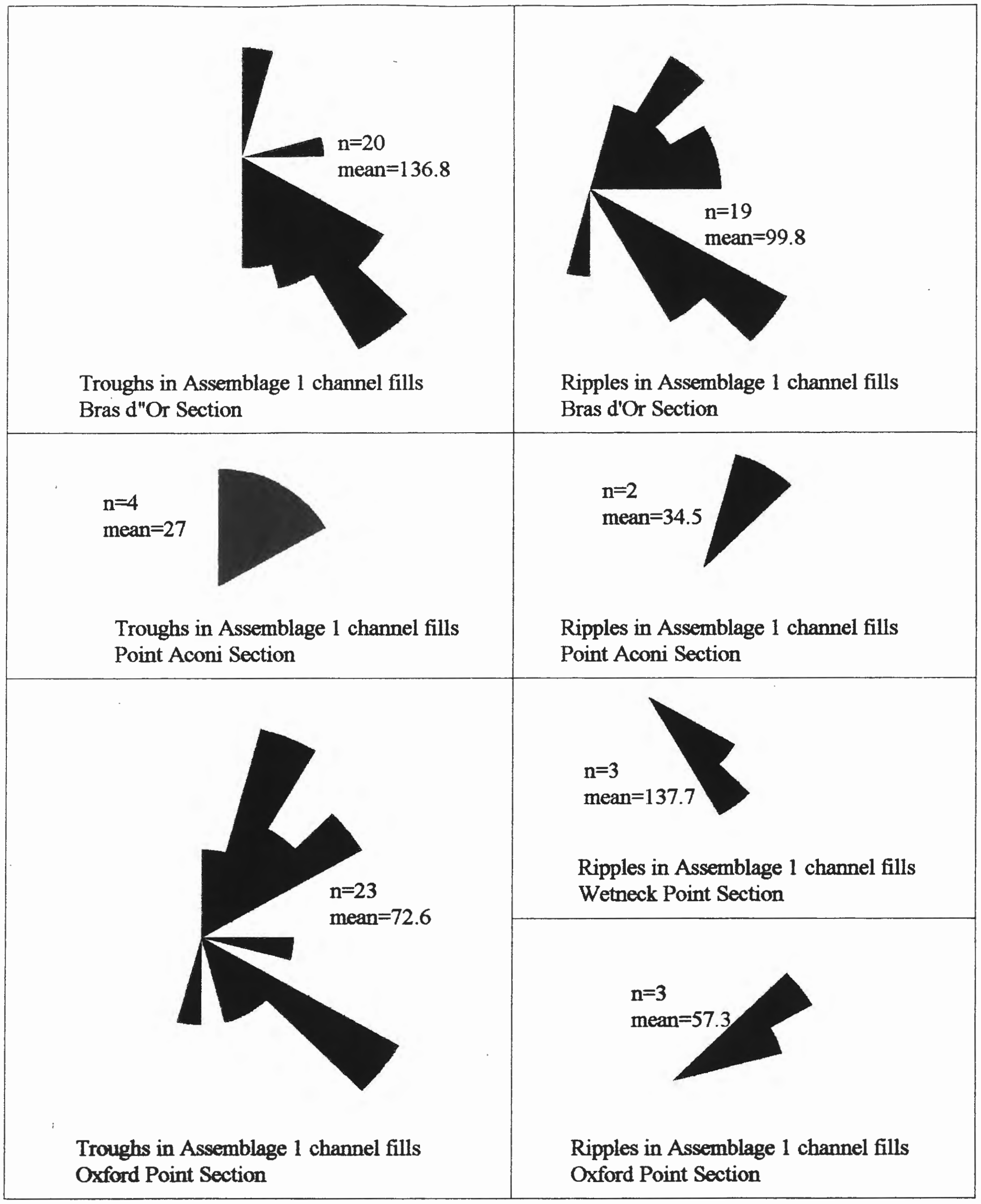


Figure 3.5. Paleocurrents from the meandering channel fills in Assemblage 1. Current directions from trough cross-bed crest intersections and ripple crests on bedding surfaces are plotted on separate rose diagrams. The area of each segment is proportional to the number of paleocurrent measurements in that zone. Outcrop locations are shown in Figure 1.7. Paleocurrent measurements for the other outcrops are in Figure 3.6.

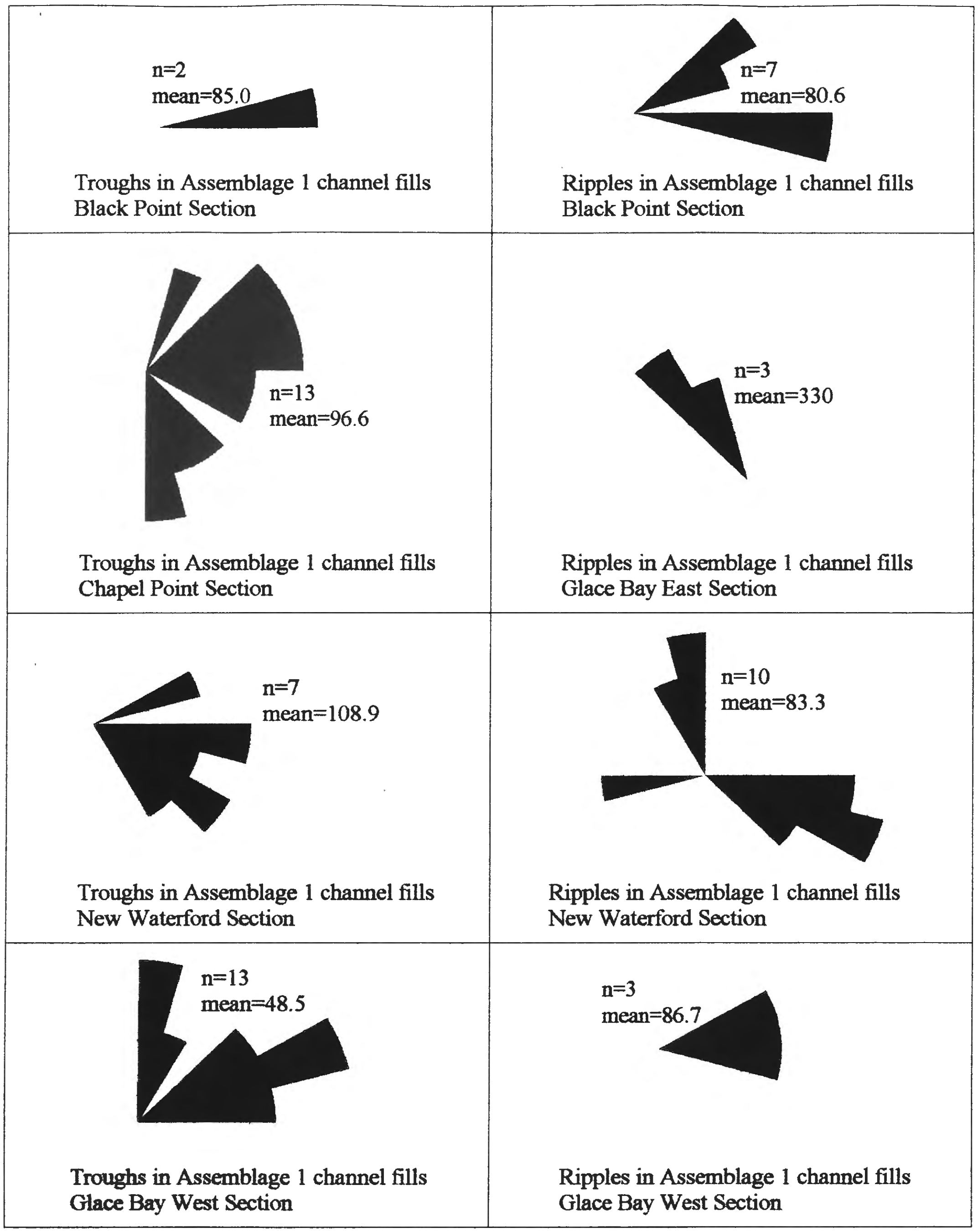


Figure 3.6. Paleocurrents from the meandering channel fills in Assemblage 1. Current directions from trough cross-bed crest intersections and ripple crests on bedding surfaces are plotted on separate rose diagrams. The area of each segment is proportional to the number of paleocurrent measurements in that zone. Outcrop locations are shown in Figure 1.7. Paleocurrent measurements for the other outcrops are in Figure 3.5.

Measurements from Westphalian B to Permian strata for the Maritimes Basin as a whole are similarly consistent (Gibling *et al*., 1992).

3.1.3 Depositional Environment

Assemblage 1 was deposited by meandering rivers on a broad, flat floodplain. Early in the development of the assemblage, the floodplain was very wet (indicated by the presence of extensive reotrophic peat swamps), and extensive peat mires were common. Later, less moisture was available, and the peat swamps became rare and local. There is, as a result, an upward decrease in the abundance and thickness of coal beds in Assemblage 1 throughout the basin. Throughout the deposition of Assemblage 1, the floodplain was abundantly vegetated: the channel bodies generally contain plant debris, and rooted zones are very common in the floodplain strata.

Foraminiferal and thecamoebian evidence suggests that the degree of marine influence decreased during Assemblage 1 deposition. Numerous brackish water foraminifera are present in the lower levels of the Assemblage; near the top of Assemblage 1, most samples were either barren, or contained thecamoebians, which are indicative of fresh-water deposition.

3.1.4 Climate

The Sydney Basin was equatorial during the Pennsylvanian (Rowley *et al*., 1985). Modern peats in equatorial coastal regions form only where precipitation exceeds evaporation throughout the year (Lottes and Zeigler, 1994). Prolonged periods of drought (less than 40 mm of precipitation during a month) during summer months (when the average temperature is greater than 10°C) adversely affect organic matter preservation (Lottes and Ziegler, 1994).

The abundance of coal and coaly shales deposited in a coastal setting in Assemblage 1 suggests that the Sydney Basin climate was tropical and wet throughout most of the year. The mires were reotrophic swamps, which are indicative of slightly seasonal, humid conditions.

3.1.5 Sea-Level

Sea-level was apparently stable during the deposition of Assemblage 1. Minor fluctuations in sea-level may, however, have been responsible for some of the vertical transitions documented above, including the meandering channel incisions (particularly the CHp pebbly meandering river channels). The upward decrease in coal and change from brackish-water foraminiferal assemblages to fresh-water thecamoebian assemblages suggests that there was a minor and gradual relative fall in sea-level during deposition. These same effects may, however, be explained by the gradual progradation of the shoreline as sediments reached the sea.

3.1.6 Tectonics

There is no evidence of local tectonic activity during the deposition of Assemblage 1; paleocurrent indicators consistently point to the northeast throughout the exposed part of the basin. There is no evidence of significant relief on the floodplain, such as alluvial fans, which might be associated with fault scarps, or less profound features such as laterally persistent seismites.

3.1.7 Glace Bay Area

The Assemblage 1 strata at Glace Bay differ slightly from the strata in the western part of the basin. The most significant differences are the lower abundance of coal, and the presence of black shales, which are absent elsewhere in the basin (Figure 2.1).

Siltstones and mudrocks associated with the coal seams and black shales in the Hub Cyclothem in the Glace Bay area contain brackish water foraminiferal assemblages indicative of estuarine and lower salt-marsh environments; a few beds also contain indicators of upper salt-marsh and freshwater marsh conditions, but these are much less common (Wightman *et al.*, 1994). Assemblage 1 strata in the Hub Cyclothem at the Bras d'Or exposure, conversely, are dominated by foraminiferal and thecamoebian assemblages indicative of freshwater marsh, upper salt-marsh and lower salt-marsh environments, while estuarine assemblages are totally absent (Table 2.3).

While Assemblage 1 was being deposited, the Glace Bay area was located closer to the sea and endured a greater degree of sea-water influence. Either the Glace Bay area was more proximal to the coastline during deposition, or it was in a sub-basin which subsided more rapidly than other parts of the basin.

3.1.8 Modern Analogues

Any analogue to the coal-bearing strata in the Hub Cyclothem (Assemblage 1) must meet the following criteria: deposition in an equatorial setting, extensive peat deposits, meandering rivers, both fresh and brackish-water influences, no major tectonic influences.

The central Sumatra basin in Indonesia meets most of the criteria for an analogue (Cecil *et al.*, 1993): it is a broad flat equatorial basin, although it is in a tectonically active area. Peat is being deposited over more than 70 000 km^2 in a network of domed bogs. A meandering river/estuary system on a well-vegetated floodplain exists in association with the deposits; the rivers are not currently aggrading. Brackish water faunas are present in the estuary and floodplain deposits, as well as in the seat-earth under the peat; fresh water faunas are present in the peats and on the floodplain, where waters have flowed off the peat dome. Because the peat mire is domed, neither brackish water, nor clastic sediments penetrate into the mire.

The central Sumatra basin, however, does differ from the Sydney Basin during Assemblage 1 deposition. The coals in the Hub Cyclothem are commonly split by crevasse splays and other floodplain sediments, and contain flora indicative of a reotrophic setting, indicating that the Sydney peats were not domed.

Although they are not equatorial, the thin extensive peats in the Barataria Basin on the Mississippi River in Louisiana are excellent analogues for the Assemblage 1 strata and thin coals in the Hub Cyclothem. The Barataria Basin is about 50 km wide and 150 km long; it receives sediment and water from the Mississippi River, and sea-water from the Gulf of Mexico. The most common elements in the basin are crevasse splays from the river, and fresh- and brackish-water marshes and peat swamps (Kosters, 1989). Sedimentation in the basin follows a relatively cyclical pattern. After an active delta lobe is abandoned, peat formation begins. If the crevasses flood regularly, very little organic matter is preserved (the resulting sedimentary sequences would probably resemble the Ml disrupted grey mudrocks). In more central parts of the basin, which are flooded less frequently, extensive peats form up to 4 m thick. Eventually, peat formation is terminated when a new delta lobe migrates to the area (Kosters, 1989). Thus, the alternation between thin peat formation and clastic sedimentation is an autocyclic process. If the Barataria Basin was buried long enough for peats to form, they would probably be about 40 cm thick (based on a 10:1 compaction ratio for peat), and frequently split by crevasse and lake deposits. The Mississippi River sediments would form channel fills similar to the CHp and CHs meandering channel fills. Thicker peats, such as those which formed the thicker splits of the Hub seam (up to 2 m in the Prince Mine), do not have analogues in the

Barataria Basin; it is likely that allogenic forces were partially responsible for the demise of the thicker peat swamps (Calder and Gibling, 1994).

3.2 Assemblage 2: Desiccated Landscape

The middle assemblage in the Hub Cyclothem extends from the base of the lowest redbed or calcrete (whichever is lower) to the top of the uppermost redbed (facies Mr mudrock) and ranges in thickness from 5 m at the Bras d'Or outcrop to 11 m at the Point Aconi outcrop. In general, the assemblage thins to the east (see Figure 3.1).

3.2.1 Facies

The six facies listed below comprise Assemblage 2:

Overbank Facies:	Ml	Laminated Grey Mudrock
	Mr	Red Mudrock
	C	Calcrete
	Gfu	Fining-Up Beds
	Gcu	Coarsening-Up Beds
Channel Facies:	CHc	Large Complex Channel fills

As a group, these facies represent a broad, flat desiccated landscape, intersected by deep channels with ephemeral flow. There were clearly periods of time during which evaporation exceeded precipitation, and the sediment supply was extremely limited (calcrete formation). Occasional floods brought sediments to the area and deposited the grey mudrocks and fining-up beds. Following the floods, the mudrocks reddened and became vertisols. The channels were quite deep (as much as 8 m at Wetneck Point) and commonly sub-aerially exposed. Because they aggraded during ephemeral flow conditions, the channel fills are complex.

Correlations within Assemblage 2 are difficult between outcrops. The calcrete, because it represents a period of extreme climatic conditions, can be used as a temporal datum through all outcrops in which all of Assemblage 2 is exposed, except for the Point Aconi exposure where the calcrete was presumably removed as the CHc valley incised.

Ml - Laminated Grey Mudrock

Most of the Ml mudrocks in Assemblage 2 are carbonate-cemented and overlie either red mudrocks (facies Mr) or the calcrete. In either case, the Ml beds represent flood events during which sedimentation was renewed and vertisol (facies Mr) or calcrete (facies C) development ceased. The presence of raindrop imprints on Mr beds where they are overlain by laminated grey mudrocks (facies Ml) suggests that the Ml sediments were deposited in intermittently filled lakes.

Ml mudrocks are overlain either by coarsening-up beds (facies Gcu), deposited during lacustrine delta progradation, or by red mudrocks (facies Mr), deposited in response to renewed exposure and vertisol development. Repeated alternation of Ml and Mr mudrocks is common as lakes filled and dried.

Mr - Red Mudrocks

Mr mudrocks overlie all of the facies in Assemblage 2. In all cases, occurrences of red mudrock (facies Mr) represent a cessation of sedimentation and the initiation of subaerial exposure.

Mr beds are overlain either by coarsening-up beds (facies Gcu) or laminated grey mudrocks (facies Ml). The laminated grey mudrocks (facies Ml) were deposited when the Mr vertisols were flooded by a lake. The coarsening-up beds (facies Gcu) probably represent flooding, followed by a delta progradation.

In many cases, particularly in the western part of the basin, red mudrocks (facies Mr) form the basal unit in Assemblage 2, and lie as much as a few metres below the calcrete (facies C). In the eastern part of the basin, the calcrete is usually the basal unit in Assemblage 2.

C - Calcrete

The calcretes in the Hub Cyclothem developed on top of laminated grey mudrocks (facies Ml), meandering channel fills (facies CHs) and coarsening-up beds (facies Gcu). In all cases, the development of a calcrete reflects a transition to a dry climate with very little sediment influx.

The calcretes are usually overlain by laminated grey mudrocks (facies Ml), or coarsening-up beds (facies Gcu). In both cases, the calcrete formation was terminated by renewed sedimentation.

Gfu and Gcu - Graded Beds

These facies do not show any clear trends, possibly because they are composite facies. The coarsening-up facies begin with either laminated or disrupted grey mudrocks (facies Ml or Md) and have the lower boundary conditions of those facies. Likewise, the upper part of a fining-up body is either a laminated grey mudrock (facies Ml) or a red mudrock (facies Mr).

CHc - Complex Valley Fills

The valley fills in Assemblage 2 incise through all types of overbank facies. The valley fill at Wetneck Point cuts through the calcrete which clearly projected as a bench into the channel at some stages of filling (Figure 3.1). All of the CHc valleys incised through the calcrete, which may have acted as a barrier to lateral migration. None of the other facies, however, appear to have resisted erosion significantly.

The CHc valley fills tend to grade up into finer strata. Throughout the exposed part of the Sydney Basin, they are succeeded by laminated grey mudrocks (facies Ml) or red mudrocks (facies Mr), indicating that they were succeeded by either standing water bodies, or by exposed, dry surfaces.

3.2.2 Paleoflow Directions

Because Assemblage 2 is predominantly muddy, few paleocurrent direction measurements are possible. The only exposed indicators of paleocurrent are ripple cross-laminae. The paleoflow directions ranged from northeasterly to easterly (Figure 3.7), with a circular mean of 34°; they are much less variable than the paleoflows in Assemblage 1.

It is difficult to document the lateral differences in paleoflow across the basin, because the Assemblage 2 strata are poorly exposed at most exposures. The only data, therefore, come from the Wetneck Point and Point Aconi exposures.

3.2.3 Depositional Environment

Most of the floodplain was emergent and dry during Assemblage 2 deposition. The water table was low, except after major floods; it did not remain high for long enough to support plants. If any plants did grow, they decomposed without leaving fossil traces. Any root traces were obliterated by vertisol development.

Most of the precipitation soaked into the ground and eventually evaporated. The only preserved major drainage channels lie near the top of Assemblage 2. They do not appear to have migrated laterally: they incised deeply and slowly aggraded vertically. Their widths are unknown, because they are not fully exposed (they are greater than 100 m wide). The calcrete (facies C) formed under conditions with very low sediment influx.

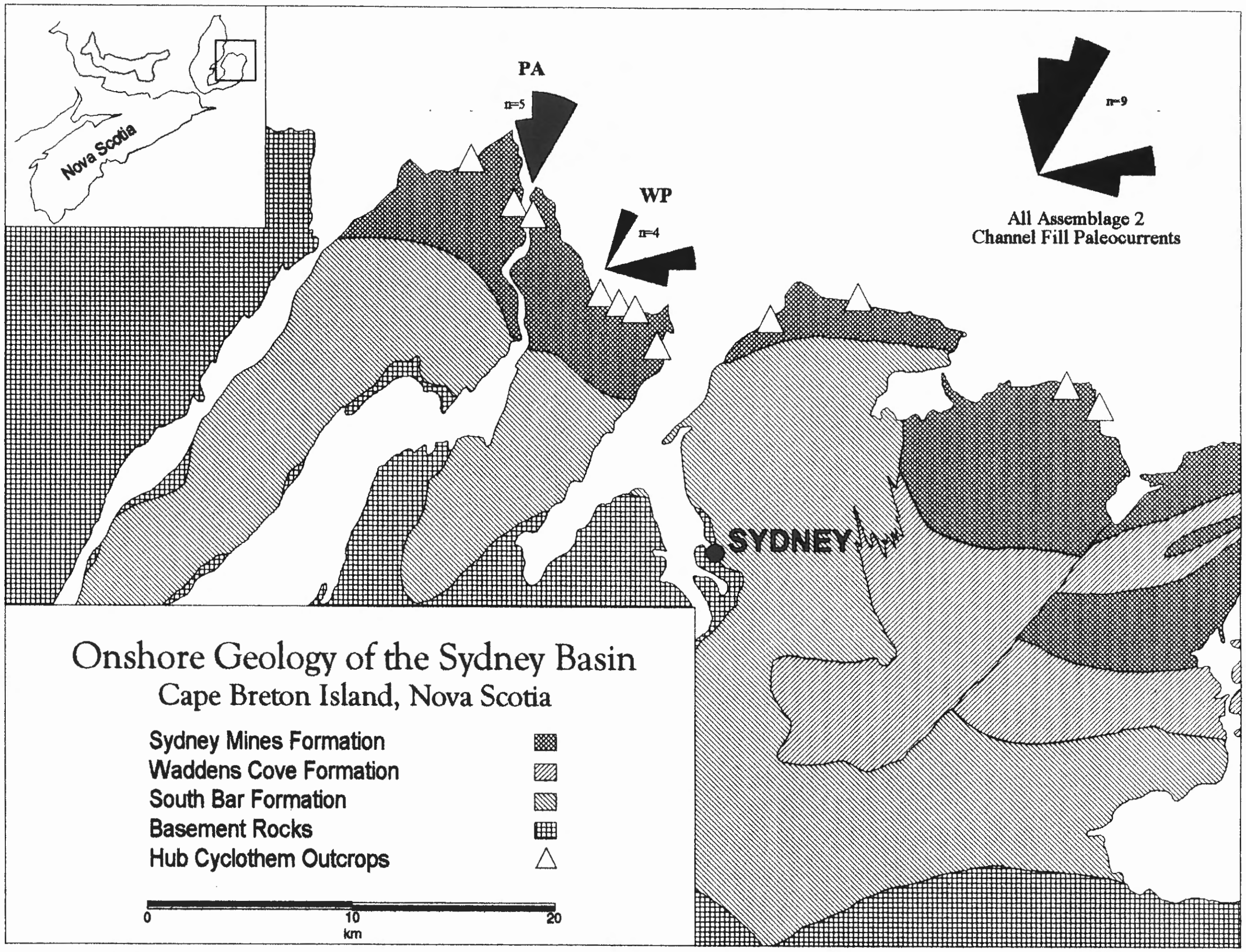


Figure 3.7. Map of the Sydney Basin summarizing the paleocurrents in Assemblage 2 channel fills (facies CHc). Ripple cross-laminae on bedding surfaces were used as paleocurrent indicators. The rose diagrams were plotted such that the area of each segment (rather than the radius) is proportional to the number of readings. The abbreviations used for outcrop names are the same as in Figure 3.1.

Any precipitation into the area must have either been absorbed into the ground, or carried away in river channels. Although no river channels are preserved near the level of the calcrete, they may have existed in parts of the basin not currently exposed.

3.2.4 Climate

Both the calcrete horizon and the numerous red vertisols indicate that the climate was dry through much of the year while the Assemblage 2 strata were being deposited. Modern nodular pedogenic calcretes form in areas in which rainfall amounts to 400-600 mm/yr, and there is a net moisture deficit; seasonal conditions usually predominate (Goudie, 1983; Tandon and Gibling, 1994). Likewise, modern vertisols form in seasonally arid, tropical to warm-temperate areas. Between 4 and 8 dry months each year are required for vertisol formation (Ahmad, 1983; Tandon and Gibling, 1994). Assemblage 2 strata were clearly deposited under the influence of a climate which was seasonally arid or semi-arid.

The upward shift from calcrete formation to mudrock (both red and grey) and channel fill deposition may reflect a gradual shift to wetter conditions. The low sediment supply responsible for calcrete formation did not continue into the upper levels of Assemblage 2.

3.2.5 Sea-Level

The position of the sea relative to the Assemblage 2 strata during deposition is unknown. All the Assemblage 2 samples which were analyzed for foraminifera and thecamoebians were barren. A relative fall in sea-level may have accompanied the initiation of calcrete formation. The resulting lowering of base level would have helped to keep sediment supply low (landward areas are usually sediment bypass zones during lowstand conditions; Allen and Posamentier, 1993), which is an important condition for calcrete formation.

The major valleys which are exposed at the upper levels of Assemblage 2 (facies CHc) may have incised either in response to a smaller relative drop in sea-level than the one which initiated Assemblage 2 deposition, or in response to the development of a more humid wet season. In either case, the valleys filled slowly with sediment under conditions similar to those in some modern anastomosed rivers, such as the Barwon River (discussed in section 2.12.2). It is likely that a there was a relative rise in sea-level while these valleys (facies CHc) were filling; this is discussed in more detail in later sections.

3.2.6 Tectonics

As with Assemblage 1, there does not appear to have been any local tectonic activity during the deposition of Assemblage 2. There is no evidence, such as alluvial fans, or large lake successions, that there were any significant topographic features during deposition. The relative fall in sea-level which may have been responsible for the incision event may have been caused by a sudden regional uplift. The Sydney cyclothems will have to be correlated with other areas to differentiate unequivocally between tectonic and eustatic effects.

3.2.7 Glace Bay Area

The Assemblage 2 strata in Glace Bay are very similar to the Assemblage 2 strata elsewhere in the basin. The Assemblage 1 strata in the Glace Bay area have a more marine foraminiferal assemblage than those in the western part of the basin; if a relative fall in sea-level occurred at the onset of Assemblage 2 deposition, it must have been of sufficient magnitude to move the shoreline away from the Glace Bay area.

3.2.8 Modern Analogues

Watts (1980) described calcretes from the Kalahari desert in southern Africa which formed under the influence of a semi-arid climate in which evaporation exceeded precipitation. Likewise, the Kalahari calcretes formed on silts and sands, and are overlain by sands which reddened *in situ*. The Kalahari calcretes are, however, thicker (up to 2.5 m) and more mature (stage 4 to 6) than the Hub Cyclothem calcretes, possibly because they formed over a greater period of time, or under conditions of more extreme aridity or temperature. Despite these differences, the African calcretes support a semi-arid climatic setting for the Hub Cyclothem calcretes.

3.3 Assemblage 3: Anastomosed River Complex

Assemblage 3, the uppermost facies assemblage in the Hub Cyclothem, extends from the top of the uppermost red mudrock (facies Mr) to the base of the seat-earth below the lowest split of the Bonar Coal Seam. The upper boundary coincides with the upper extent of carbonate-cemented strata below the Bonar Seam. Assemblage 3 ranges in thickness from 13 m at Point Aconi to 22 m at New Waterford, and tends to thicken to the east.

3.3.1 Facies

Only the three facies listed below are present in Assemblage 3:

Overbank Facies:	SLg	Laminated Grey Siltstones
	SLr	Red Siltstones
Channel Facies:	CHu	"U" Shaped Channel fills

Carbonate cement, which is absent in Assemblage 1 strata, and present in only some of the Assemblage 2 strata, is ubiquitous throughout Assemblage 3 strata.

SLg - Laminated Grey Siltstones

The SLg siltstones form almost all of the floodplain and overbank material in Assemblage 3. They were deposited during sheet flood events when the anastomosed channels (facies CHu) overflowed. The SLg beds are laterally extensive beyond outcrop scale, except where they are truncated by anastomosed channel incisions. Red siltstones (facies SLr) sharply overlie and underlie SLg beds and represent flood events carrying materials from a different source.

SLr - Red Siltstones

The SLr beds are present only at the Glace Bay exposures and, to a lesser extent, at the New Waterford exposures. They are similar in form to the laminated grey siltstone beds (facies SLg) in that they are laterally extensive and relatively planar. They are sharply overlain and underlain by laminated grey siltstone beds (facies SLg) and laterally truncated by anastomosed channel fills (facies CHu).

CHu - "U" Shaped Channel fills

The CHu channel fills incise through both red and grey siltstones (facies SLr and SLg). They are capped by laminated grey siltstones (facies SLg), deposited during sheet floods after the channels filled.

3.3.2 Paleoflow Directions

Assemblage 3 paleoflow directions are highly consistent: they vary by less than 60° across the basin, and tend to be within a range of 20° at each outcrop (Figure 3.8). The average direction is northeasterly (with a circular mean of 24°), which is consistent with the other assemblages in the Hub Cyclothem, and with the other cyclothems in the Sydney Mines Formation (Gibling *et al.*, 1992). This relatively small range of paleoflow directions

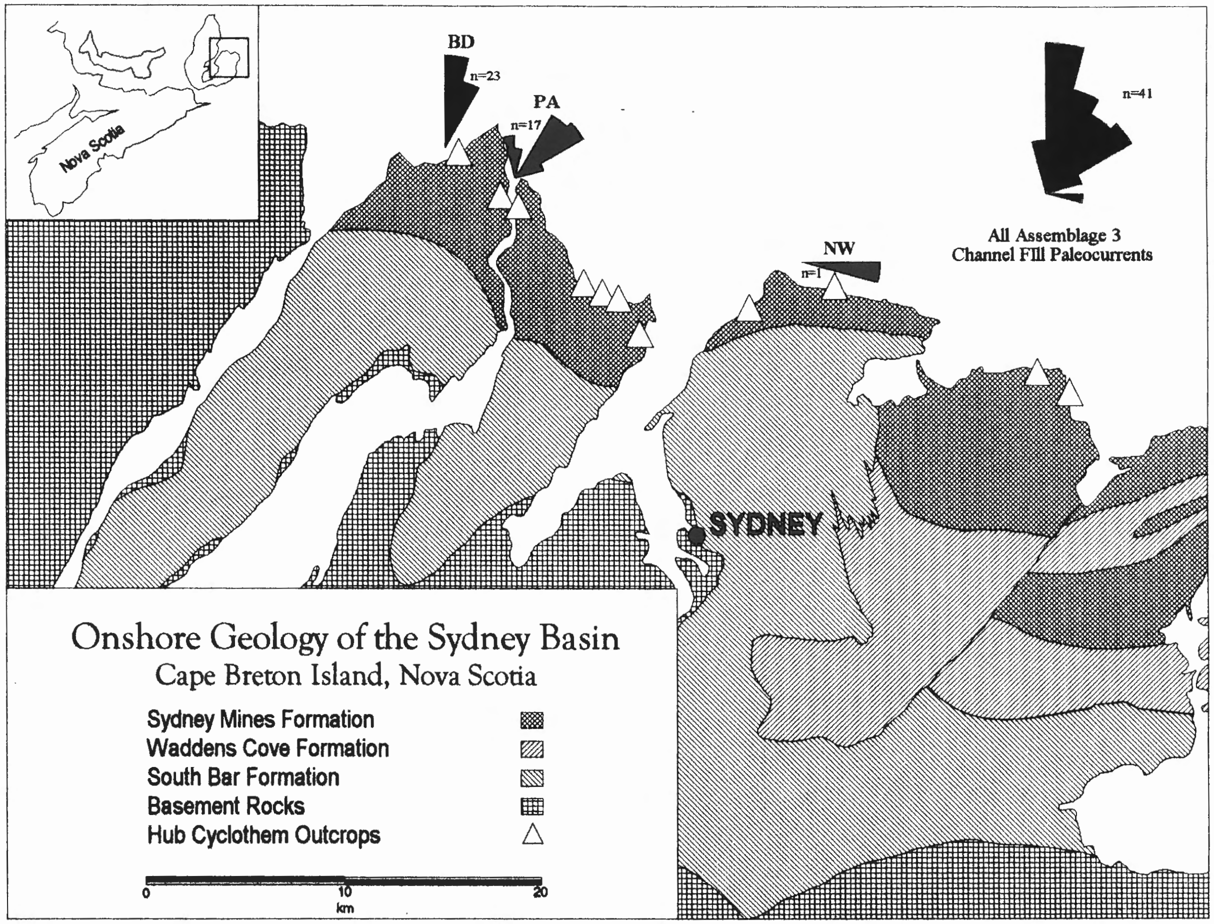


Figure 3.8. Map of the Sydney Basin summarizing the paleocurrents in Assemblage 3 anastomosed channel fills (facies CHu). Ripple cross-laminae on bedding surfaces were used as paleocurrent indicators. The rose diagrams were plotted such that the area of each segment (rather than the radius) is proportional to the number of readings. The abbreviations used for outcrop names are the same as in Figure 3.1.

is common in some modern anastomosed rivers (Tornqvist, 1993). The channels had very low sinuosity and, therefore, little variability in paleoflow directions.

3.3.3 Depositional Environment

The Assemblage 3 strata were deposited on a broad flat floodplain, intersected by numerous anastomosing channels. The floodplain and channel banks were either sparsely vegetated, or totally unvegetated; no plant remains or root traces have been preserved. The floodplain was subaerially exposed for much of the time, as indicated by the abundant mudcracks and raindrop imprints, and the sparse vertebrate trackways.

The channel bodies incised and filled quickly during flood events. Channels tended to avulse, rather than migrate in response to sediment aggradation. The presence of early carbonate cement in the floodplain sediments may have inhibited channel migration.

Modern rivers (and ancient river deposits, when possible) are classified on the basis of their plan view geometry. Because the Hub Cyclothem outcrops in the Sydney Basin show only a cross-sectional view of the strata, the plan view geometry of the CHu channels can only be inferred on the basis of paleoflow data and architectural elements. Because they appear to have aggraded vertically and did not migrate laterally, they are most likely anastomosed river deposits; the unidirectional paleocurrent indicators are also more consistent with an anastomosed river setting than a meandering channel setting. The sheer abundance of channels in the floodplain sediments suggests that channel switching was a frequent event.

3.3.4 Climate

The presence of carbonate cement throughout all Assemblage 3 facies and the apparent lack of any vegetation suggests that the climate remained relatively arid through much of the year, as it did during the deposition of Assemblage 2. The long periods with little precipitation and negligible sediment supply which were responsible for the calcretes and vertisols in Assemblage 2, however, did not continue into Assemblage 3 deposition. Floods were frequent during Assemblage 3 deposition: paleosols did not form, and the channels filled rapidly with sediment. Well developed mudcracks, vertisols and tetrapod trackways indicate that emergent dry conditions persisted through much of the year. The channel fills contain coarse sediments deposited under conditions of intense flow. The Assemblage 3 climate was, therefore, semi-arid, but probably with a pronounced period of strong precipitation.

3.3.5 Sea-Level, Tectonics and River Anastomosis

Some modern anastomosed river complexes occur in areas in which base level is rising in response to either a downstream blockage (e.g. Smith and Smith, 1980) or rising sea-level (Tornqvist, 1993). Because the Assemblage 3 channels are widely distributed across the floodplain, it is unlikely that the development of anastomosis was the result of a river blockage; a regional rise in base level is more likely. This regional rise can be attributed to eustatic sea-level rise or tectonic subsidence. A drastic increase in sediment supply may also have caused the channels to aggrade vertically as downstream areas became clogged with sediment and effectively reduced the gradient of the reach; this possibility is discussed in Chapter 4 (section 4.3.3).

The presence of very sparse foraminifera in two samples, however, suggests that there was a degree of brackish water influence on the Assemblage 3 strata during deposition. Sea-level, rather than seasonal sediment clogging, may, therefore, have been responsible for the development of the anastomosed river system. Both factors may have been working in unison to create the sedimentary patterns in Assemblage 3.

3.3.6 Glace Bay Area

Although the Assemblage 3 strata are not fully exposed in the Glace Bay area, it is clear that they differ from the Assemblage 3 strata in other parts of the basin. Extensive red siltstones (facies SLr) are present at all exposed levels of Assemblage 3 strata in Glace Bay, but are rare at New Waterford and totally absent in other parts of the basin. As discussed previously, however, the Assemblage 3 redbeds do not appear to have formed *in situ*, and probably represent a different sediment source area in the east, rather than a different depositional setting.

3.3.7 Modern Analogues

Anastomosed river systems which cover broad, flat plains are uncommon in modern arid regions. Suitable analogies, however, can be obtained from Cooper's Creek in Central Australia (Rust, 1981). Cooper's Creek is a large, multi-channel, aggradational system in an area with a seasonally semi-arid to arid climate and very low gradient. The system is dry, except during major flood events. The floodplain is largely unvegetated, due to the arid climate. Bedforms are very similar to those found in the Hub Cyclothem: mostly planar cross-stratified and ripple cross-laminated sands; the channels switch by avulsion, rather than migration. Mudcracks and trackways (cattle) are common on the floodplain silts and muds; evaporites are present in some floodplain units, but are not ubiquitous. The principal cause of river anastomosis in Cooper's Creek is the very low gradient, combined with local zones with reduced gradient (Rust, 1981). Bank stabilization by vegetation, which is commonly cited as the cause of channel switching (rather than lateral migration) (Smith and Smith, 1980), may not be a major factor, as the banks are only partially vegetated. The banks may, however, have been partially stabilized by the carbonate-cemented floodplain sediments.

The Schaik system in the Rhine-Meuse delta, Netherlands, is an anastomosed river system which aggraded vertically in response to rising sea-level until about 5000 years ago (Tornqvist *et al.*, 1993). While it is not climatically analogous to the Hub Cyclothem anastomosing river system, it does have a similar tectonic (very quiet) and possibly eustatic (relative rise in sea-level) setting. Bank vegetation is not an important factor in the development of the anastomosed system (Tornqvist *et al.*, 1993).

3.4 Summary

Three facies assemblages comprise the Hub Cyclothem. The basal assemblage was deposited on a floodplain with meandering rivers; reotrophic peat swamps were common. The Assemblage 1 climate was wet throughout the year, with a minimal dry season; sea-level was stable. Assemblage 1 extends from the base of the Hub Seam and Cyclothem to the base of the lowest redbed or calcrete.

Assemblage 2 was deposited under the influence of a semi-arid climate with common subaerial conditions. Evaporation was greater than precipitation most of the time. A relative drop in sea-level may have occurred at the onset of calcrete formation. Assemblage 2 extends from the base of the lowest redbed, or calcrete, up to the top of the highest occurrence of red mudrocks (facies Mr).

Assemblage 3 was deposited by anastomosing rivers on an unvegetated floodplain. The climate was semi-arid and strongly seasonal. There may have been a rise in relative sea-level. Assemblage 3 extends from the top of the highest red mudrock (facies Mr), to the top of the Hub Cyclothem (the base of the seat-earth of the lowest split of the Bonar Coal seam).

CHAPTER 4

DEPOSITIONAL MODELS

4.0 Introduction

Because there is no unequivocal method for determining the relative state of sea-level during the deposition of the Hub Cyclothem strata, two depositional models are proposed and discussed in this chapter. In the first model, all depositional changes are explained in terms of climate change and autocyclic events. The second model incorporates effects of sea-level change. Throughout this chapter, unless stated otherwise, all references to sea-level change refer to relative changes in sea-level, because it is not possible to unequivocally differentiate between regional tectonic events and global eustatic events, with data solely from within the Hub Cyclothem. Relative changes in sea-level are defined as the net effects of eustatic events, tectonic events and changes in sediment supply. For instance, a drastic increase in sediment supply would tend to move the shoreline in a seaward direction, creating an effective drop in sea-level. Future correlations of the Hub Cyclothem with other cyclothems in the United States or Europe may help to resolve the relative importance of tectonism and eustacy, biostratigraphic resolution permitting.

Before presenting and discussing the models, it is necessary to evaluate the relative effects of allogenic and autogenic events.

4.1 Autocyclicity versus Allocyclicity

Before a depositional model for any set of strata can be derived, the relative effects of allogenic and autogenic forces must be evaluated. Although the differentiation between allogenic and autogenic forces in a sedimentary basin is a commonly discussed subject (e.g. Gibling and Bird, 1994; Cecil *et al.*, 1989; Read and Forsyth, 1989), there are no clear rules for distinguishing between the two. Allogenic events (those derived from causes outside the basin), such as climate change, regional tectonics and sea-level change, are all major events which affect the entire basin. Any allogenic events should, therefore, leave an expression in the Hub Cyclothem strata at the same time line across the basin. Autogenic effects (those derived from within the basin), such as channel switching, peat compaction and local tectonics are local events which probably occurred frequently during the deposition of the Hub Cyclothem strata and should occur at different stratigraphic levels in different parts of the basin; they will not be correlatable across the basin.

In this section, the various transitions which are common in the Hub strata will be evaluated to determine whether they result from autogenic or allogenic events. The transitions are divided into two groups: major transitions, which are the transitions from one assemblage to another; and minor transitions, between facies within each assemblage.

4.1.1 Allogenic Transitions

Assemblage transitions in the Hub Cyclothem are shown on Figure 3.1. In all cases, these transitions represent basinwide changes among drastically different depositional systems representing different climatic and possibly eustatic conditions. They are, therefore, allocyclic transitions; the specific allogenic factors affecting these transitions, such as tectonics, eustatic sea-level change and climate change, are discussed in later sections in this chapter.

Some of the facies transitions may also have been allogenically influenced. The thick coals which are present in the lower half of Assemblage 1 (2 m of coal in the Prince Mine, for instance), represent long periods of time (thousands of years) during which the peat swamps were in equilibrium with their environment. It is possible that allogenic events, such as sea-level fluctuations or climate changes stressed the swamps and hindered peat production; once peat production had slowed, peats became topographic lows and clastic deposition was initiated.

The upward transition from the calcrete to the red vertisols and grey mudrocks may also have been affected by allogenic forces (see section 3.2.4).

4.1.2 Autogenic Transitions

There are many different facies changes in each assemblage, each caused by either allogenic or autogenic effects, or a combination of both. These transitions are not correlatable across the basin, and are not obviously allogenic in nature. Certain features, such as the large channel incisions in Assemblage 1, may be attributed to either autocyclic channel switching, or a minor relative fall and subsequent rise in sea-level. The cessation of peat formation which led to the transition from coal to mudrock may be the result of a period of intense flooding, or may be the result of local ponding as the peat compacted.

Differential subsidence related to peat compaction is a likely cause of much of the channel switching in Assemblage 1. This mechanism has been invoked to explain deposition in other basins in the Westphalian (eg. the Warrior Basin; Gastaldo *et al.*, 1991). In the latter example, peat deposition continued over most of the basin, while river channels aggraded and migrated over small areas. Following deposition, the highly compressible peat zones subsided substantially, while the less compressible river channel sands did not subside significantly and became topographic highs. Eventually the river channels migrated or avulsed away from these topographic highs and into peat mires, which had become topographic lows. The abandoned river reaches, which became topographic highs were ideal sites for peat formation and became peat mires. Thus, an autocyclic pattern emerged in which peat mires naturally formed over old river systems, and river systems migrated to peat mires. As noted in the previous section, allogenic factors may have halted peat formation in the thicker peats (those which remained in equilibrium with their environment for thousands of years) before the autogenic forces were able to have an effect.

The large channel bodies in Assemblage 2 incised either in response to a sea-level fall or a drop in base level associated with a drying climate; the incision is, therefore, allogenic. Likewise, the calcrete in Assemblage 2 formed in response to a period of aridity.

The channel bodies in Assemblage 3 are interpreted to have an autocyclic component. The large number and small size of the channel bodies precludes the possibility that they incised and aggraded in response to extrabasinal effects. There were allogenic factors, however, which affected the autocyclic channel switching. Because the climate was seasonally arid, the overbank sediments were carbonate-cemented and inhibited lateral channel migration, which, in turn, contributed to the development of channel anastomosis.

4.2 Background to the Models

This section briefly summarizes the major features of the Hub Cyclothem which must be considered in a depositional model:

⇒ The Hub Cyclothem is composed of three facies assemblages, all of which are correlatable across the onshore part of the basin (about 60 km).

⇒ Each assemblage was deposited under unique depositional circumstances of climate and possibly sea-level.

⇒ Assemblage 1 was deposited under the influence of a humid, weakly-seasonal climate.

⇒ Assemblages 2 and 3 were deposited under the influence of seasonally arid climates.

⇒ Sediment supply during Assemblage 2 time was very low.

⇒ High intensity floods and long periods of drought were both common while Assemblage 3 strata were being deposited.

⇒ Both brackish-water and freshwater faunas are present in Assemblage 1.

⇒ Assemblages 2 and 3 contain no fossil flora.

⇒ Meandering river channels dominated during the deposition of Assemblage 1.

⇒ Anastomosing river channels dominated Assemblage 3.

⇒ Paleoflow directions are relatively constant across the basin within each assemblage.

⇒ All Assemblage 3 strata are carbonate-cemented.

⇒ The transition from Assemblage 3 to the Assemblage 1-type strata in the overlying Bonar Cyclothem is sharp.

⇒ Red strata are found in Assemblage 3 in the Glace Bay exposure and, to a lesser extent in the New Waterford exposure.

⇒ Black shales are present in the Assemblage 1 strata at Glace Bay. They are absent elsewhere.

⇒ Aside from the three major assemblages, the Hub Cyclothem strata cannot be correlated between outcrops, except where they are very close.

In the next two sections, the two depositional models (climate change and combined climate and sea-level change) are presented. In each case, a set of hypothetical causes and effects are presented; later in this chapter the two models are evaluated.

4.3 Model 1 - Climate Change Model

The transitions among and within the three assemblages can be explained solely in terms of climatic change and related autocyclic responses. In this section, a model is proposed which provides a depositional framework for the Hub Cyclothem under circumstances in which sea-level is either constant or distant from the exposed strata.

It is clear that local tectonic effects did not significantly affect the deposition of the Hub Cyclothem: paleocurrent directions are relatively constant, immature sediments are rare, there is no evidence of significant topography during deposition, and alluvial fan material is not present. There are, however, thickness variations in the Hub Cyclothem across the basin. These variations may be the result of either differential subsidence due to peat compaction, or local tectonic and compactional drape effects over basement structures. The Glace Bay area, in particular, may have been affected by basement effects (Gibling and Rust, 1990)

Cyclothem models which invoke only climate change have been proposed in the past for other basins (e.g. Beerbower, 1961; Cecil, 1990), and are effective in explaining the depositional environment of cyclothems deposited in terrestrial settings. Because there is evidence for a minor degree of marine influence in Assemblage 1 (brackish-water agglutinated foraminifera - see Chapters 2 and 3), the presence of the sea must be considered even if it is not a major driving force.

4.3.1 Assemblage 1

At the onset of Assemblage 1 deposition, the Sydney Basin was in an equatorial setting and had a weakly seasonal climate (humid conditions throughout most of the year). Extensive peat mires formed and were intersected by meandering river channels which spilled floodplain sediments over surrounding areas. Trees and plants were abundant on the floodplain and in the peat mires; root systems were well developed and extensive. Lakes formed in depressions created by peat compaction; lacustrine deltas prograded over the lakes. Siderite nodules formed in hydromorphic paleosols along roots and bedding planes.

These conditions led to the deposition of the extensive coals and rooted siltstones which dominate the lower part of Assemblage 1. The meandering rivers were often large and carried sediments as coarse as small pebbles which were deposited on point bars. Siderite nodules are a common early diagenetic feature in most of the non-coal strata. Fossil roots, leaves and tree trunks are all common, particularly in the lower half of the assemblage, where coals are more common.

The shoreline must have been nearby, as there are brackish water foraminifera in the coal seat-earths. Although the peat mires probably were not domed, clastic incursions did not preclude the formation of relatively thick and extensive peats. As in the modern Barataria Basin in the Mississippi Delta (Kosters, 1989), sediments periodically bypassed the peat mires, and areally extensive peats formed. Channels did, however, frequently spill sediments into the peat mires, creating the splits which are common in the Hub coals.

The Sydney Basin climate slowly dried during Assemblage 1 deposition. There is an upward decline in the abundance and thickness of coal seams, as well as a decrease in the abundance of rooted zones. Preserved tree trunks are found only in the lower parts of the assemblage, where large flood events deposited enough sediment in a short period of time to preserve upright tree trunks.

Throughout the deposition of Assemblage 1, marine incursions were common; flow in the river channels probably had an estuarine component. Both brackish-water foraminifera and fresh-water thecamoebians are present in the assemblage 1 strata.

Conditions were slightly different in the Glace Bay area (the most easterly of the exposed strata): the coals are shalier, and black shales with coprolites and fish scales are present. The black shales are not present elsewhere in the basin. The microfossil assemblages represent more marine conditions (see Chapters 2 and 3). The Glace Bay area was most likely topographically lower than the other exposed areas during Assemblage 1 deposition, and represents a site more proximal to the sea.

Strata at other levels in the Cumberland Group in the Glace Bay area were also deposited in deeper water conditions than their counterparts elsewhere in the basin. Hacquebard (1983) and Gibling and Wightman (1994) suggest that the Glace Bay area was a sub-basin within the Sydney Basin; it subsided faster than other parts of the basin, possibly in response to activity on basement blocks.

4.3.2 Assemblage 2

The shift from Assemblage 1 to Assemblage 2 deposition represents a drastic climatic shift from an everwet humid climate to a seasonally arid (dry for at least eight months each year) climate. Droughts often persisted for many years and the sediment supply was limited. Most of the floodplain was subaerially exposed during Assemblage 2 deposition. Drainage may have been limited to a few major drainage channels (facies CHc) which incised deeply through the floodplain. The major channels did not migrate laterally: except during major flood events, the channels were not filled to capacity. All the channels incised down through the calcrete, which acted as a barrier to lateral migration. Because there was little precipitation, vegetation was rare on the floodplain.

The transition from Assemblage 1 deposition to Assemblage 2 deposition was abrupt and represents an intensification of the drying trend which persisted throughout Assemblage 1 deposition. The upward transition from calcrete to mixed red and grey mudrocks may represent an increase in sediment supply in response to increased precipitation.

4.3.3 Assemblage 3

Following the deposition of Assemblage 2, the climate in the Sydney Basin grew wetter, but remained highly seasonal. Because precipitation fell only during a short rainy season, the floodplain remained unvegetated. During the rainy season, the unvegetated floodplain was eroded easily and streams carried large sediment loads as intense rains severely eroded the unprotected river banks in upland areas. During the dry season, the water table dropped and lakes drained. At the onset of the rainy season, new channels cut into the floodplain and carried large sediment loads eroded from the unvegetated floodplain and upland areas. As the lakes and channels filled with water and sediment, the water table (and base-level) rose. Eventually, the channels filled and either avulsed, or spilled over onto the floodplain. During the following dry season, base level fell again.

The channels did not migrate laterally to accommodate the large sediment loads, because the large sediment loads and low regional gradient created an effective base-level rise which made channel avulsion the preferred method of channel change. Anastomosis in many modern anastomosed river systems is attributed to either cohesive, vegetated floodplains which inhibit lateral migration, or to rises in base level (Tornqvist, 1993).

In central Australia, Cooper's Creek is a large complex of anastomosing river channels which avulse during the rainy season over a mostly unvegetated floodplain (Rust, 1981). Because the river is inland in a tectonically quiet area, eustatic and tectonic effects cannot cause a base level rise. Rather, the low gradient of the region, the larger sediment loads, and the small rise in the water table during the rainy season are responsible for the avulsive nature of the rivers.

4.4 Model 2 - Climate and sea-level change model

This model incorporates most of the features of the climate change model described above, but with the added effects of relative changes of sea-level. The relative changes may represent either regional tectonic effects, or eustatic sea-level changes. Because the exposures in the study area cover a relatively small area (about 30 km wide) and a small span of time (an estimated 200 000 years: Gibling and Bird, 1994), it is difficult to differentiate between eustatic and regional tectonic effects. In all cases in this section, therefore, any reference to sea-level change refers to relative changes in sea-level, which may be attributed to either eustatic or tectonic effects. Once again, the model will be presented in three sections, each one representing the depositional conditions responsible for a single assemblage.

4.4.1 Assemblage 1

The first facies assemblage was deposited under the influence of a climate which remained humid throughout most of the year, as described above. The shoreline was nearby and relatively stable: there were no significant incision events. Individual channel incisions may represent brief and minor sea-level falls; sea-level rebounded soon thereafter, however, and the channels filled. An overall, but minor, relative drop in sea-level was maintained throughout Assemblage 1 deposition, indicated by the upward decrease in the abundance of coal and brackish-water foraminifera.

4.4.2 Assemblage 2

Assemblage 2 deposition began when the climate had become dry enough to produce red vertisols. A relative fall in sea-level accompanied the climate change at the onset of Assemblage 2 deposition. Modern calcretes form only in areas which receive almost no sediment influx over a period of a few thousand years (Leeder, 1975; Tandon and Gibling, 1994). Either there was negligible flow through the basin while the calcrete was forming, or major paleovalleys incised and carried all of the flow out of the basin; unfortunately, however, none of these paleovalleys is currently exposed in the Hub Cyclothem. Following the formation of the calcrete (which represents the driest conditions reached during the deposition of the Hub Cyclothem), smaller valleys incised as much as 10 m through Assemblage 2 strata and filled very slowly with muddy and sandy sediments. These valleys incised in response to either a major flood event, or a smaller relative fall in sea-level. The valleys filled either as the shoreline prograded following the regression, or in response to a rise in base level during the subsequent transgression.

4.4.3 Assemblage 3

Assemblage 3 deposition began when sea-level began to rise and floods began to wash over the entire floodplain. Base level continued to rise throughout Assemblage 3 time, and the river channels were unable to carry their sediment or water loads. As a result, the channels aggraded rapidly and avulsed frequently to create the anastomosed river system. The dry climatic conditions also influenced the development of an anastomosed system because the rivers carried a very large sediment load during the wet seasons. During the dry season, conditions were similar to those discussed in the previous (climate only) model.

The Rhine-Meuse Delta in the Netherlands alternated between meandering and anastomosed river systems during the Holocene. The anastomosed systems formed as sea-level rose and cohesive bank material developed. In the Netherlands, clays and organic deposits form the cohesive bank materials (Tornqvist, 1993). In the Hub Cyclothem, the extensive carbonate-cemented channel deposits and floodplain silts probably acted as a cohesive bank and aided the development of an anastomosed river system.

Base level rise is commonly invoked as a mechanism in the development of anastomosed river systems (Tornqvist, 1993). The cause of the base level rise, however, is not always sea-level rise. Downstream channel blocking by eolian (Jacobberger, 1988) and alluvial (Smith and Smith, 1980) deposits can create an effective base level rise. In both cases, however, the blockage is limited to a single river system in a relatively confined area. In the Sydney Basin during the deposition of the Hub Cyclothem, the base level rise responsible for the fluvial transition occurred at the same stratigraphic level over an area 30 km wide. It is unlikely that downstream blocking could have changed the fluvial style over such an extensive area. Likewise, it is unlikely that the blockage would have persisted long enough to deposit 15 m of sediment. Therefore, it is most likely that sea-level rise was responsible for the base level rise.

4.4.4 Coincidence of Climate and Sea-level Change

In this second model, the onset of a seasonally arid climate is coincident with a relative fall in sea-level. The subsequent relative rise in sea-level (which led to the deposition of the CHc valley fills and all of Assemblage 3) preceded the change to an everwet humid climate (at the base of the Bonar coal seam in Assemblage 1-type strata). Relative change in sea-level is the most commonly invoked driving force in cyclothem models and most workers attribute the Carboniferous sea-level fluctuations to changes in Gondwanan ice extent (e.g. Maynard and Leeder, 1992). It is very likely that the climatic changes which drove the changes in ice volume were related to Milankovitch forcing, given the loosely defined time frame of cyclothem formation (Calder and Gibling, 1994). The climate changes, therefore, were global in scope. Because climate change drives the sea-level change, it is reasonable that the two occur at similar times. This broad coincidence of sea-level and climate changes has been inferred for other areas (Wanless and Shepard, 1936; Tandon and Gibling, 1994).

Lags between the onset of transgression and the shift from a seasonally arid climate to a humid climate have been suggested for Quaternary sediments in Australia (Nanson *et al.*, 1993). They note that arid conditions continued in continental interiors for at least 10 000 years following the onset of the Holocene transgression. A similar lag may have been in effect along the headwaters to the Shoalhaven River in Australia (which, being near the coast, is more analogous to the Hub Cyclothem than the examples from the continental interiors), where arid conditions persisted almost to the maximum level of the Holocene transgression (Nott and Price, 1991).

4.5 Discussion

4.5.1 Climate Change Model vs. Climate and Sea-level Change Model.

While both models adequately explain the vertical and horizontal variations in the Hub Cyclothem strata, the combined sea-level and climate change model is more consistent with models proposed for other cyclothems in the Sydney Basin and the American Midwest, and addresses the occurrence of estuarine biota. Studies of Quaternary sediments throughout the world also show that coincident climatic and eustatic changes are common (Nanson *et al.*, 1992).

In the Backpit Cyclothem, also in the Sydney Mines Formation, paleosol assemblages have been used in conjunction with foraminiferal assemblages to document concurrent climate and sea-level changes (Tandon and Gibling, 1994). Other cyclothems within the Sydney Mines Formation have been interpreted primarily in terms of relative changes in sea-level, using foraminiferal assemblages (e.g. Gibling and Wightman, 1994; Wightman *et al.*, 1994). Because other cyclothems in the Sydney Mines Formation, both above and below the Hub Cyclothem were deposited as sea-level varied, it is likely that relative changes in sea-level were, in fact, a major factor in the deposition of the Hub Cyclothem.

Cyclothems in other basins have been widely documented (see Riegel, 1991 for a review). In many cases, sea-level change has been invoked as the dominant driving force. Because the cyclothems are often marine, or coastal, relative sea-level changes may be clearly documented. Although climate changes are not often documented (their effects are difficult to distinguish in marine sections), cyclical climate change (caused by eccentricities in the Earth's orbit) is often cited as the driving force behind the periodic sea-level changes (Cecil, 1990; Calder, 1994).

4.5.2 Tectonics versus Eustatic Sea-Level Change.

Although both models discount local tectonic effects, episodic regional tectonism cannot be discounted: it is very difficult to discriminate between regional tectonism and eustatic sea-level change without inter-regional correlations. The basin was subsiding during the Westphalian; this subsidence was steady, although episodes of increased or decreased subsidence may have occurred. Gibling and Bird (1994) have calculated a subsidence rate of 15 m per 10^5 yr for Westphalian D strata near Sydney (using the time scale of Lippolt and Hess, 1985). Local tectonic effects, however, such as faulting, folding and tilting have distinctive effects, none of which are recorded in the Hub Cyclothem.

Previous workers have similarly concluded that most of the faults within the Sydney Basin were tectonically quiescent during Westphalian D to Stephanian time (Rust *et al.*, 1987; Langdon and Hall, 1994). However, the Cabot Fault, the Hollow Fault, the St. George's Bay Fault and the Mid-bay Fault were all active at that time and may have had regional-scale effects on the Sydney Basin (Langdon and Hall, 1994).

The basin bounding faults were, however, probably active and controlled the subsidence of the basin. Faults in the Glace Bay area were probably more active than those elsewhere in the basin, as indicated by the increased subsidence in that area. Increased fault movement near the Glace Bay area could also have led to more intense uplift and erosion of the local upland regions; this may explain why there was a red source area in the uplands (to provide sediment to the SLr siltstones) in the Glace Bay area, but not elsewhere in the basin.

It is possible, however, to speculate on the relative importance of eustatic and regional tectonic effects (Heckel, 1984; Leeder, 1989; Klein and Kupperman, 1992; Klein, 1993). The cyclothems in the Sydney Mines Formation represent a repetitive cyclical depositional pattern; cyclothem thicknesses are relatively constant, although there is a general upward increase in thickness through the formation (Gibling and Bird, 1994). Milankovitch driven glacio-eutstatic sea-level changes would be expected to produce a regularly cyclical sedimentary pattern. Conversely, tectonic effects are more likely to produce a more irregular pattern of sedimentation (Calder, 1991).

During the Westphalian D and Stephanian, when the Sydney Mines Formation was being deposited, Gondwanan glacial conditions were repeatedly waxing and waning. At that time sea-level fluctuated by 50 to 100 m in response to glacial advances and retreats (Crowley and Baum, 1991; Maynard and Leeder, 1992). Because large-scale eustatic sea-level changes were common while the Hub Cyclothem strata were being deposited, it is likely that eustatic elements are the primary component of the relative changes in sea-level at that time.

4.5.3 Termination of Peat Formation

The autogenic model for peat termination described in sections 4.3.1 and 4.4.1 applies well for the thin coal splits which constitute most of the coal in the Hub Cyclothem. Near the base of Assemblage 1, however, thicker coals are present. In the Prince Mine, for instance, the coal is about 2 m thick. Using a compaction ratio of 5:1 (Ryer and Langer, 1980), and a peat accumulation rate of 2 mm/year (Cecil *et al.*, 1993; Calder, 1994), the 2 m coal represents 10 000 years of deposition. Calder (1994) and Calder and Gibling (1994) suggest that thick peats, which represent long periods of time, were in equilibrium with their environment, and allogenic factors must have disrupted this balance before clastic depositional processes could become dominant. They suggest that a shift in climate, possibly in response to short term Milankovitch cycles (precession-related), would disrupt the equilibrium of the peat mire with its environment and allow the autogenic processes of peat compaction and channel migration to take effect.

Although this model may explain the demise of some of the thicker splits of the Hub coal seam (such as the 2 m split in the Prince Mine), the highly split nature of the Hub coal seam suggests that other factors may have been more significant. Calder and Gibling's (1994) model is based on coals in the Cumberland Basin (Calder, 1994) and coals in the North American midcontinent (Udden, 1912; Wanless and Weller, 1932), which are relatively thick and have few splits; distinctly different facies (such as limestones) overlie the coal seams. The Hub seam, however is extensively split at most exposures, and the thick occurrences of it are only present at a few locations (see Appendix B). As well, thin splits of the Hub seam are present throughout Assemblage 1, suggesting that the demise of peat forming environments was a gradual process. This argues for a different model for peat termination. Perhaps conditions during the formation of the Hub peats were slightly too seasonal for the peat swamps to reach full equilibrium with their environment. If the peat swamps were somewhat stressed at all times, peat formation could have been locally terminated during major storm events; the thick splits of the Hub seam represent areas which resisted termination for a long period of time. These areas with thick peats may have survived because they were in locations which were more conducive to peat formation (micro-climatic variations within the basin may have been responsible), or in areas which were not affected during major storms (distant from major channels). It is clear, however, that conditions became less suitable for thick peat accumulation throughout the deposition of Assemblage 1. This may be a response to the allogenic factors described in the previous paragraph, or a response to gradually falling base-level as the shoreline prograded.

4.5.4 Time and Milankovitch Orbital Cycles

The average duration of a Sydney Mines Formation cyclothem is about 200 000 years (Gibling and Bird, 1994); other cyclothems have similar average durations (Heckel, 1986), despite large variations among time scales used (Calder, 1994). Because the cyclothems may have formed in response to regularly repeated climate and sea-level changes, many workers cite Milankovitch orbital cycles as the controlling factor responsible for the changes (Heckel, 1986; Leeder, 1988; Gibling and Bird, 1994); in particular, they cite the long cycles of orbital eccentricity (which have periodicities in the order of 10^5 years; Berger, 1977).

The climatic and eustatic changes which may have been responsible for the deposition of the Hub Cyclothem were probably predominantly caused by the long cycles of eccentricity of the Earth's orbit, based on the time scale of cyclothem deposition. A single cycle through the eccentricity of the Earth's orbit probably caused the shift from a low seasonality humid climate to a seasonally semi-arid climate and then back to a low seasonality humid climate. However, the eccentricities in the Earth's orbit are very gradual, and would probably cause gradual climatic and eustatic changes; the evidence in the Hub Cyclothem suggests that the climatic changes, in particular, occurred over very short time spans. Perhaps shorter term climatic changes were caused by precession-related Milankovitch cycles which have a much shorter time frame (in the order of 10^4 years; Berger, 1977; Collier *et al.*, 1990). The gradual upward decrease in the thickness and abundance of coal splits through Assemblage 1 is probably related to eccentricity changes. Thick splits, such as the 2 m split in the Prince Mine, however, occur only at the base of the cyclothem. Conditions suitable for long term peat accumulation began suddenly when the climate shifted from seasonally semi-arid to humid at the onset of Hub coal formation and may have ended suddenly early during the deposition of Assemblage 1; this sharply bounded time for thick peat accumulation may have been caused by the superposition of eccentricity-related and precession-related effects. Likewise, the rapid transition from a humid climate to a semi-arid climate at the onset of Assemblage 2 deposition, and the termination of calcrete formation (in response to increased sediment influx) may also have been related to the superposition of eccentricity-related and precession-related effects.

The major climatic and possible eustatic changes recorded in the Hub Cyclothem strata may have been caused primarily by cyclic changes in the eccentricity of the Earth's orbit. The sedimentological changes observed, however, are not gradational. The effects of orbital precession may have alternately worked in conjunction and in opposition to the effects of orbital eccentricity; the net effect would be periods without climatic change (when the precessional effects worked in opposition to the eccentricity effects) punctuated by rapid climatic change (when precessional effects worked in harmony with eccentricity effects).

4.5.5 Assemblage 3 Red Strata

Assemblage 3 redbeds are abundant in the Glace Bay exposure and are also present in the New Waterford exposure. These redbeds differ from Assemblage 2 redbeds in that they did not form *in situ*, and do not necessarily represent arid conditions. Rather, they suggest that the source area for the Assemblage 3 strata was different in the west than in the east. Iron-rich volcanic rocks (which weather to red sands and silts) may have formed the eastern flank of the Sydney Basin during Hub Cyclothem deposition (Gibling *et al.*, 1987). The western flank of the basin was dominated by granitic rocks which are less prone to reddening. Some may also have come from the erosion of Assemblage 2 redbeds or other red strata in upland regions.

The transported redbeds are not present, however, in Assemblage 1 or 2 strata. During Assemblage 1 deposition, the climate was humid through most of the year and upland regions may have been vegetated and less actively eroding.

During Assemblage 2 deposition, the river channels probably carried most of the sediment past the exposed part of the basin and deposited them in more distal areas; they are not, therefore, present in the modern Assemblage 2 exposures; this is particularly likely if there was a relative drop in sea-level during Assemblage 2 deposition.

The transgressive, or sediment clogging effects which were active during Assemblage 3 deposition would have been conducive to the deposition of transported red sediments. In general, the transported red sediments are finer and less dense than the quartz and feldspar sands which were deposited in the Assemblage 1 channels. They would, therefore, only be deposited when the channels were dumping their finer sediments: a condition which existed whenever the Assemblage 3 channels breached their banks.

4.5.6 Relevance to Cyclothem Studies

Although the importance of eustatic sea-level change and climate change in cyclothem formation is gaining general acceptance, autocyclic events, primarily delta-lobe switching, are still most commonly cited as being the driving forces behind clastic cyclothem formation (e.g. Ferm, 1970). This study of the Hub Cyclothem (a clastic cyclothem) indicates that allocyclic processes are active in the formation of some clastic cyclothems, and that the coals and paleosols in them are a response to global events such as sea-level change and climate change.

4.6 Summary.

The depositional patterns in the Hub Cyclothem may best be explained in terms either of climate change, or a combination of climate and sea-level change.

Assemblage 1 strata were deposited in a weakly seasonal, humid climate. Assemblage 2 strata were deposited in a semi-arid, seasonal climate. The Assemblage 3 climate was also semi-arid, but with a pronounced rainy season.

A relative fall in sea-level probably occurred at the onset of Assemblage 2 deposition; during Assemblage 2 deposition, most of the drainage from the basin may have been carried through large paleovalleys (although none are currently exposed). Sea-level rose throughout Assemblage 3 deposition. It is likely that the relative changes in sea-level were eustatic in origin, and related to Milankovitch driven changes in Gondwanan ice extent.

The second depositional model, which incorporates both climate change and relative changes in sea-level, better explains the depositional conditions which led to the formation of the Hub Cyclothem. It is more consistent with models for other cyclothems in the Sydney Mines Formation, and other Carboniferous cyclothems worldwide.

The time frame of Hub Cyclothem deposition (about 200 000 years; Gibling and Bird, 1994) suggests that long term Milankovitch cycles (related to eccentricities in the Earth's orbit) caused the climatic and eustatic changes which may have been responsible for the depositional patterns in the Hub Cyclothem. Shorter term Milankovitch cycles (related to precessional changes in the Earth's orbit) may have alternately worked in harmony with and opposition to the eccentricity-related cycles to create the sudden climatic and eustatic changes suggested by the depositional patterns in the Hub Cyclothem.

CHAPTER 5

SEQUENCE STRATIGRAPHY

5.0 Introduction

Sequence stratigraphy is widely used to model and interpret stratigraphic successions, primarily in nearshore and deltaic areas. Using the models developed in Chapter 4, the Hub Cyclothem can be placed in a sequence stratigraphic context. In a sequence stratigraphic framework, the Hub Cyclothem is an excellent analogue for stratigraphic successions in the subsurface of hydrocarbon-charged basins.

Sequence stratigraphic models, as developed by the Exxon Group (Van Wagoner *et al.*, 1988), are based on the identification of three distinct types of bounding surface: the maximum flooding surface, the transgressive surface, and the sequence boundary. These three surfaces bound three systems tracts: the highstand, lowstand, and transgressive systems tracts (Van Wagoner *et al.*, 1988). Many good reviews of sequence stratigraphic concepts can be found in the literature (e.g. Wilgus, *et al.*, 1988; Galloway, 1989; Walker, 1992). Figure 5.1 is a cross-section through the Sydney Basin with each of the major surfaces and systems tracts indicated. The sequence stratigraphic units used in the Exxon models were defined using seismic records in a proximal to distal basinal section of considerable length. Their identification, however, is difficult in exposures along a transverse basinal section, as in this study. Each of the surfaces and its relevance to the Hub Cyclothem is discussed below.

5.1 Maximum Flooding Surface

In sequence stratigraphy, the maximum flooding surface (which often lies within a condensed section) represents the maximum rate of sea-level rise. It separates the transgressive systems tract from the overlying highstand systems tract (Van Wagoner *et al.*, 1988). In the Hub Cyclothem, the top of the lowest (and usually thickest) split of the

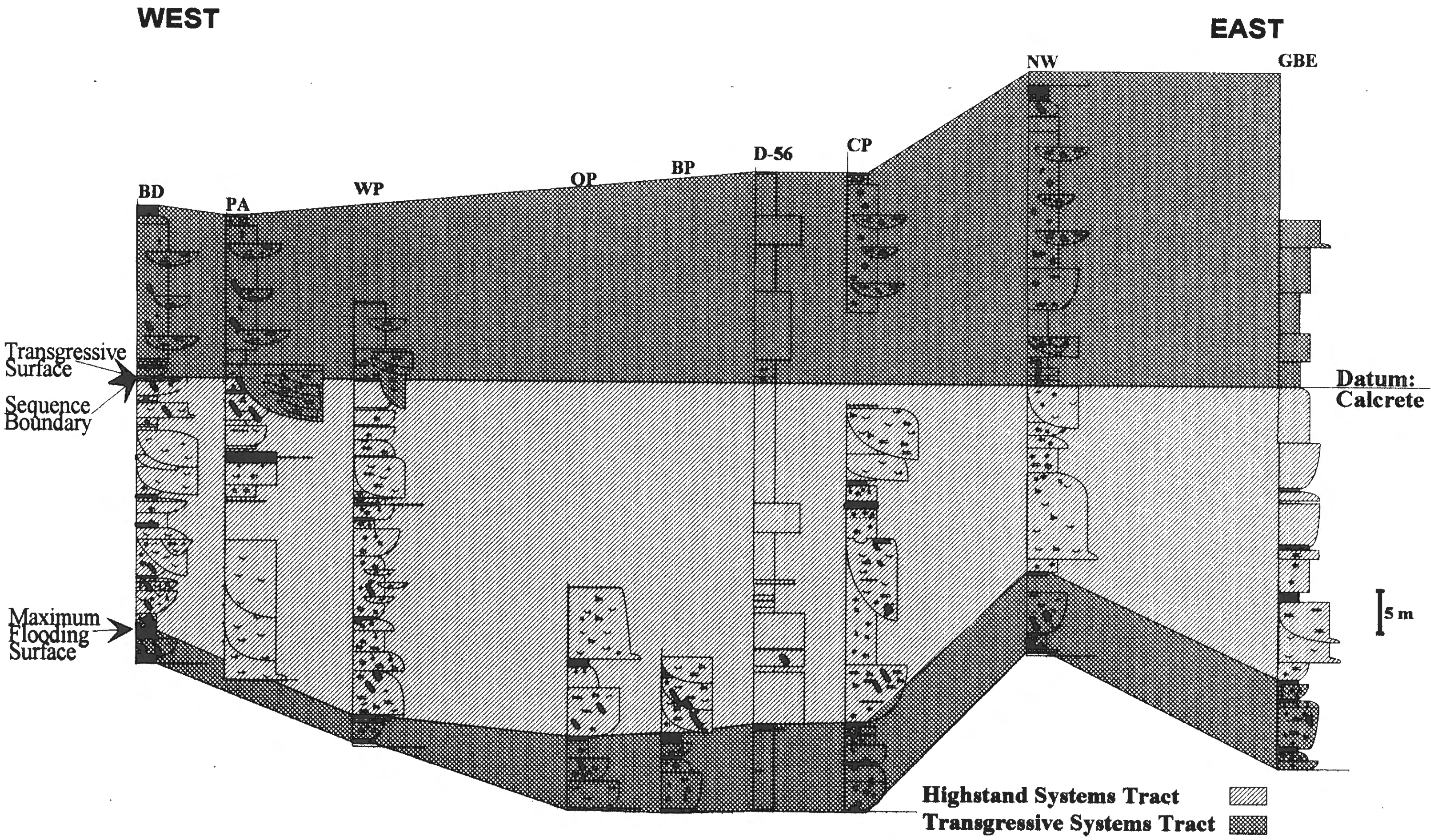


Figure 5.1. Sequence stratigraphic interpretation of the Hub Cyclothem. The maximum flooding surface lies at the top of the lowest major split of the Hub coal seam. The sequence boundary and the Transgressive Surface are coincident at the top of the calcrete. There is no lowstand systems tract in the Hub Cyclothem. The same outcrop sections are used in Figure 3.1.

Hub seam can be interpreted as the maximum flooding surface, and most of the Assemblage 1 strata can be assigned to a highstand systems tract.

This interpretation is, however, not as straightforward as it is in fully marine zones (where sequence stratigraphic models were developed). The maximum flooding surface is usually found in a condensed section, which is a thin, but extensive marine black shale with a distinct marine fauna. The strata of the Hub Cyclothem lie too far inland for the development of open-marine conditions, even during the highest transgression; the location of the maximum flooding surface must, therefore, be inferred in other ways. The strata below the Hub seam are similar to those in Assemblage 3 of the Hub Cyclothem, which were probably deposited during a relative rise in sea-level, and consequently lie below the maximum flooding surface, in the transgressive systems tract. The strata within Assemblage 1 were deposited during a sea-level highstand, with a higher degree of marine influence than the other assemblages. The maximum flooding surface must lie between these two zones. The most reasonable placement for the maximum flooding surface is at the top of the lowest split of the Hub seam, because this represents the time at which the peat mire was flooded. The same conclusion was reached for Sydney Mines Formation cyclothems in general by Gibling and Bird (1994). Banerjee (1994) reached a similar conclusion for the maximum flooding surface in Manville Group coals in Alberta. Kosters and Suter (1993) provide a modern example from the Mississippi Delta; they found that the thickest peats occur behind the shorelines formed at maximum transgression.

5.2 Sequence Boundary

In sequence stratigraphy, the sequence boundary separates a highstand systems tract from an overlying lowstand or transgressive systems tract. It represents the time at which sea-level fell significantly, and formed a regionally extensive erosional surface. Accompanying the unconformity are a basinward shift in facies, stream rejuvenation and a downward shift in coastal onlap (van Wagoner *et al.*, 1988). Because all the Hub Cyclothem strata were deposited in brackish and fresh-water settings, the sequence boundary is demarked by large channel incisions and extensive subaerial exposure.

The top of the calcrete is the sequence boundary in the Hub Cyclothem. It is the most distinctive indicator of extensive subaerial exposure in the cyclothem. Major paleovalleys may have incised in response to this relative fall in sea-level; these paleovalleys are, however, hypothetical, as none are currently exposed in the Hub Cyclothem outcrops.

5.3 Transgressive Surface

The transgressive surface is often difficult to identify unequivocally. In fully marine sections, benthic faunas may indicate deepening conditions. In coastal sections, a ravinement surface may lie near the transgressive surface; the ravinement surface, however, represents the movement of a coastline in a landward direction during a transgression, rather than the onset of transgression (van Wagoner *et al.*, 1988). In marginal marine to terrestrial successions, such as the Hub Cyclothem, the transgressive surface is often virtually coincident with the sequence boundary, because the lowstand systems tract was not deposited. During a lowstand, sediments tend to bypass coastal zones, which are either in an erosional regime, or are sediment bypass areas; in either case, no stratigraphic record is preserved (Posamentier and Vail, 1988).

Following calcrete formation, sedimentation was renewed and the red and grey mudrocks were deposited. Any paleovalleys which may have incised when sea-level fell would have filled during the transgression (and possibly during the lowstand as well). The sediments above the calcrete, therefore, belong in the transgressive systems tract, and the transgressive surface must be placed at the top of the calcrete. The bed above the calcrete at Bras d'Or (sample PA45 on Figure 2.2 and Table 2.3), contains brackish-water foraminifera (*Trochammina*), suggesting that the transgression began either during, or very soon after the calcrete was deposited.

5.4 Highstand Systems Tract

Most sequence stratigraphic models assume that the basin subsides at a steady rate. During the deposition of the highstand systems tract, sediment influx will either exceed, match, or be less than the rate at which accommodation space is created due to subsidence. The resulting shoreline will either prograde, remain stable, or retrograde; the shoreline must not, however, retrograde beyond its position at the time of maximum flooding, otherwise, the retrogradational surface is, by definition, the maximum flooding surface, and all underlying strata are part of the transgressive systems tract (Posamentier and Vail, 1988). The highstand systems tract in the Hub Cyclothem extends from the top of the thickest lower split of the Hub coal seam to the top of the calcrete, and shows a gradual upward decrease in the abundance of brackish water foraminifera, suggesting that the shoreline was prograding into the basin during the highstand. This may have been accompanied by gradual climatic drying.

5.5 Lowstand Systems Tract

During a lowstand, deposition continues in deeper parts of a basin, but may stop in more landward areas (Suter and Berryhill, 1985; Tesson *et al.*, 1990; Allen and Posamentier, 1993). Because the Hub Cyclothem strata are relatively proximal, there was no significant deposition during the lowstand period. The calcrete formed, in part, during the lowstand. Because calcrete formation is a diagenetic, rather than depositional phenomenon, the calcrete is placed in the highstand systems tract. There is, therefore, no lowstand systems tract in the Hub Cyclothem.

The Gironde Estuary in France was subjected to a fall and rise in sea-level during the Holocene (Allen and Posamentier, 1993). The lowstand systems tract in the Gironde Estuary is very thin (a few metres thick at the most) in landward areas, and may be locally absent. During the lowstand, sediments were deposited rapidly in nearshore areas; progradation up the estuary, however, was very slow and most of the landward areas did not aggrade during the lowstand.

5.6 Transgressive Systems Tract

In the Hub Cyclothem, all strata between the top of the calcrete and the top of the basal split of the Hub coal seam comprise the transgressive systems tract. The rising sea-level forced the streams to rapidly aggrade and avulse, creating the anastomosed river complex found in Assemblage 3. At the onset of the transgression, however, base level was very low, and the Assemblage 2 paleovalleys (facies CHc, and any of the proposed paleovalleys) provided ample accommodation space for sedimentation as base level rose. The anastomosed river system (Assemblage 3) formed when sea-level had risen to the point where the paleovalleys (facies CHc) had been filled and the whole floodplain was frequently flooded.

5.7 Discussion

The Hub Cyclothem does not fit into standard sequence stratigraphic models, which were developed for marine strata, because the more proximal and distal portions of the strata are not exposed. This model can, however, be used as a predictive framework for interpreting offshore seismic and drill information when it becomes available.

The facies assemblages and systems tracts do not coincide perfectly in the Hub Cyclothem. The maximum flooding surface lies slightly above the base of Assemblage 1; the transgressive surface lies slightly above the base of Assemblage 2 (at the top of the calcrete); the sequence boundary is virtually coincident with the transgressive surface. These small discrepancies suggest that climate rather than relative change in sea-level was the dominant force controlling sedimentary patterns during the deposition of the Hub Cyclothem strata.

5.8 Summary

Because sea-level change was a significant influence during the deposition of the Hub Cyclothem, the cyclothem can be placed in a sequence stratigraphic framework. The sequence boundary lies at the top of the calcrete in Assemblage 2. The transgressive surface also lies at the top of the calcrete, less than 1 m above the sequence boundary. The top of the lowest split of the Hub coal seam is the maximum flooding surface.

Most of Assemblage 1 and all of Assemblage 2 below the top of the calcrete comprise the highstand systems tract. The lowstand systems tract is absent. The remainder of Assemblage 2, all of the Assemblage 3 strata and the basal split of the Hub coal seam comprise the transgressive systems tract.

CHAPTER 6

ECONOMIC SIGNIFICANCE

6.0 Introduction

The Hub Cyclothem is economically relevant in two ways, one proven and one potential. The coals in the cyclothem have a direct economic significance: the Hub seam is currently being mined in the Prince Mine near Point Aconi. The cyclothem as a whole, however, is an excellent analogue for fluvial and valley-fill deposits in hydrocarbon-charged basins. In this chapter, both economic aspects of the Hub Cyclothem are discussed.

6.1 Coal

The Hub seam has been studied previously, and is reasonably well understood (e.g. Nova Scotia Department of Mines and Energy, 1987; Birk and White, 1991; Hacquebard, 1993; Marchioni *et al.*, 1994). The Prince Mine, near Point Aconi, is the only actively producing mine on the Hub seam, and one of the two largest coal mines in Nova Scotia. The Hub seam has been mined elsewhere in the basin in the past; as well, bucket and wheelbarrow coal collection is currently common along the coastal exposures as local residents collect coal for their furnaces. The Hub seam comprises high sulphur (2.5 to 6.2%) and low ash (5-9%) high volatile A coal (Hacquebard, 1993).

The foraminifera in the coal zone (Table 2.3) indicate that the coals were deposited in a brackish-water setting; this is consistent with the high sulphur levels in the coals (Hacquebard and Donaldson, 1969; Birk and White, 1991; Gibling *et al.*, 1989). Marchioni *et al.* (1994) came to a similar conclusion based on the presence of moderate amounts of pyrite in the coal seams; pyrite is especially common near the tops and bases of the coal splits, which are zones representing high water levels (Marchioni *et al.*, 1994).

The thickest splits of the Hub coal seam are near the base of the Hub Cyclothem; the thickness of the splits decreases upward through the cyclothem. Exploration drill holes should extend through the entire Hub Cyclothem and terminate in the carbonate-cemented strata which underlie the lowest split of the Hub coal. The red mudrocks which lie a few metres below the base of the Hub coal can be easily used as a marker below the coal zone.

The meandering channel bodies (facies CHp and CHs) which incise locally through the coal seams present difficulties in the underground mining operations where the automatic machinery contacts the sandstone bodies (Forgeron, 1980). This problem will be present in any underground mine of the Hub seam. The only way to truly determine the location and extent of channel bodies over the coal seam is through drilling; the spacing between drill holes must not exceed the minimum width of the channel fills (at least 100 m in this study). The pebbly meandering channel fills (facies CHp) are more likely than the sandy meandering channel fills (facies CHs) to incise through the coals and extra care should be taken to locate any pebbly channel fills in mining areas. Both types of meandering channel fills are highly sinuous (paleocurrent directions vary through about 200°), but trend northeasterly overall.

Prediction of the mud filled hollows which disrupt mining operations in the Prince Mine (see Chapter 1) is very important, as the hollows reduce the economic viability of the mine. This study does not, however, provide new insight into the nature of the hollows, as they were not identified in the coastal outcrops. It is likely that they represent ponds which may have formed in the peat swamps following major storm events (see section 4.5.3). Unless the streams feeding these ponds can be traced through the roof strata in the Hub, the prediction of the mud filled hollows will remain difficult.

Marker beds in the Hub Cyclothem are rare. At the scale of mine geology, however, there are certain beds which could act as a datum. The clearest datum in the cyclothem is the calcrete horizon; it, unfortunately, lies more than 20 m above the coals, which is higher than most of the drill holes in the mine extend. Many of the coarsening-up bodies (facies Gcu) are correlatable over distances in excess of a few kilometres, and could act as good marker beds above the coals. The red mudrocks which lie a few metres below the Hub coal zone would make distinctive and clear marker beds. Few drill holes, however, are drilled down from mining operations.

No new mining areas for the Hub seam were identified during the research for this thesis. Potential mines, however, may exist either inland, or under the ocean. The Hub seam thickness varies greatly between outcrops. Although many exploration holes have been drilled in the past, areas still exist where thick Hub seam strata may exist. The extensive splitting of the Hub seam is an important factor in the exploration for new mines in the Hub seam. Bras d'Or, Oxford Point and New Waterford areas appear to have the thickest basal splits and the least degree of splitting.

6.2 Hydrocarbon Potential

There is very little history of oil exploration or occurrences in the Sydney Mines Formation: a few litres of aromatic hydrocarbons seeped from sandstones in the roof strata of the Phalen Mine on the Harbour seam in 1993, and again in 1994, releasing noxious fumes into the mine atmosphere (John Calder, Nova Scotia Department of Natural Resources, personal communication, 1995). In many ways, however, the Hub Cyclothem represents an excellent exploration target, and can be used as an analogue for terrestrial floodplain deposits in the subsurface of hydrocarbon-charged basins. In order to have an attractive exploration play, four features must be present: a suitable reservoir rock, an effective seal (cap rock), confirmed source potential and favorable thermal history.

6.2.1 Reservoir Rocks.

The CHp channel bodies are excellent reservoir rocks: they have good porosity, and tend to be thick (up to 15 m in multistoried bodies) and extensive (more than 200 m wide and many kilometres long). The CHs channel bodies are less ideal reservoirs, because their porosity appears to be lower, and because they contain more clay material, which can cause problems during enhanced recovery (the solvents used in enhanced recovery often react with clays). Although some of the splay and bayfill bodies have good porosity, they are too thin to be good reservoir rocks.

Because of their close association to the coal seams, the meandering channel fills (facies CHs and CHp) are probably suitable reservoirs for coalbed methane. The channel bodies at the Oxford Point and Black Point exposures are probably the best suited for coalbed methane exploration, because they are thick channel fills which are directly juxtaposed against relatively thick coals (Figure 3.2). Additionally, coalbed methane may be found chemically packed into the coal seams.

The CHc channel bodies in Assemblage 2 are poor reservoir rocks, because of the high abundance of siltstone and mudrock, and because the sandstone bodies are small and lack interconnectedness. They hypothetical major paleovalley fills in the Hub Cyclothem, which may incise down from the level of the calcrete. Paleovalley fills, up to 20 m thick, have been identified in other Sydney Mines Formation cyclothems (Gibling and Bird, 1994); they are filled with fine and medium grained sandstone, and could be excellent reservoir rocks if they had an appropriate cap rock and source bed. It may be possible to locate the Hub Cyclothem paleovalley fills using seismic reflection profiling methods.

The CHu channel bodies in Assemblage 3 are also poor reservoirs because the extensive early carbonate cements filled in the porosity before hydrocarbons could migrate into the pore spaces.

6.2.2 Cap Rocks.

The muds in Assemblage 1, which enclose the CHp and CHs channel fills, are good barriers to hydrocarbon migration. Channel fills are usually good stratigraphic traps, because they are fully enclosed in relatively impermeable floodplain materials. The carbonate-cemented strata in Assemblage 3 might also make an excellent cap zone which would deter hydrocarbon migration out of the lower strata in the cyclothem.

6.2.3 Source Rocks.

The black shales in Glace Bay have good source potential: they contain type I kerogen and have oil and gas potentials between 29.9 and 172.11 kg of hydrocarbon per tonne of shale (see Chapter 2). Unfortunately, they are thin (about 30 to 60 cm thick); thicker beds may, however, lie offshore in more basinal areas.

The Hub Coal seam has not been analyzed for hydrocarbon potential. Rock Eval data for dull bands in the Harbour seam (less than 100 m below the Hub seam) in the Glace Bay area show that the bands contain type I or II kerogen and could be good hydrocarbon source rock if they were thicker (Gibling and Kalkreuth, 1991). Marchioni *et al.* (1994) also analyzed Harbour seam dull bands at Glace Bay. They found that the oil and gas potential (less than 30 mg of hydrocarbon per gram of organic carbon) of the dull bands is very low; they, therefore, have very little potential to produce oil. Because it contains a smaller proportion of dull bands than the Harbour seam, the Hub seam is even less likely to produce oil.

Marchioni *et al.* (1994) analyzed five samples from the Hub seam in the Prince Mine, near Point Aconi. They found that the Hub seam contains an average of 82% vitrinite (range from 81 to 83%), 11% inertinite (range from 3 to 13%) and 8% liptinite (range from 6 to 15%); they noted that very thin bands with up to 30% inertinite and up to

25% liptinite occur throughout the seam; they do not, however, constitute a significant proportion of the seam volume. It is the liptinite bands which have the highest oil potential of the macerals (Marchioni *et al.*, 1994).

Much better source rocks are present in Sydney Mines Formation equivalents in other parts of the Maritimes Basin, particularly under the Gulf of St. Lawrence (Wightman *et al.*, 1994). Similar source rocks may lie in the offshore areas of the Sydney Basin.

6.2.4 Thermal Maturation

The Hub seam coals have vitrinite reflectance values of approximately 0.75 %Ro in the western part of the basin (where they are classed as high volatile A bituminous), and values of approximately 0.85 %Ro near Glace Bay, and at depth (where they are classed as medium volatile bituminous; Hacquebard, 1993). These reflectance values indicate that the organic matter in the Hub coals is in the peak maturity zone for oil production, and well into the gas production window, as well (Dow, 1977; Bustin *et al.*, 1985). They are also at a suitable level of maturity for coalbed methane production.

6.2.5 Summary

The Hub Cyclothem contains some excellent stratal associations which could be effective stratigraphic traps for conventional oil and gas if buried in a hydrocarbon charged basin. Although the source rocks in the exposed part of the basin are subeconomic, better source rocks may lie offshore, making the Sydney Mines Formation a possible exploration target. Very little petroleum exploration drilling has been done in the basin; two holes were drilled on a basement high, but did not intersect any economic oil or gas zones (Gibling, *et al.*, 1987). The data presently available are not adequate to asses the hydrocarbon potential of the Sydney Basin.

The Hub Cyclothem may be a promising exploration target for coalbed methane, however, as there are thick channel fills in close association with the coals. The coals are at a suitable level of thermal maturity for coalbed methane production.

The Hub Cyclothem is an excellent analogue for floodplain hydrocarbon plays in other basins. The Manville Formation, for instance, in the Western Canada Sedimentary Basin, contains numerous river and valley fill stratigraphic oil and gas traps (Wood and Hopkins, 1992), but has poor exposures at surface; the depositional models from the Hub Cyclothem could help to further develop models in Manville fields.

6.3 Conclusions

Within the Sydney Basin, the Hub seam may be a source for future mines. Because the Hub seam thickness varies greatly over relatively short distances, detailed exploration will, however, be required. The thickest coals with the least degree of splitting can be found near the Bras d'Or, Oxford Point, and New Waterford exposures.

Coalbed methane associated with the Hub seam may also be a viable exploration target, as there are suitable reservoir rocks in close association with coal seams. The channel fills near Black Point and Oxford Point are particularly attractive targets.

The Hub Cyclothem contains effective reservoir and cap rocks for potential petroleum reservoirs. Effective, but thin source beds are exposed at Glace Bay; although the dull bands in the coal seams have better source characteristics than most coal seams, they are not abundant enough to act as an economic source. Better source beds may lie offshore. Overall, the Hub Cyclothem has poor oil and gas potential, except in the offshore, where better source rocks may be present.

The Hub Cyclothem as a whole is a useful analogue for oil and gas bearing valley fill and river deposits in other sedimentary basins.

CHAPTER 7

CONCLUSIONS

The Hub Cyclothem, in the coal-bearing Sydney Mines Formation, is extensively exposed in coastal exposures, along approximately 30 km of depositional strike. It provides an excellent study area in which to document the impacts of climate and sea-level change on floodplain deposits. The following points summarize the main conclusions of this thesis:

1. The Hub Cyclothem is best divided into three facies assemblages, all of which are correlatable across the basin. The basal assemblage was deposited by meandering rivers on a well-vegetated coastal floodplain with extensive peat deposits. The middle assemblage was deposited on a very dry floodplain with extensive calcretes; deep channels cut this floodplain, but did not migrate laterally. The uppermost assemblage was deposited by anastomosing rivers on an unvegetated floodplain. Apart from these three assemblages, the strata can rarely be correlated from one outcrop to the next, coals and the calcrete being notable exceptions.

2. The depositional patterns can be explained by climate change alone, or by a combination of climate and sea-level change. In the climate change model, the first assemblage was deposited under the influence of a weakly seasonal, humid climate; the second assemblage was deposited following a rapid switch to a climate that was semi-arid for much of the year; the third assemblage was deposited in a climate that was seasonally dry, but had a pronounced rainy season. In the combined climate and sea-level change model, the first assemblage was deposited in a humid climate, during a highstand; the second assemblage was deposited in a seasonally dry climate. A relative

fall in sea-level occurred early during the deposition of Assemblage 2; most of the Assemblage 2 sediments were deposited during the subsequent transgression. The third assemblage was deposited in a seasonally dry climate, also during the transgression. Although both models adequately explain the depositional characteristics of the Hub Cyclothem, the second model, which incorporates sea-level change, better explains the patterns observed among the facies, flora and fauna.

3. The Hub Cyclothem can be placed into a sequence stratigraphic context. The top of the calcrete in Assemblage 2 is the sequence boundary; the transgressive surface is coincident with the sequence boundary, because no sediments appear to have been deposited in the exposed part of the Hub Cyclothem during the lowstand. The maximum flooding surface is at the top of the thickest split of the Hub Coal seam. All of the strata between the top of the thickest split of the Hub Coal seam and the top of the calcrete lie in the highstand systems tract. The remainder of the cyclothem lies in the transgressive systems tract. No lowstand systems tract is present in the exposed part of the Hub Cyclothem.

4. The Hub Cyclothem is a producing coal resource, but has relatively poor potential as a hydrocarbon exploration target (although offshore areas may be more suitable). Better potential may lie in coalbed methane exploration in the thick channel fill bodies in Assemblage 1, wherever they are in close association with coal seams. The Hub Cyclothem is a good analogue for river and floodplain reservoirs in other hydrocarbon charged basins.

APPENDIX A - EXPOSURE LOCATIONS

Bras d'Or: The entire cyclothem is exposed between Morrison's Pond and the Brogan coal pit. Access can be gained by walking through the Brogan pit, or more easily via a small road which goes past Morrison's Pond to the coast. Much of the cyclothem is accessible at high tide, but the central part can only be reached within about two hours on either side of low tide.

Point Aconi: Most of the cyclothem is exposed across the river from the Alder Point fish plant, up to the Brogan Pit. It is easiest to drive to the coast along a driveway about half way up the exposure; permission should be sought from the owners. Access can also be gained by walking through the Brogan Pit. The central part of the cyclothem can be reached at any tide. The upper part of the exposure can only be reached at low tide.

Alder Point: Only the upper third of the cyclothem is exposed, but both splits of the Bonar seam are visible. Access is only possible at low tide, on calm days. Park at the fish plant and walk to the beach behind the small store. Be sure to wear a hard hat, because falling debris is common.

Wetneck Point: The cyclothem is exposed only up to the level of the redbeds in this locality. Access is easy: either drive to the upper end of the exposure along the gravel (mud) road, or walk across the beach from Oxford Point to the base of the cyclothem. Be sure to arrive within about one and a half hours of low tide, preferably at a time during the month when tides are particularly low. Expect to get wet feet.

Oxford Point: Only the base of the cyclothem is exposed, but the channel bodies are impressive. A paved road leads to the top of the cliff above the exposure, and easy pathways lead to the beach on both sides of the exposure. The beach is accessible within three hours of low tide.

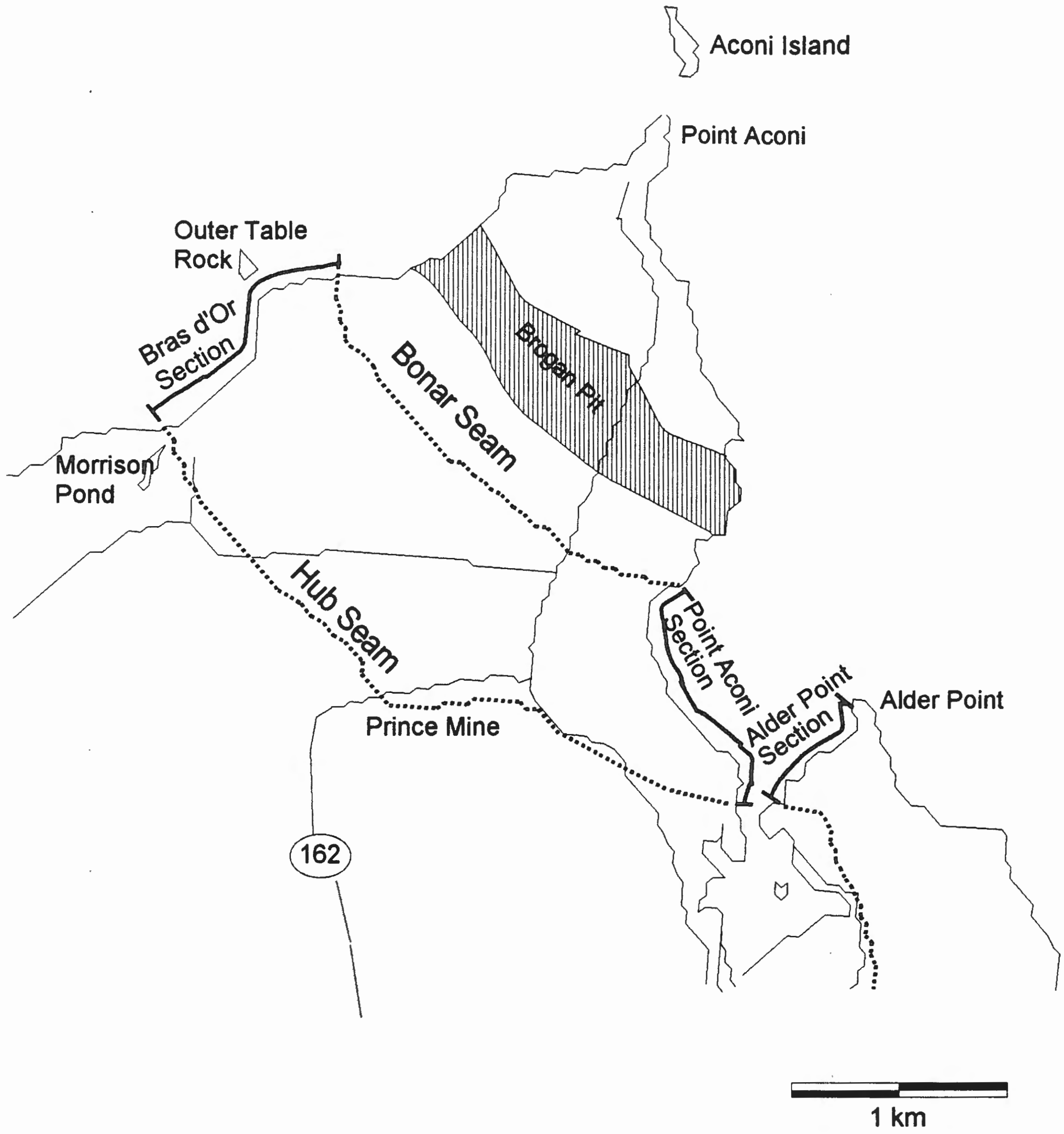
Black Point: Only the base of the cyclothem is exposed. In situ tree trunks are abundant, and the coal is well exposed. Park at the western side of the exposure and walk along the beach to see the base of the cyclothem, or walk along the top of the cliff and down to the beach on the other side to see the top of the cyclothem. The beach is reasonably accessible at all times, except for high tide, on calm days. Some rock scrambling is required in places.

Chapel Point: This is an excellent exposure, although the central part of the cyclothem is missing. Park on the beach at Lloyd Cove, and walk south to see the base of the cyclothem, or north to see the top. Expect to get wet feet, unless you arrive at absolute low tide, on a totally calm day, during the spring tide.

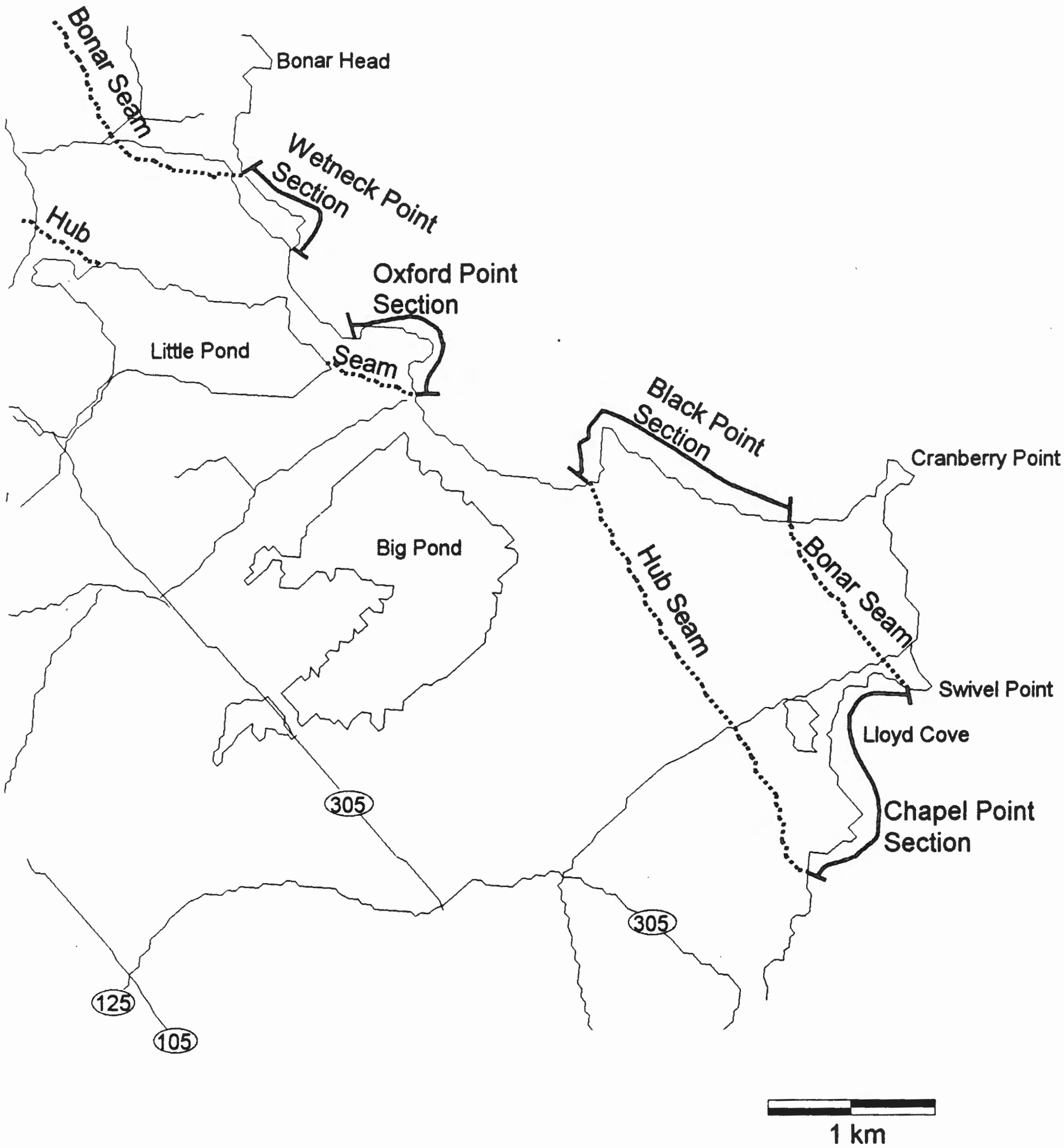
Victoria Mines: The strata dip very steeply through this exposure, and much of the outcrop is buried. In general, this is the least useful of the Hub Cyclothem exposures. Access is easy at any tide, although the best outcrop is below water at high tide. The Hub seam can be found by digging in the beach on the south side of Petries Point, about 30 m south of the exposed channel sandstones. The Bonar coal is well exposed 5 km north of Petres Point along the beach.

New Waterford: The Hub Cyclothem is fully exposed. All but the highest levels can be seen by parking at the harbour and walking both ways along the beach. To see the uppermost levels of the exposure, you must park at the old ruins near Micks Hole, west of New Waterford and scramble down to the beach (have a look for possible tidal rhythmites in the overlying Bonar Cyclothem on your way down). Except for one point which is inaccessible at all tides, most of the beach can be visited at any time except for high tide. The slabs of granite on the beach are old tombstones.

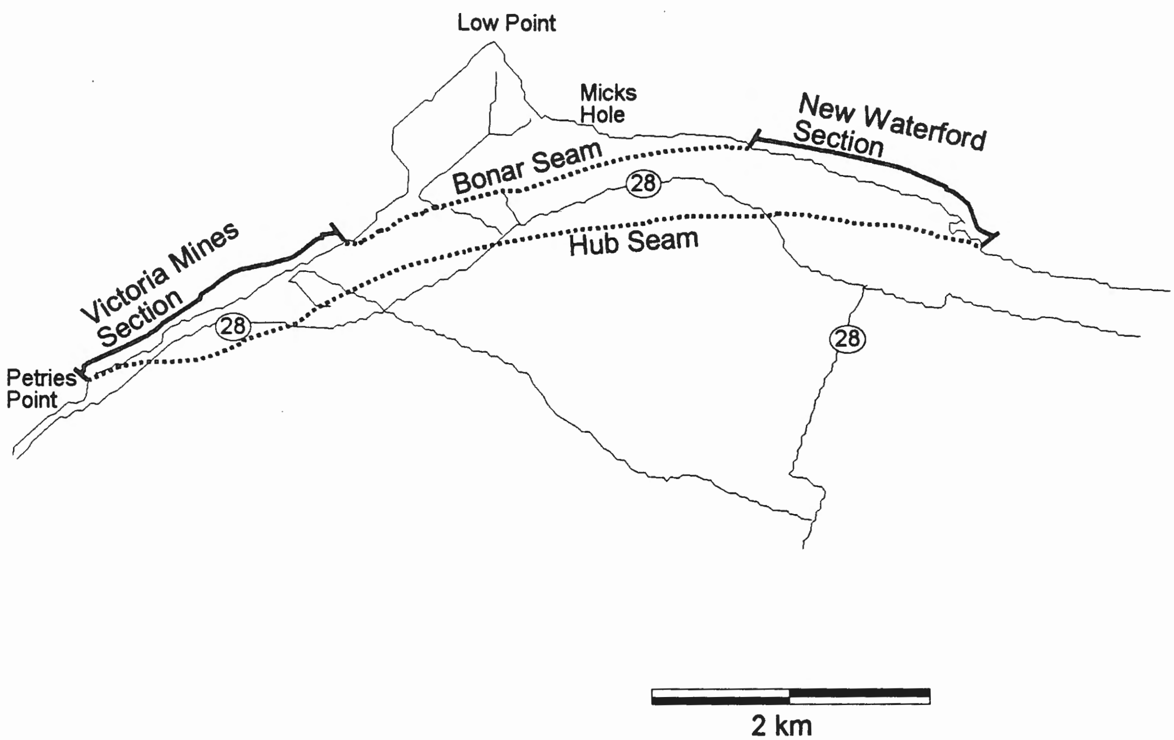
Glace Bay: Most of the beach is inaccessible, even at low tide, unless you like swimming. The bottom half of the cyclothem is exposed on both sides of the Marconi Monument (a good place to park - just follow the tourist attraction signs). The parts of the beach which are accessible (near the base of the cyclothem on both sides), are accessible at any tide. Parking is also available near the armory to reach the bottom of the cyclothem on the east side of the Marconi Monument.



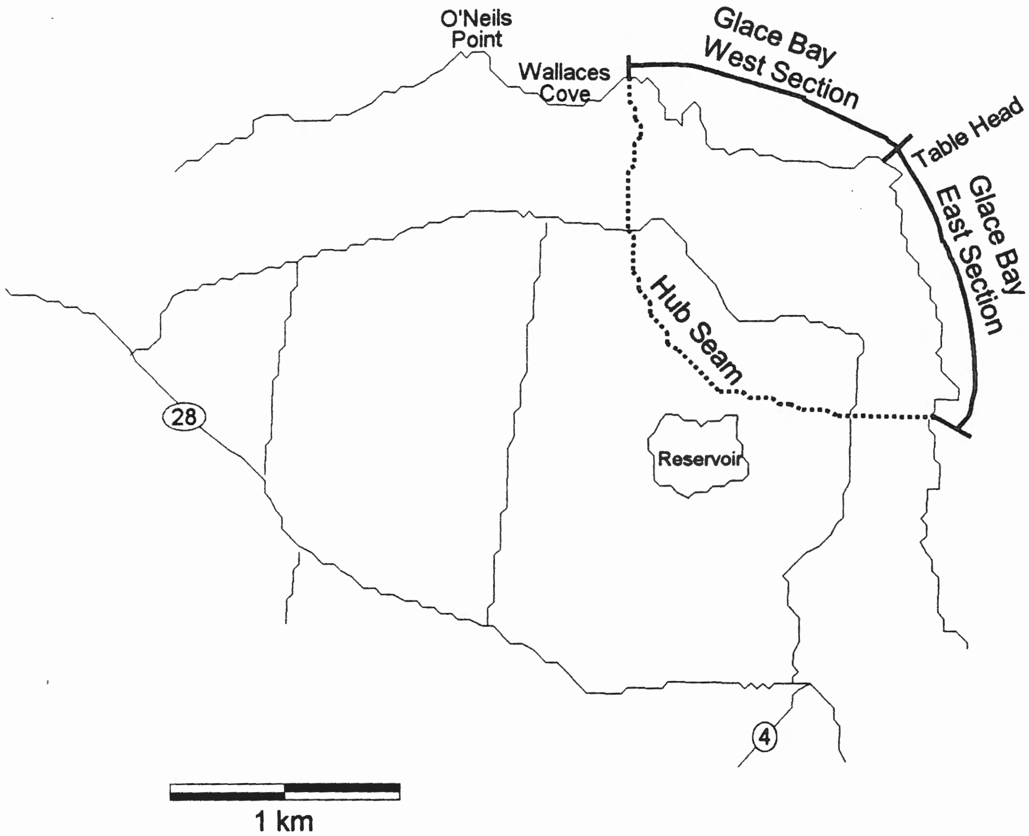
Location map for the Bras d'Or, Point Aconi and Alder Point Sections.



Location map for the Wetneck Point, Oxford Point, Black Point and Chapel Point Sections.



Location map for the Victoria Mines and New Waterford Sections.

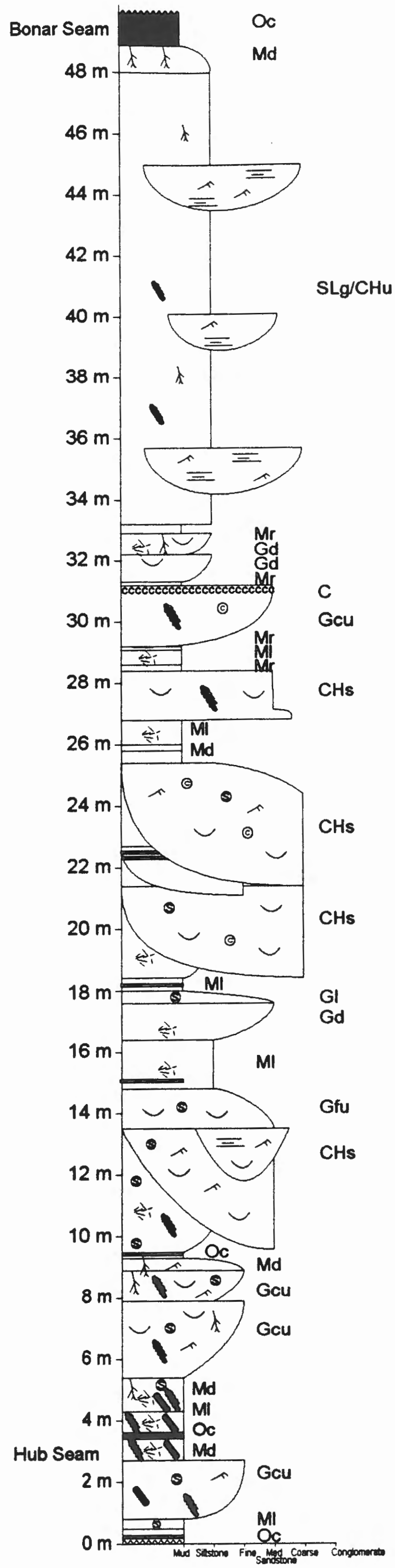


Location map for the Glace Bay West and Glace Bay East Sections.

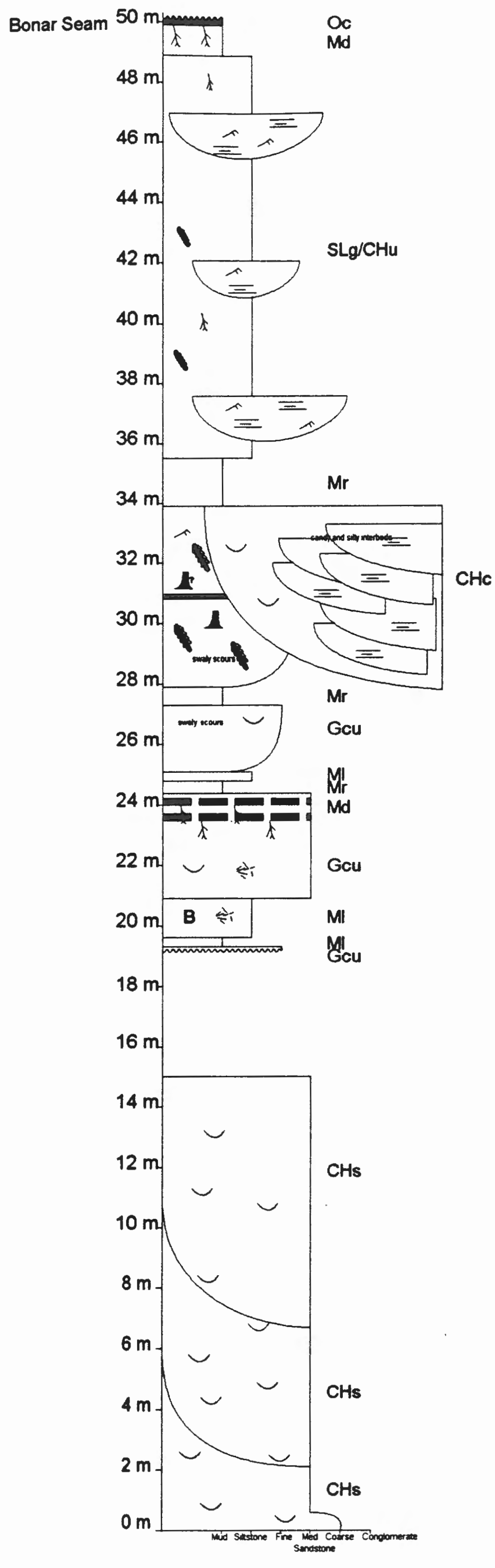
APPENDIX B

STRATIGRAPHIC COLUMNS FOR THE HUB CYCLOTHEM EXPOSURES

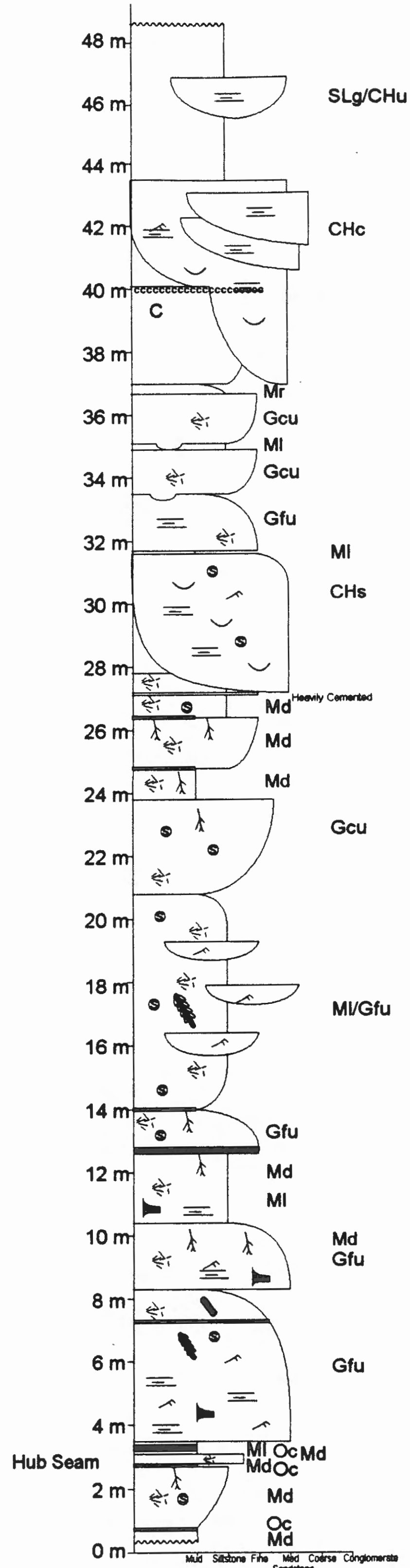
Bras d'Or Section



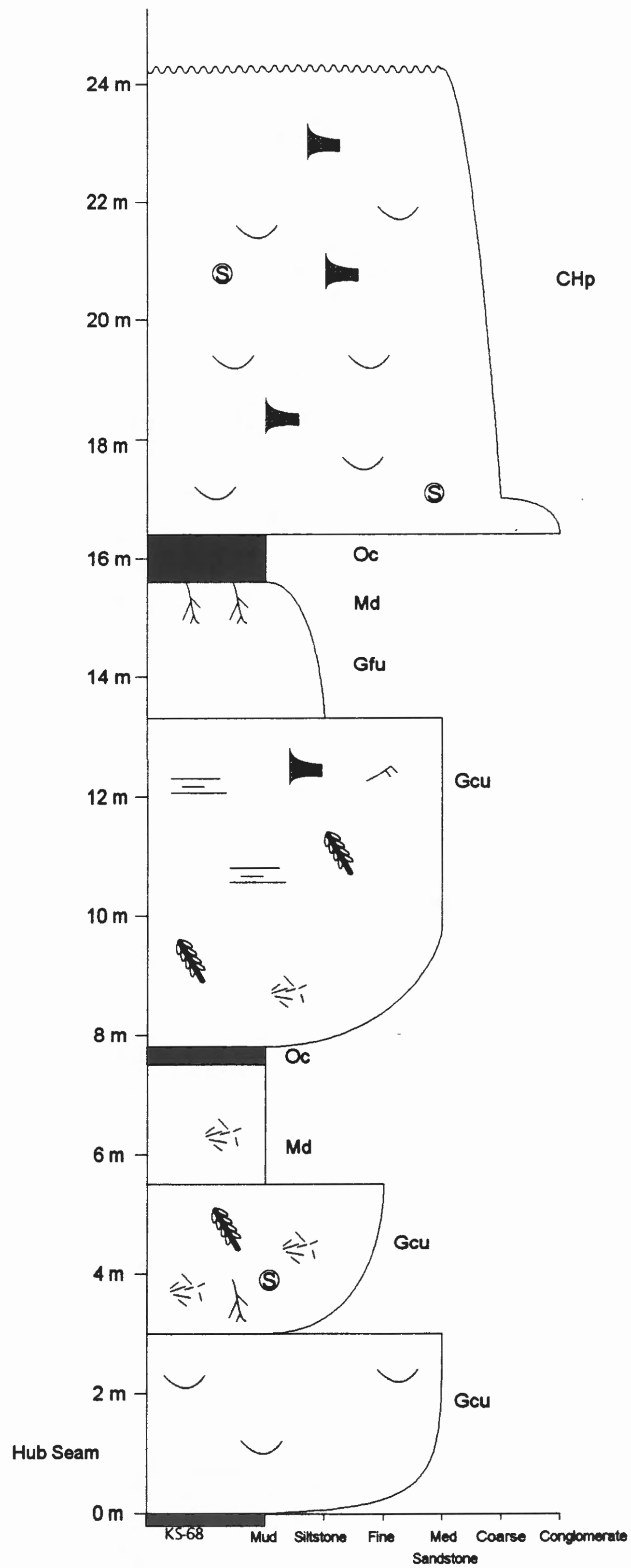
Point Aconi Section



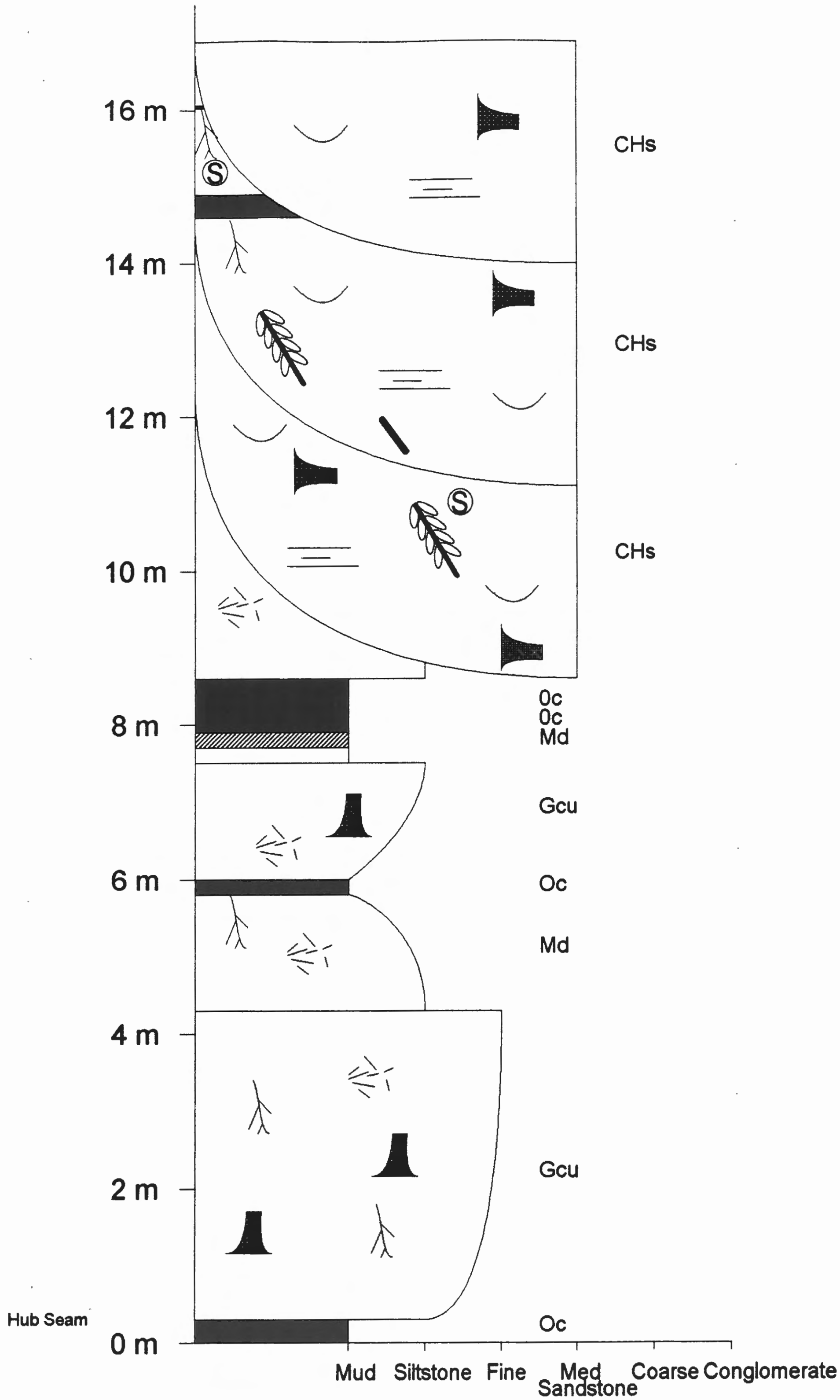
Wetneck Point Section



Oxford Point Section



Black Point


16 m
14 m
12 m
10 m
8 m
6 m
4 m
2 m
0 m
Hub Seam
CHs
CHs
CHs
Oc
Oc
Md
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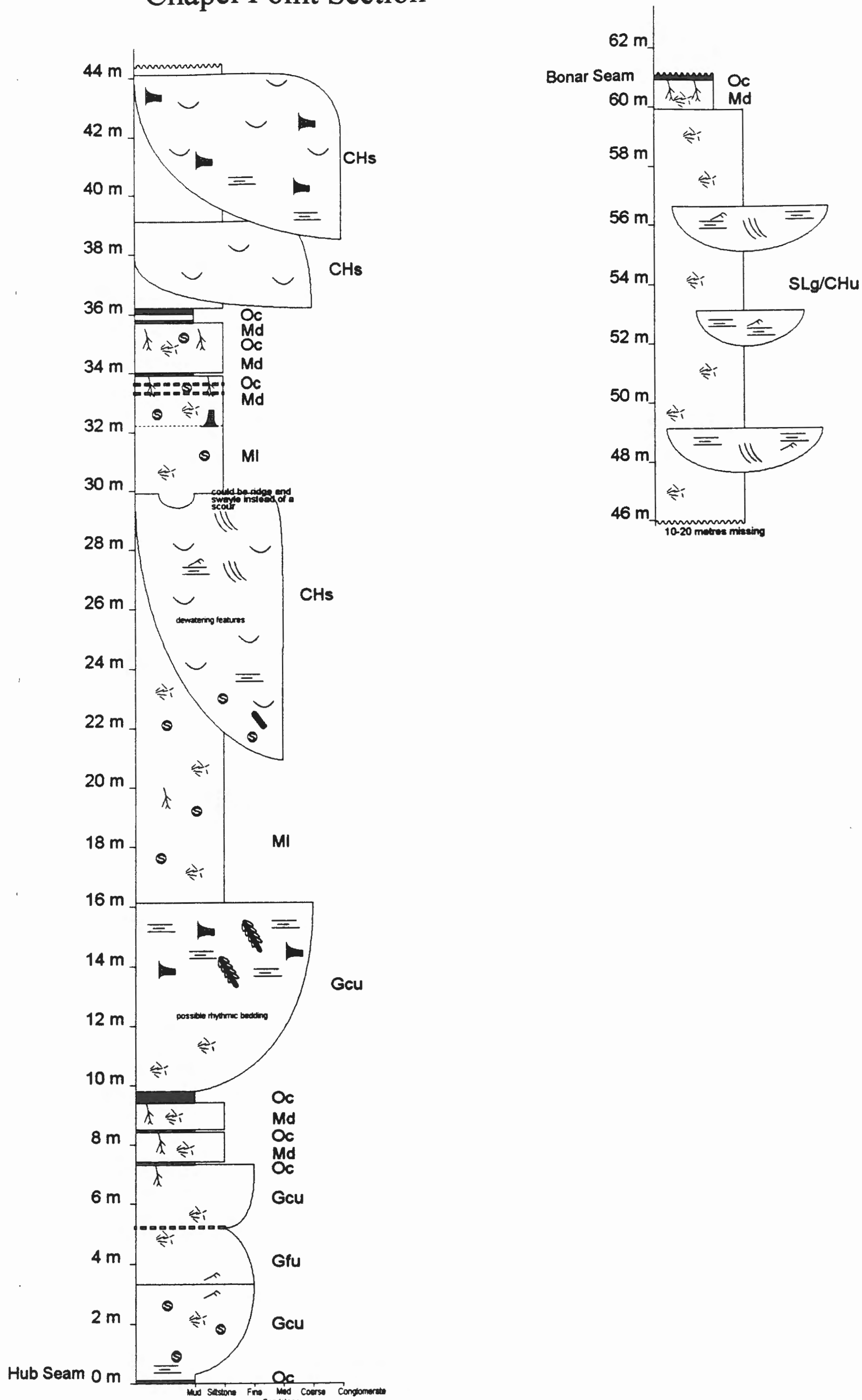
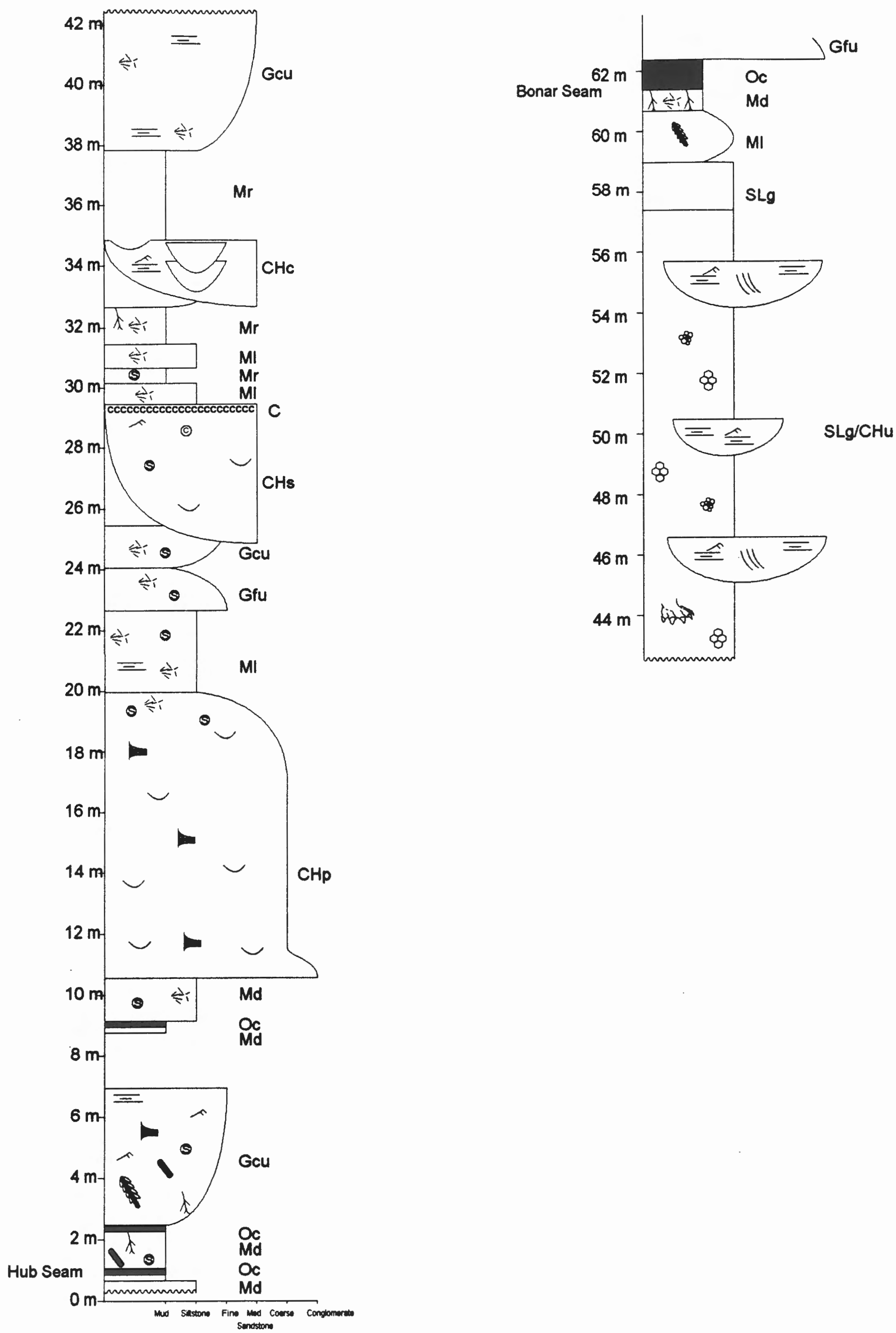
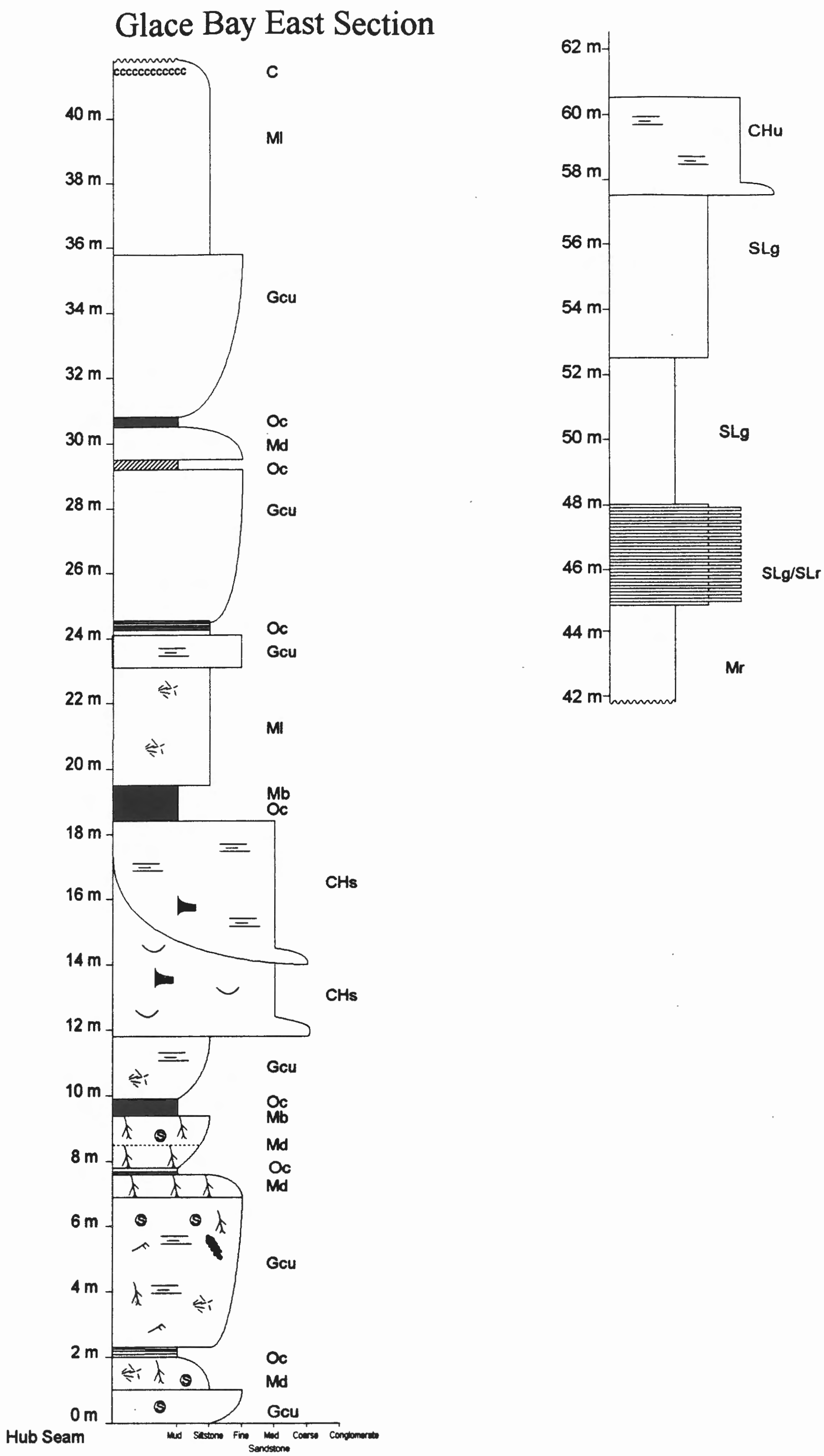
S
S
Mud
Siltstone
Fine
Med
Sandstone
Coarse
Conglomerate

Chapel Point Section



New Waterford Section





Glace Bay East Section
C
Ml
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Mb
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CHs
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Gcu
Oc
Mb
Md
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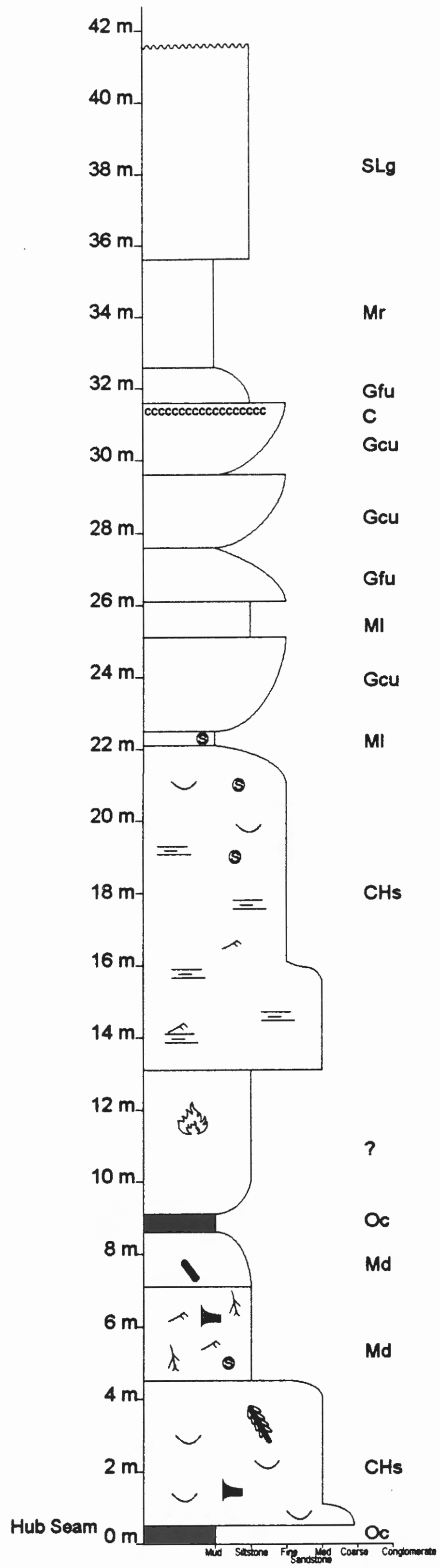
Gcu
Oc
Md
Gcu
40 m
38 m
36 m
34 m
32 m
30 m
28 m
26 m
24 m
22 m
20 m
18 m
16 m
14 m
12 m
10 m
8 m
6 m
4 m
2 m
0 m
Hub Seam
Mud
Siltstone
Fine
Med
Coarse
Conglomerate
Sandstone
62 m
60 m
58 m
56 m
54 m
52 m
50 m
48 m
46 m
44 m
42 m
CHu
SLg
SLg
SLg/SLr
Mr

Glace Bay West Section



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