# SEDIMENTOLOGY, STRATIGRAPHY AND PALEOECOLOGY OF THE LATE CARBONIFEROUS SYDNEY MINES FORMATION AT MORIEN BAY, NOVA SCOTIA

By:

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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled "Sedimentology, Stratigraphy and Paleoecology of the Late Carboniferous Sydney Mines Formation at Morien Bay, Nova Scotia" by Heidi Lindsay McDonald in partial fulfilment of the requirements for the degree of Master of Science.

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# ABSTRACT

Coastal exposures of the Sydney Mines Formation (Westphalian D) at Morien Bay, Nova Scotia record stacked high-frequency sequences 11-38m thick of fluvial and restricted marine strata with economic coals. The cliffs at Morien Bay are among the world's best continuous Carboniferous coal measure exposures. Sections 75-160 m thick at Schooner Pond, Long Beach, and Morien South provide a ~10km downdip direction traverse that encompasses the McRury to Bouthillier coal seam interval. The dominant facies assemblage represents a poorly drained coastal plain and comprises grey sandstone and shale, hydromorphic paleosols, thick coals and distributary channel bodies. The coals are sulphur-rich, suggesting a marine influence, and are up to 2.8 m thick. A second facies assemblage represents a well drained alluvial plain and comprises red mudstone, nodular calcrete, vertic red and grey paleosols, and dryland channel bodies; it predominates at Morien South. Repetition of these facies assemblages represents cycles of relative sea level change, probably linked to glacioeustasy which is inferred to have dominated the formation's stratal architecture.

Applying a sequence stratigraphic framework, flooding surfaces are indicated by thick, extensive coal seams or thin coal or coaly shale. Maximum flooding surfaces can be represented by faunal-concentrate limestones rich in bivalves and ostracods and form excellent regional stratigraphic markers. Three main types of sequence boundary are (a) single well-defined calcretes with minimal sedimentation for long periods, (b) sequence boundary zones of vertisol-type paleosols several metres thick in areas of higher sedimentation, and (c) sequence boundary zones of small paleovalley fills or larger dryland channel bodies in association with paleosols. Some calcretes can be correlated between sections and across the basin. The vertisol-type paleosols are also widespread but more difficult to correlate. Within seven stacked sequences, wetland facies and economic coals are well represented within the Transgressive and Highstand Systems Tracts. 'Dry' and 'wet' subdivisions of the Highstand Systems Tract reflect upward passage into red and grey dryland facies which may represent falling sea level prior to the formation of the sequence boundary. Systems tract terminology could not always be applied to the alluvial plain strata.

Stratal packages thicken in Morien Bay when compared to sections in the western part of the Sydney Basin, due to increased subsidence. Particularly at Morien South, increased amount of red floodplain material suggests a more proximal and well-drained region towards the southern limb of the Morien Syncline. Unidirectional paleocurrent data from channel bodies yields an overall paleoflow direction of 347° (NNW) with vector means of paleocurrent measurements of 029° (ENE), 001° (N), and 334° (NNW) at Schooner Pond, Long Beach and Morien South, respectively. This suggests a local source to the south of Morien Bay, probably the Proterozoic rocks of the Scatarie Ridge and regional sources within the northern Appalachian Mountains. Some channel bodies with NE paleoflow indicate a subsidiary mode sub-parallel to the axis of the Morien Syncline.

An abundant paleobotanical record in grey, coal-bearing strata comprises erect lycopsids, prostrate logs and abundant compression flora. Thirty lycopsid trees in growth position had trunk diameters from 0.25-0.6 m. *Lepidodendron* sp. and *Sigillaria* sp. are the two main lycopsids identified. Compression flora consists of pteridosperms (*Alethopteris* sp. and *Neuropteris* sp.), marattialean tree-ferns (*Pecopteris* sp.), sphenophytes (*Sphenophyllum* sp.), *Cordaites*, and *Calamites*. Few plant specimens were recovered from redbed intervals. A rare, well-preserved tetrapod trackway with 18 tracks is provisionally attributed to *Baropezia sydnensis*, a temnospondyl amphibian.

# ACKNOWLEDGEMENTS

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# Chapter 1: INTRODUCTION

## 1.1 Historical Background to Coal Mining at Morien Bay

The Sydney Basin of Nova Scotia has been a major coal-producing region since the 1700's. Several coal seams have been extensively mined in the nearshore and onshore parts of the basin. The Sydney Coalfield hosts the largest coal resource in eastern Canada and was the centre of coal mining in Nova Scotia in recent years (Calder et al., 1993). The coalfield is located on the northeastern coast of Cape Breton Island (Fig. 1) and extends 50 km from Cape Dauphin in the west to Morien Bay (Boehner and Giles, 1986). Up to five mines existed in the Morien Bay area alone.

The Late Carboniferous Sydney Mines Formation at Morien Bay has been of geologic and economic interest since its extensive and easily accessible coal seams first provided an excellent fuel source for the French military and local residents in the early 1700's (Gregory, 1978). The history of coal mining in the area has been summarized by MacDonald (1995). Coal mining commenced here in 1720 and Baie de Mordienne (as it was first called by the French settlers) became the site of the first commercial coal mining in North America, leaving on vessels to the Fortress of Louisbourg and Boston. South of Long Beach the Blockhouse Mine was established close to the shore by the French, utilizing the room and pillar method of mining. After the final fall of Louisbourg in 1758, the mine was then run by the English and as much as 3000 tons of coal was mined annually. Mordienne became known as Cow Bay at this time.

The local demand for coal lessened and by 1766 operation of the mine fell under government regulation. Active mining continued, though sometimes erratically, until the mid 1850's. The Gowrie mines, on the north side of Cow Bay, were leased in 1861 and

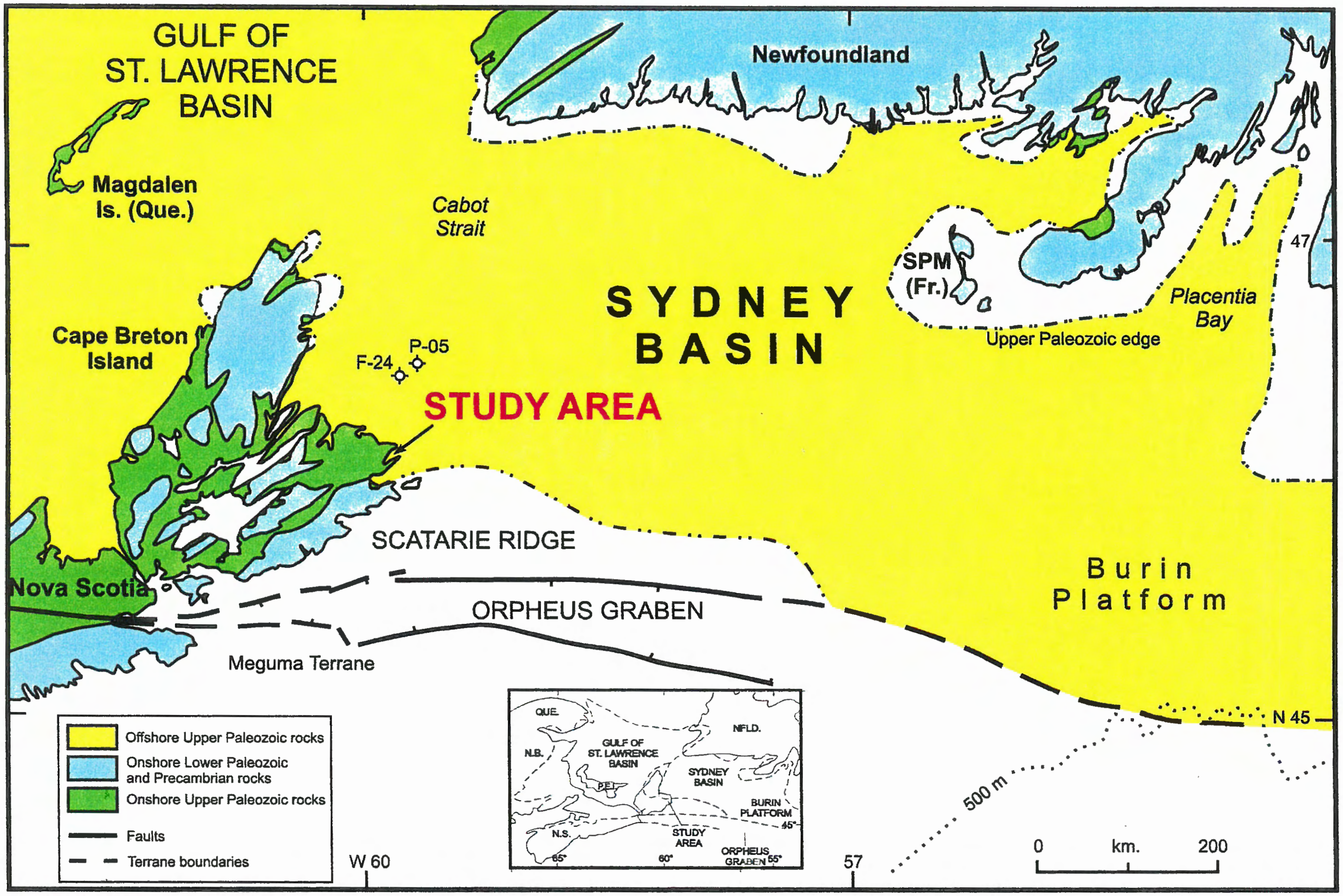


Figure 1. Geologic setting and offshore extent of the Sydney Basin, eastern Canada. Modified after Pascucci et al. (2000) and Batson and Gibling (2002). F-24 and P-05- Offshore exploratory wells. SPM- St. Pierre and Miquelon (France).

prosperous years of coal mining and expansion followed. Cow Bay was transformed from a quiet agricultural community to a thriving and bustling mining and shipping centre. In 1864 the Blockhouse area (Fig. 2) was a hub of activity, with miners' houses, colliery buildings, shops, forges, barns and stables. However, in 1868, the Blockhouse Colliery was the site of Canada's first coal miner's strike, and the mine never seemed to return to the prosperity of earlier years. The Blockhouse property was eventually acquired by the Dominion Coal Company in 1893, which dismantled and moved the colliery buildings to the more prosperous mining districts of Reserve and Caledonia. The Gowrie mines seemed to have more success than the Blockhouse in later years and continued production until 1897. The name of Cow Bay was officially changed to Port Morien in 1895. Numerous small mines were established around South Head but did not survive long due to shipping and financing problems. In 1903 the North Atlantic Colliery Ltd. began working the seams extending under the bay, but faltered by 1912 with numerous strikes and water problems. By 1930 the last operating mine in this district ceased production. Port Morien would never return to the prosperous coal mining days of the past and very little evidence of the coal mining history is preserved. Today at the Blockhouse, little more than a gentle pasture and magnificent view of Morien Bay remains.

### 1.2 Significance of Morien Bay for Sequence Analysis

Exposures near Sydney and Morien Bay are among the best of the world's Carboniferous coal measures. The coastal cliffs provide excellent exposures to investigate alluvial, coal, and coastal plain deposits. This study will focus on the

Figure 2. Sketch of Cow Bay (Morien Bay) in 1873. From MacDonald (1995).

sedimentology, sequence stratigraphy, and paleoecology of three stratigraphic sections along Morien Bay. The presence of widespread coals allowed earlier workers (Robb, 1876; Hayes and Bell, 1923; Boehner and Giles, 1986) to establish correlations with great certainty, allowing stratal packages <20 m thick to be correlated along strike over distances of tens of kilometres. A major component involves recognition of cycles of lithofacies and key stratigraphic surfaces. Cyclothems and sequences have been studied elsewhere in the Sydney Basin (Gibling and Bird, 1994; Tibert and Gibling, 1999) but the Morien Bay locality provides excellent exposures of the Sydney Mines Formation that have not been studied in detail with regard to sedimentology, ideas of cyclicity, and sequence stratigraphy. Morien Bay outcrops allow for high resolution stratigraphic analysis and the tracing of key surfaces and systems tracts landward into more proximal, better drained settings. This is difficult to accomplish elsewhere in the Sydney Basin as the outcrops are mainly along depositional strike (northwest-southeast), whereas Morien Bay outcrops run roughly southward (approximately parallel to paleoflow). Interpretation of past climatic conditions and relative sea level position are possible through the recognition of sequences and the application of a sequence stratigraphic framework. Short-period climate change during the late Carboniferous in the Sydney Basin has received only modest documentation (Tandon and Gibling, 1994).

Recognition of sequence boundaries is a critical component of sequence analysis. The signature of these unconformity surfaces may be cryptic in outcrop. This thesis illustrates the difficulty of absolute identification of sequence boundary surfaces in coastal plain, non-marine, or interfluve deposits. At least three different expressions of these surfaces and associated strata are preserved in the sections at Morien Bay. Most of the boundaries represent some measure of break in sedimentation and, therefore, a time gap. Identification of these surfaces in outcrop is the first problem addressed, followed by attempts to correlate these surfaces between measured sections, and then across the basin area onshore. As their signature can change across the coastal plain, tracing and matching these surfaces presents many obstacles. The lateral change from dominantly grey to red beds is also addressed as this represents an important change in alluvial plain depositional conditions. The issue of separating strata of highstand and transgressive systems tracts from 'sequence boundary' strata is investigated, requiring the evaluation of the effects of the falling stage of relative sea level on the coastal plain. Finally, the paleobotanical record is considered as a test of these interpretations.

### 1.3 Aims of Study (Objective and Scope of Project)

Sections studied at Morien Bay help complete the stratigraphic record for the entire basin and allow for investigations of the basin's history. The objectives of this thesis are as follows:

1. To complete detailed stratigraphic sections from coastal outcrops at Long Beach, Schooner Pond and Port Morien, Nova Scotia, updating past lithological sections;
2. To correlate the sections based on stratigraphy, facies assemblages, and the floral and faunal record;
3. To apply and test sequence stratigraphic principles on all stratigraphic sections, with identification of key surfaces, sequence boundaries and systems tracts (essentially applying a high-resolution sequence stratigraphic framework to a cratonic basin);
4. To observe and test concepts of relative sea level rise and fall across a Carboniferous coastal plain; this involves sequence boundary representation and evaluating the

significance of lateral transition from dominantly grey to red alluvial beds at several stratigraphic levels;

5. To compare the findings of the study with previous work in other parts of the basin ;
6. To provide some ground truthing (links between floral assemblages and lithofacies) to the sedimentological interpretations completed in other parts of the basin by using the paleoecological record preserved at Morien Bay

## 1.4 Methodology

The study area is located in northeastern Cape Breton Island, Nova Scotia (Fig. 1). Fieldwork along Morien Bay and at Schooner Pond was performed over the summer months of 2000 and 2001. Detailed stratigraphic sections from three continuous coastal outcrop sections, over ~10 km in downdip direction, were measured. These three sections were named Schooner Pond, Long Beach and Morien South for the purpose of this study (Fig. 3). The total thickness measured in the three sections ranged from 74 to 160m. In order to completely map the three sections, fieldwork had to be organized around the tides. Parts of the sections were accessible at all times but others were only accessible at low tide. The extensive wave-cut platform allowed for three-dimensional representation of the cliff outcrops in many cases at low tide. Most mapping was performed on the falling tide.

The measurements collected included centimetre-scale, unit-by-unit mapping of the Sydney Mines Formation at the three study sections. Units were defined as beds that have a lithology different from that above or below or are distinctive in outcrop. For each unit, the thickness, lithofacies, grain size, basal contacts, degree of paleosol development, sedimentary structures, and paleontological features were recorded. These data were

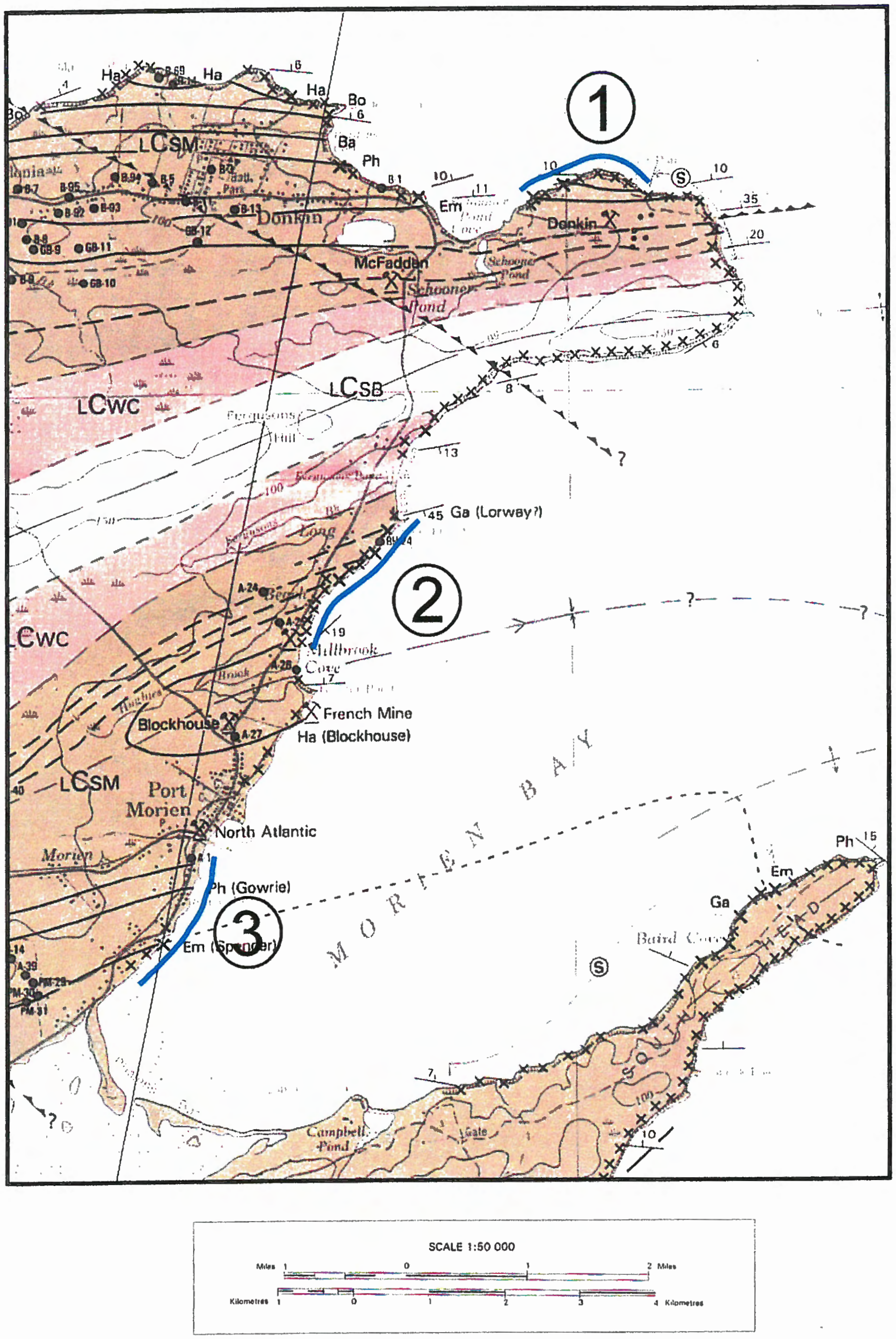


Figure 3. Geological map of the study area. Numbered stratigraphic sections are as follows: 1. Schooner Pond; 2. Long Beach; 3. Morien South. From Boehner and Giles, 1986.

collected and maintained through a chronological set of field notes and charts. Any sedimentary structures present allowing for paleoflow direction measurements were recorded. Representative samples of different lithologies, key surfaces, and faunal concentrate horizons were collected. Detailed observation and location of floral specimens was performed at each study section and numerous samples were collected for further systematic identification where possible. Evaluation of floral assemblages in the context of cyclic sedimentation and sequence stratigraphy may allow for a larger scale analysis linked to allocyclic features.

Rock samples of all facies present were collected to help characterize the key rock types present. Representative samples from certain lithologies were cut and produced into thin sections at the Thin Section Preparation Laboratory at Dalhousie University. Fifteen thin sections were created from the samples and analyzed for composition, grain size and correlation purposes.

Many computer software programs were used for data analysis in this thesis. LogPlot 99 was used for production of accurate stratigraphic section logs and facies representations. Corel Draw9 was then used to take the scaled logs and produce stratigraphic columns complete with facies colours, sedimentary structures, paleontological data and overlying text. Microsoft Excel was utilized for creation of all facies proportion graphs and abundances. Oriana was used for accurate interpretation of directional paleoflow data.

# Chapter 2: GEOLOGIC SETTING

## 2.1 Maritimes Basin

The Maritimes Basin is a large, 148 000km$^2$, post-accretionary basin in the northern Appalachian Mountain Range (Williams, 1974). The Maritimes Basin, displayed in Figure 1, encompasses the area of Atlantic Canada presently underlain by upper Paleozoic rocks in distinct structural basins (van de Poll et al., 1995). Approximately 70% of the basin is offshore under the Gulf of St. Lawrence (St. Peter, 1993). The term “Maritimes Carboniferous Basin” was used by Roliff (1962) and was simplified to the “Maritimes Basin” (Williams, 1974). It is a structural remnant of a larger depocentre that originated following the mid-Devonian Acadian Orogeny (Gibling et al., 1992).

The Late Carboniferous was a time of climatic contrasts and warm, rainy, equatorial swamps extended across eastern Europe to England and Maritime Canada, and into the mid-continent of North America (Scotese and McKerrow, 1990). In the southern polar region large ice sheets covered the Gondwanan super-continent (Fig. 4). Nova Scotia and the Maritimes Basin lay within palaeoequatorial Euramerica. By the beginning of the Permian (Scotese and McKerrow, 1990) it had drifted northwards to a palaeolatitude of ~12°, crossing the equator. The Maritimes Basin lay at the palaeosouthern margin of the Appalachians in a palaeogeographic region distinct from the Appalachian Basin to the west (Calder, 1998). These mountains provided a drainage divide and a phytogeographic and orographic climate barrier between the two areas (Calder, 1998). East of the Appalachians lay the Maritimes-West European Province, a contiguous geographic entity, which includes Nova Scotia, Britain and southern parts of Europe.

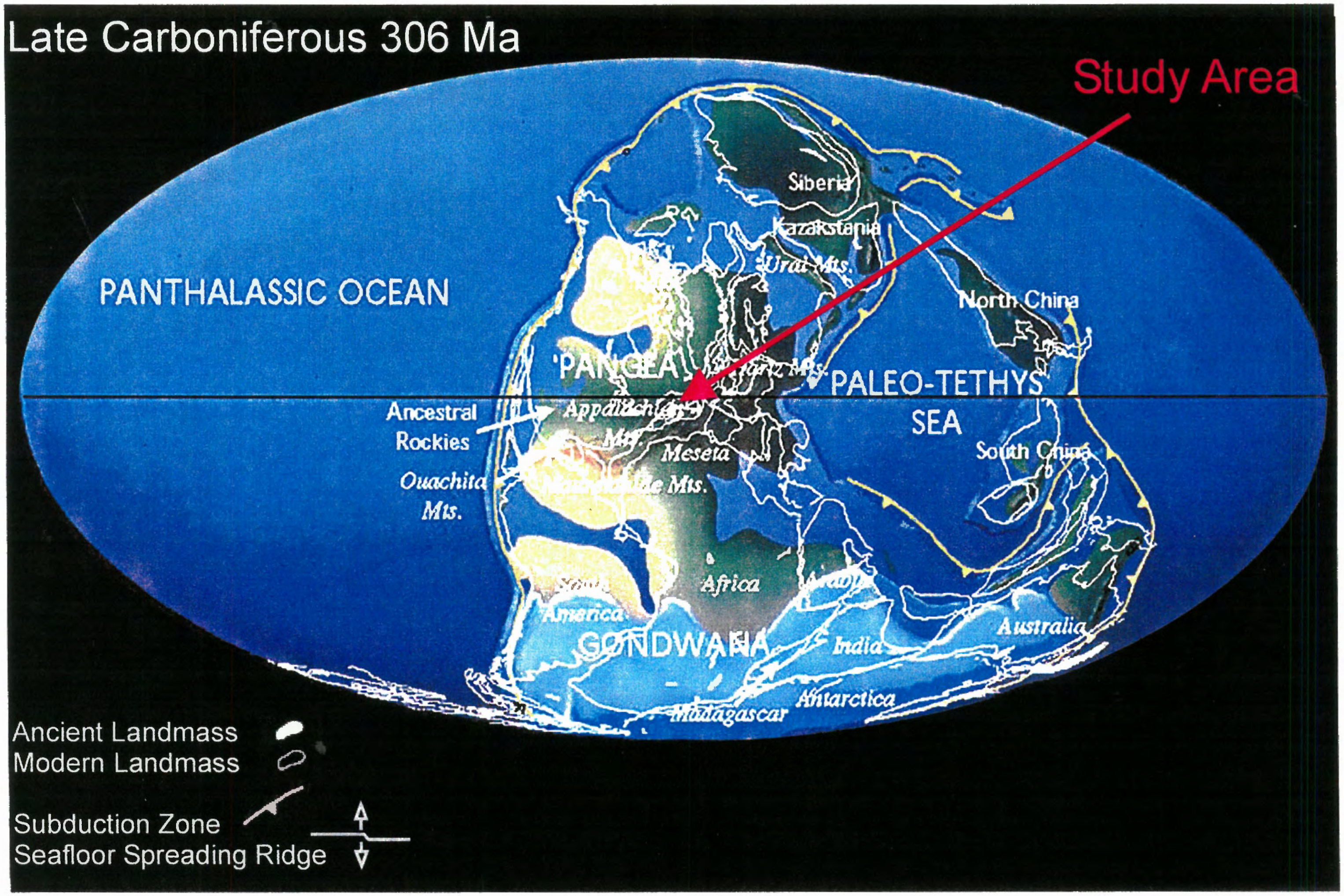


Figure 4. Paleogeographic map of the Late Carboniferous (~306 Ma). Modified after Scotese and McKerrow (1990).

## 2.2 Stratigraphy of the Maritimes Basin

In eastern Canada the Upper Paleozoic rocks were deposited in a series of northeast and east trending basins. Local and regional unconformities exist, yet most groups or equivalents can be identified in most of the subbasins. Bell produced a stratigraphic subdivision of six major units in the Maritimes Basin over a 50-year period (1912-1960). Units were defined on a mixture of lithostratigraphic (mainly facies) and biostratigraphic (mainly macrofloral and palynological) criteria (Kelley, 1967). Figure 5 is a stratigraphic column representing the major units within the Carboniferous basin-fill of the Sydney Basin. More recent work has led to further understanding and correlation of the different tectonostratigraphic packages of the Maritimes Basin as discussed below.

### *2.2.1 Horton Group*

Horton Group strata onlap Acadian basement with angular unconformity (van de Poll et al., 1995). Deeper basinal areas may contain an earlier mid-late Devonian fill. The Horton Group is Early Carboniferous (Mississippian) age, and includes latest Devonian locally (Fig. 5), which in the Sydney Basin, is represented by the McAdams Lake Formation. The group consists of red and grey conglomerates, mudstones, arkosic sandstones, oil shales and minor non-marine evaporites (van de Poll et al., 1995). The Horton Group is divided into three formations in most basins and consists of a lacustrine unit bounded by upper and lower alluvial units. The lacustrine unit may represent a regional phase of rapid subsidence where organic-rich shales were widely deposited (Gibling, 1995), and is present as the Horton Bluff, South Lake and Strathlorne Formations in individual basins. Common to Horton Group strata are ostracods, fish

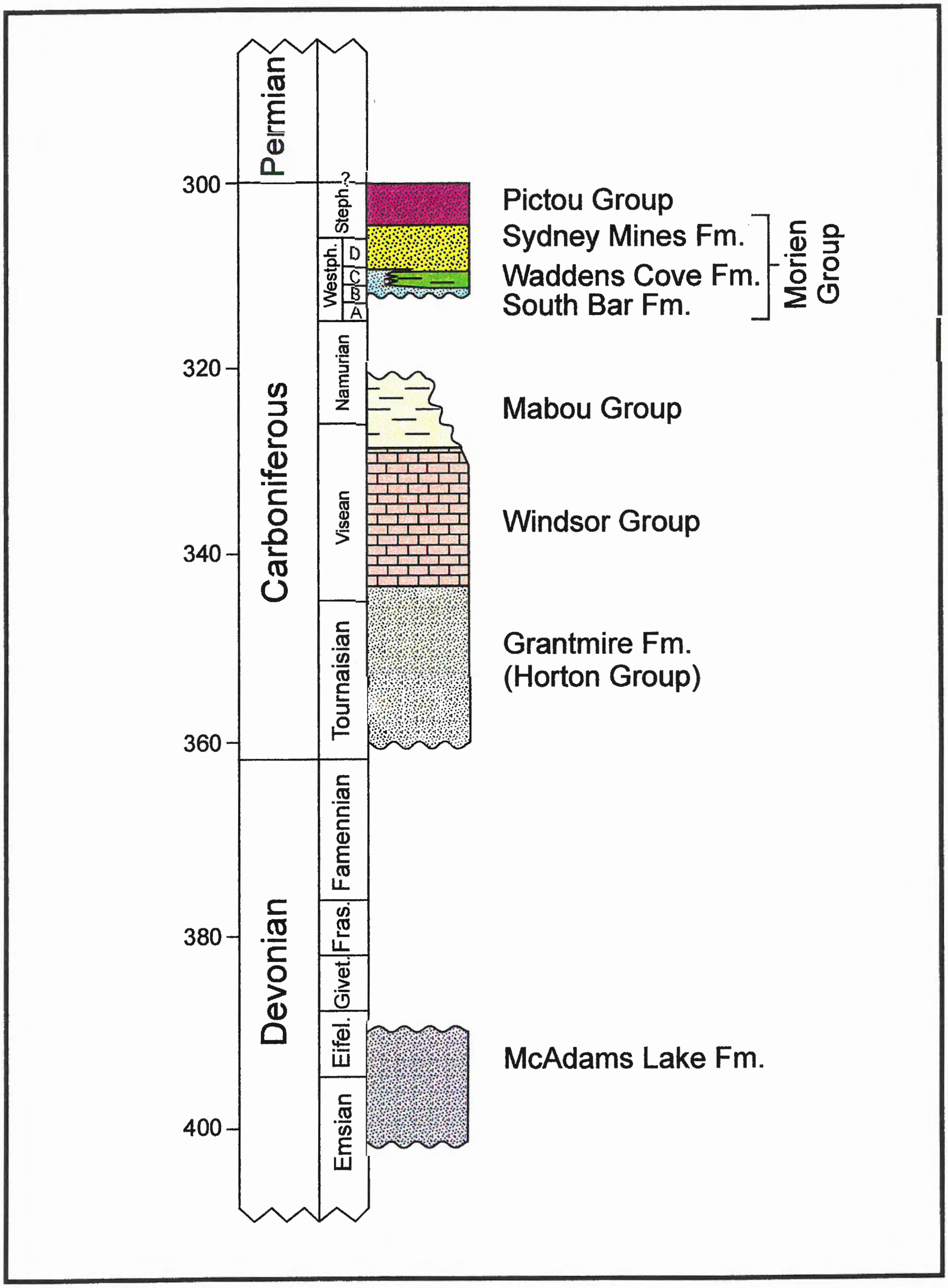


Figure 5. Upper Paleozoic stratigraphy of the Sydney Basin. Modified after Gibling et al. (2002). Formations and ages from Boehner and Giles (1986), White and Barr (1998) and Grant, and McAlpine (1990). Time scales from Hess and Lippolt (1986), Okulitch (1999) and Tucker et al. (1998). Eifel., Eifelian; Fras., Frasnian; Givet., Givetian; Steph., Stephanian; Westph., Westphalian; Fm., Formation.

fossils and fossilized plant remains, but coal is rare (van de Poll et al., 1995). Horton Group strata occupy fault-bounded basins across Atlantic Canada (Hamblin and Rust, 1989).

### *2.2.2 Windsor Group*

The Windsor Group is the main and only unequivocal marine unit in the upper Paleozoic rocks of the Maritimes Basin. It is of Middle-Late Visean age (Fig. 5) (Utting, 1978; Giles, 1981) and consists of marine limestones, evaporites and intercalated red beds. The Windsor Group reaches 1000 m in stratigraphic thickness (Boehner, 1986) though it is thickened in some areas due to evaporite diapirism. Giles (1981) recognized five major cycles of marine transgression and regression, the dominant facies trend being an overall upward decrease in the proportion of evaporites. These cycles may reflect glacioeustacy (cf. Veevers and Powell, 1987).

### *2.2.3 Mabou Group*

Mid-Carboniferous rocks in the Maritimes Basin are difficult to correlate as the continental strata are transitional with the underlying marine Windsor Group and appear to be associated with major tectonic events (Gibling, 1995). Bell (1944) assigned these rocks to the Canso-Riversdale Groups, but recent review of the nomenclature by Ryan et al. (1991) re-assigned the Canso strata to the Mabou Group, as advocated by Belt (1964) and the Riversdale strata to the revised Cumberland Group in Nova Scotia. The terms Canso and Riversdale are abandoned. The age range of the Mabou Group is Late Visean to early Westphalian A (Fig. 5) (Gibling, 1995). Belt (1964, 1965, 1968) recognized two main assemblages of red and grey strata: (1) A red assemblage of fluvial interchannel deposits of red and grey-green calcareous mudstones with subordinate sandstones (thin channel bodies), and (2) A lacustrine assemblage of dark-medium grey laminated shale with minor mudstone, and carbonate-cemented sandstone (with red fluvio-lacustrine intercalations). In the Sydney Basin, the first assemblage is represented by the Point Edward Formation and elsewhere by the Pomquet Formation. The second assemblage is represented by the Cape Dauphin Formation in the Sydney Basin and is correlative with the Hastings Formation on mainland Nova Scotia. In the Sydney Basin, Boehner and Giles (1986) described the lacustrine Mabou Group as consisting of sandstone, siltstone, shale, limestone and sulphate evaporites with associated thick dark shales.

### *2.2.4 Cumberland and Pictou Groups*

The Cumberland and Pictou Groups consist predominantly of thick alluvial successions. Braided-, meandering- and anastomosed-fluvial and alluvial fan deposits are all represented (Gibling, 1995). The age of the strata ranges from late Namurian to early Stephanian (Cumberland Group) and mid-Westphalian to early Permian (Pictou Group). The major economic coal deposits of Nova Scotia are found within the Cumberland Group. The Cumberland Group includes coal-bearing red and grey conglomerate, sandstone, mudstone, limestone and shale. The Stellarton Formation and Morien Group, of the Stellarton and Sydney Basins respectively, are also assigned to the Cumberland Group (Ryan et al., 1991). The detailed stratigraphy of the Morien Group is discussed in Section 2.3.2. Red strata with only minor coal overlying the Cumberland Group are assigned to the Pictou Group, following practice advocated by Ryan et al. (1991).

Deposition of the Cumberland Group took place in alluvial fans and braidplains with axial braided and meandering river systems (Bell, 1938; Calder, 1985, 1991; Salas, 1986). The Pictou Group differs from the Cumberland Group in the predominant red colour of the alluvial sandstones and mudstones and the scarcity of conglomerate and coal (Ryan et al., 1991). Post-Carboniferous strata are not well known in the Sydney Basin, yet are present elsewhere in the region.

### 2.3 Sydney Basin

Upper Paleozoic strata of the Sydney Basin are well exposed onshore in northern Cape Breton Island and extend offshore towards Newfoundland and eastward under the Laurentian Channel and Grand Banks (Bell and Howie, 1990). The Sydney Basin is a smaller, component basin of the regional Maritimes Basin, and its extent is shown in Figure 1. It covers an area of 36 300 km$^2$ (King and MacLean, 1976) with 98% of it beneath the Laurentian Channel, and the basin contains about 4 km of late Paleozoic strata (Howie and Cumming, 1963; Howie and Barss, 1975; Williams and Haworth, 1984). Upper Paleozoic strata elsewhere in the basin may also be linked to the Sydney Basin. Carboniferous strata occupy fault-bounded basins in the Cabot Strait (Langdon and Hall, 1994), coal-bearing Westphalian B-D strata overlie basement rocks in Placentia Bay, Newfoundland (King et al., 1986; Miller, 1987), and Lower and Upper Carboniferous rocks underlie the Burin Platform and the eastern Grand Banks (Bell and Howie, 1990; MacLean and Wade, 1992; Pascucci et al., 2000). Fault zones of the Cabot Strait border the basin to the north (Langdon and Hall, 1994) and separate the basin from the Maritimes Basin beneath the Gulf of St. Lawrence (Pascucci et al., 2000). Proterozoic rocks of the Scatarie Ridge border the basin to the south (Pascucci et al., 2000) while the extent of the basin to the east is undefined.

The Sydney and Glace Bay area has been a major economic coal-mining region since the early 1700's. For years, the main coal-producing regions in eastern Canada were the mines in the Sydney Basin. Today coal mining has all but disappeared from Cape Breton Island with the large commercial coal mines ceasing operations. The Phalen Mine in New Waterford closed in 2000, followed by the Prince Colliery in Point Aconi in 2001. Mineable reserves remain, however, in the Donkin Block, offshore.

### 2.3.1 Structure of the Sydney Basin

The extent and structure of the Sydney Basin was first determined using shipboard geophysical and seismic techniques by King and MacLean (1976) as the majority of the basin is offshore (Fig. 1). They concluded that the structural style is simple and, except for local folding, broadly saucer-shaped with beds dipping towards the deeper, central part of the basin. The coal measures form a seismic reflection package that dips gently and onlaps basement rocks across the subsea part of the basin (Pascucci et al., 2000). Northeast-trending faults cut the lower Carboniferous strata, and tectonic activity was mid-Carboniferous or older because most faults within the strata can not be traced across the basal Morien unconformity (Pascucci et al., 2000).

Figure 6 illustrates the structural geology of the onshore and nearshore part of the Sydney Basin. Morien strata dip steeply near the Georges River Fault and at up to 50° on the limbs of the Bridgeport and Cape Percé anticlines, where they are cut by low-angle reverse faults (Haites, 1951, 1952; Hacquebard, 1983; Courtney, 1996). The two boundary faults show considerable vertical displacement at the western and southeast corners of the basin (Hacquebard, 1983).

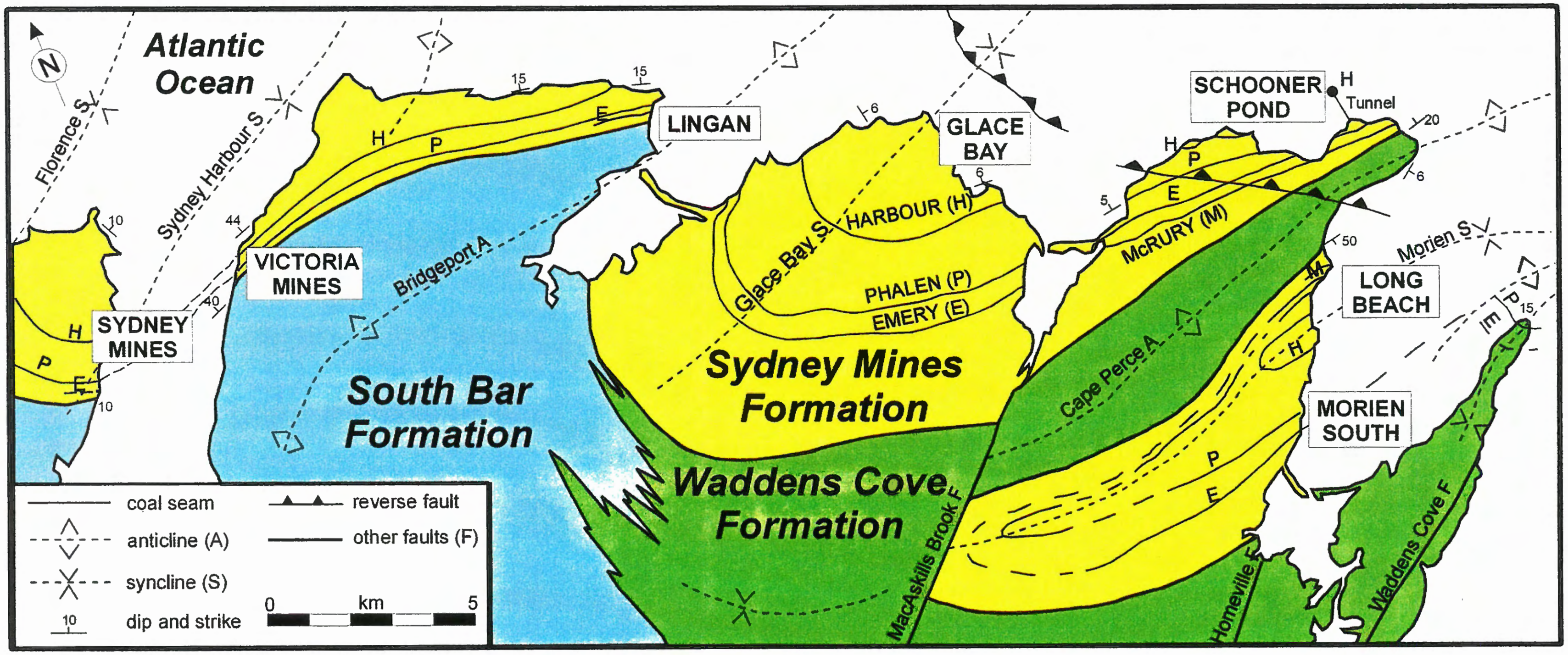


Figure 6. Geological map and structure of the onshore Sydney Basin. Modified after Gibling et al. (2002) and Pascucci et al. (2000).

Haites (1951) suggested a latest Carboniferous-Permian age for deformation, by comparison with the US Appalachians and Europe. Stratal thickness (Robb, 1876; Hacquebard, 1983) and facies evidence (Hacquebard, 1983; Gibling and Bird, 1994; Tandon and Gibling, 1997; Tibert and Gibling, 1999) indicate some synclines were paleotopographic lows during deposition of the Morien Group. This suggests modest movement on faults in the underlying basement and/or compactional draping over the faulted blocks (Hacquebard, 1983). These structures probably originated through variable subsidence due to sediment load, enhanced by differential compaction of the coal measure strata (Hacquebard, 1983). As the coal seams are a little thicker in local synclines, rather than the anticlines, the folding was likely initiated by warping during deposition (Hacquebard, 1983). Folding and faulting of Carboniferous strata is especially prominent in the southeastern part of the basin. The more intense deformation in the southeastern part of the basin reflects an active tectonic phase, probably during the Permian, linked to reactivation of basement faults and transpressional events (Pascucci et al., 2000; Gibling et al., 2002).

### *2.3.2 Morien Group*

Hayes and Bell (1923) applied the name 'Morien Group' exclusively to coal-bearing strata in the Sydney Basin. Morien strata (Duckmantian/Bolsovian to Cantabrian) now are included within the Cumberland Group coal measures (Calder, 1998). These strata are approximately 1800 m thick and rest on Visean/Namurian strata with an angular unconformity that correlates broadly with the Mississippian-Pennsylvanian unconformity of the Appalachian Basin (Calder, 1998; Pascucci et al., 2000). The coal measures reach maximum thickness in the Glace Bay and Port Morien districts

(Hacquebard, 1983). They have been divided into three biostratigraphic zones based on plant and spore fossils (Barss and Hacquebard, 1967). The group is further divided into the South Bar, Sydney Mines and Waddens Cove formations (Boehner and Giles, 1986) (Fig. 5).

The South Bar Formation (SBF) consists of grey sandstone, pebbly sandstone, and conglomerate with rare coals present. The SBF is a broadly upward fining succession about 1 km thick. It forms a braided river deposit dominated by trough cross-bedded sandstone (Rust and Gibling, 1990). Thick coals are rare, but numerous thin coals are found at many levels.

The Sydney Mines Formation (SMF) was deposited from meandering rivers and distributary channels traversing well to poorly-drained floodplains upon which extensive peat deposits formed periodically (Hacquebard and Donaldson, 1969; Masson and Rust, 1990). Large channel deposits often show well-developed ridge and swale topography and lateral accretion sets (Gibling and Rust, 1987, 1993). Tough faunal concentrate carbonaceous shales and limestones, up to 1m thick, contain a rich biota dominated by ostracodes and bivalves. These layers can also include domal stromatolites and xenacanthid shark remains (Masson and Rust, 1983, 1984). Sparse agglutinated foraminifera have been found in associated shales, implying periodic marine influences (Wightman et al., 1994). Economic coals up to 4.3 m thick exist in the SMF (Hacquebard, 1983) and represent the largest coal reserve remaining in eastern Canada.

The Waddens Cove Formation (WCF) is approximately 840 m thick (Gibling, 1995) and interfingers with the South Bar and Sydney Mines formations (Fig. 5). The WCF is predominantly red in colour with few economic coals and numerous channel deposits of low width-to-thickness ratio. It commonly includes red and grey sandstone and mudstone. Deposition likely occurred from sinuous channels in incised valleys, confined in part by silica-rich paleosols which developed in associated floodplain and channel-top sandstones (Gibling and Rust, 1990, 1992).

Paleoflow for the Sydney Mines Formation was broadly northeastward and rivers that traversed the basin probably rose within the Appalachian Orogen and drained eastward to marine basins in southern Europe (Gibling et al., 1992). The Sydney coalfield can be considered a paralic basin, as the banded autochthonous coals likely accumulated in extensive peat bogs that were formed and buried where the vegetation grew (Hacquebard, 1983). The splitting of coal seams is repeatedly observed across the Sydney Basin. Coal seam splitting is a common feature of all coals deposited in paralic basins and is the result of the interaction between peat deposition and fluvial sedimentation (Hacquebard, 1983). Seam splitting can represent changes in base-level or migration of delta lobes. Potential for hydrocarbons exists, as shown by gas seeps on the seafloor and along faults within the mines (Haites, 1951). Basal carbonates of the Windsor Group display oil shows (Pascucci et al., 2000; Gibling et al., 2002). Numerous gas shows also have been recorded from the Murphy et al. North Sydney P-05 and Shell et al. North Sydney F-24 wells (Fig. 1; Pascucci et al., 2000).

### *2.3.3 Coals*

The coal-bearing sequence contains 13 seams that attain metre-scale or greater (0.9 - 4.3 m thick), all mined in the past except for the youngest three coals (Hacquebard, 1983) and many more seams less than one metre in thickness. Figure 7 shows the major coal seams of the Morien Group. The Harbour and Phalen seams are the two most

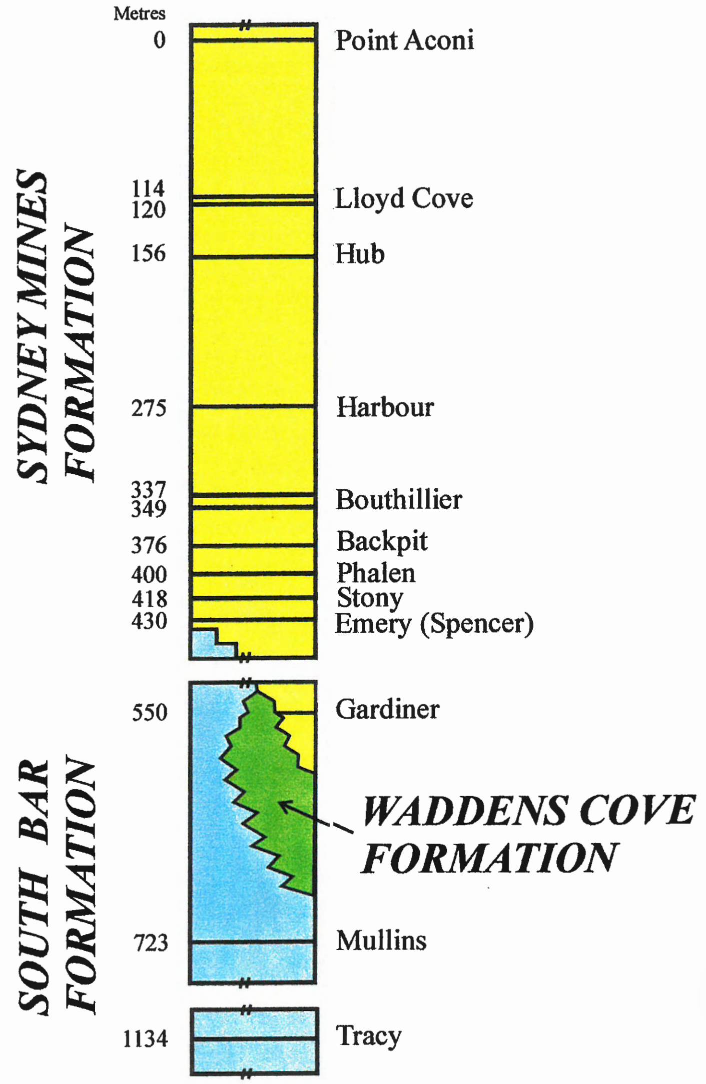


Figure 7. Stratigraphic sequence of Morien Group coal seams. From Marchioni et al. (1996).

productive seams, having been worked extensively in the offshore area adjacent to the coast (Hacquebard, 1983). The Sydney Mines Formation seams are high-volatile C to medium-volatile bituminous coals, with vitrinite reflectance values of 0.59 to 1.29%$R_o$ (Hacquebard and Donaldson, 1969; Hacquebard, 1983, 1998; Marchioni et al., 1996). They are banded humic coals with vitrinite predominant and low to moderate inertinite and liptinite. The coals contain abundant pyrite and average a sulphur content of 0.8-6.2%. A high ash content (>10%), dull banding and common seam splits suggest that the mires were periodically inundated and rheotrophic (Marchioni et al., 1994; White et al., 1994; Calder et al., 1996).

The mean sulphur content ranges from 2-7%, depending on where the sample is taken within the basin (Hacquebard and Donaldson, 1969). High sulphur content of coals is consistent with marine influence, but could also reflect derivation of sulphur from the thick, karstified evaporites of the Windsor Group which underlie the basin and may have formed part of the hinterland (Bell, 1929; Gibling et al., 1989). Evidence supporting this idea includes the presence of the major hiatus underlying the Morien Group and the abundance of reworked Visean palynomorphs in Morien strata (Dolby, 1988).

### 2.4 Previous Work – Sydney Basin

Exact identification of coal seams within the stratigraphic sections proved difficult in some areas where exposures and previous study information were limited. In order to confirm the coal seam identifications in the study stratigraphic sections, numerical comparisons were made with previous coal seam data from the study area and across the Sydney Basin. Many of these sources were at least seventy-five years old and could not be exactly followed due to natural changes in coastal exposures, past mining of seams in certain areas, and anthropogenic effects. However, a rough estimate of strata between coal seams was made in most cases and compared to measurements of the sections of this thesis. The area that provided most ambiguity was the Schooner Pond section. The most recent geological map (Boehner and Giles, 1986) shows only two coal seams exposed in this area, the Emery and Phalen seams. However, from the field mapping performed in this thesis, another significant coal seam was recognized.

MacNeil (1985) studied the coal seams in the Donkin area, investigating the Gardiner, Odell and McRury coal seams. The McRury seam is quite variable in thickness with a split developing in the seam south of Donkin (MacNeil, 1985). MacNeil (1985) studied mainly the area west of Schooner Pond Cove (Fig. 3) but found that the upper leaf of the McRury seam appeared in coastal exposures east of Schooner Pond Cove (MacNeil, 1985) as well. This corresponds to the first coal seam encountered on the beach at the Schooner Pond study section and supports this study's identification of the McRury seam as cropping out at Schooner Pond, contrary to the latest geological map (Boehner and Giles, 1986). This map has the McRury coal seam inland with no coastal exposure in this area. In summary, the seams exposed and measured along the Schooner Pond stratigraphic section are considered by the author to represent the McRury and Emery seams. While the Phalen seam could not be reached here by foot, the seam is visible and crops out approximately 8-10 m further up the vertical cliff face, from the end of the measured section.

In the Port Morien area, previous studies (namely Robb, 1876, and Hayes and Bell, 1923) helped the author confirm coal seam identifications. Some seams identified in the earlier studies did not exist in the coastal exposures in 2000 due to both past mining activities and coastal erosion. However, the measured strata thickness intervals between coal seams provided a simplistic record to use for comparison. At Long Beach the Emery, Phalen, Backpit, Boutilier and Harbour coal seams were recognized. The Emery to Boutilier stratigraphic interval here is studied in most detail. At Morien South, on the opposite side of the Morien syncline, the Emery to Backpit coal seam interval was studied.

The Sydney Basin has a long history of economic and academic studies that have led to the present day geological understanding of the Morien Group strata. Table 1 describes the major contributors of previous work in the Sydney Basin, with emphasis on the Sydney Mines Formation and the Morien-Donkin study area.

**Table 1. Previous Work in the Sydney Basin and Morien Bay area**

| **Author and Year** | **Scientific Contributions** |
|---|---|
| **Geological Mapping and Coal Mining** | |
| Brown 1871 | Subdivision of late Carboniferous strata of Sydney Basin into (1) Productive Coal Measures and (2) Millstone Grit. |
| Robb 1876 | Measurement of coastal stratigraphic sections in the Sydney Coalfield and major coal seams. Earliest mapping of Morien Bay and the coalfield. |
| Fletcher 1875-1909 | Geological report on the Sydney Coalfield. |
| Hayes & Bell 1923 | Named Late Carboniferous coal-bearing strata the "Morien Series". |
| Haites 1952 | Report on economic geology of the Sydney Coalfield. |
| Hacquebard and Donaldson 1969 | Paper on Carboniferous coal deposition associated with flood plain and limnic environments in Nova Scotia, contrasting Sydney and Pictou Coalfields. |
| Hacquebard 1983 | Economic evaluation of the Sydney Coal Basin. |
| Boehner & Giles 1986 | Produced geological map of the Sydney Basin. Formally divided Morien Group into Sydney Mines, South Bar, and Waddens Cove Formations. |
| **Paleontology and Biostratigraphy** | |
| Hayes et al. 1938 | Described three macrofossil biostratigraphic zones within Morien Group: *Lonchopteris, Linopteris obliqua, and Ptychocarpus unitus.* |
| Bell 1938, 1944 | Descriptions of the flora of the Sydney Coalfield. |

| | |
|---|---|
| Barss & Hacquebard 1967 | Assigned biostratigraphic zones to Morien Group from spore assemblages: *Vestispora, Torispora, and Thymospora.* |
| Zodrow & McLandish 1978 | Grouped upper two Hayes et al. (1938) macrofossil zones into the *Linopteris obliqua* zone. |
| Zodrow & Cleal 1985 | Related macrofloral zones of Sydney Basin to European strata. |
| Thibaudeau & Medioli 1986 | Described thecamoebians and freshwater forams from the Sydney Mines Formation. |
| Calder 1998 | Compiled floral and faunal listings of the "Morien Group". |
| **Sedimentology and Stratigraphy** | |
| Best 1984, Rust et al. 1983, Gibling & Rust 1984 | Informally divided Morien Group strata into "upper Morien Group" and "Morien Group". |
| Gibling et al. 1992 | Paleoflow and drainage patterns of the "Morien Group". |
| Gibling & Bird 1994 | Recognition of cyclothem successions in the Sydney Mines Formation. |
| Marchioni et al 1996 | Depositional history of coal seams in "Morien Group". |
| Tandon & Gibling 1997 | Recognition of calcretes and sequence boundaries in the Sydney Mines Formation. |
| Batson & Gibling 2002 | Architecture of channel bodies and paleovalley fills in the Sydney Mines Formation. |
| **Structural and Seismic Geology** | |
| King & MacLean 1976 | Seismic exploration of areal extent of the Sydney Basin. |
| Gibling et al. 1987 | Tectonic setting of Sydney Basin. Emphasis on onshore exposures. |
| Pascucci et al. 2000 | Late Paleozoic to Cenozoic structural history of the offshore Sydney Basin. |
| Gibling et al. 2002 | Deformation of coal measures within the Sydney Basin. |

## Chapter 3: FACIES AND FACIES ASSEMBLAGES

Coal-bearing strata, characteristic of the Sydney Mines Formation, are recognized at Morien Bay, Nova Scotia. Sedimentary facies were identified and correlated at all three outcrop sections and grouped into facies assemblages based on lithology, sedimentology and fossils. These facies assemblages broadly represent those documented in other parts of the Sydney Basin by Gibling and Bird (1994), White et al., (1994), Tandon and Gibling (1997), and Batson and Gibling (2002).

For semi-quantitative descriptions of facies, sedimentary structures and fossils were classified as abundant, common, uncommon, or rare. Table 2 shows the results of this classification as well as further detail on each facies. The facies are divided into groups: 1= coal, 2= limestones, 3= clay-rich sheets, 4= silt- and sand-rich sheets, 5= channel bodies. Facies proportions at Schooner Pond, Long Beach, and Morien South are shown in Figure 8. The distribution of all facies present at each section is graphically represented. Differences between the two distributions will be discussed in Section 3.2 (Facies Assemblages). Appendix 1 contains the measurements used in facies calculations.

### 3.1 Facies Descriptions

#### *Facies 1: Coal*

Numerous economic coal seams (former peats) are recognized within the Sydney Mines Formation. The McRury to Harbour coal seam intervals are represented in the study sections (Fig. 7). Generally the coals are bright banded, humic coals ranging from 0.14-2.8m in thickness. Thin, millimeter-scale vitrinite layers are prominent in hand specimen, with numerous mudstone partings present within the larger seams (e.g., the Phalen seam). All types of coal, regardless of rank or thickness, qualify as histic horizons

Table 2. Facies Recognized in sections at Long Beach, Morien South and Schooner Pond

| GROUP | FACIES # | NAME | COLOUR | GRAIN SIZE | SEDIMENTARY FEATURES | FOSSILS | THICKNESS ave(range) | INTERPRETATION |
|---|---|---|---|---|---|---|---|---|
| Coal | 1 | COAL | black | organic material, clay | a: banded humic coals, thin vitrinite layers and mudstone partings; c: yellow (pyrite) weathering stains | a: macroflora and plant fragments, organic material | 0.9m (0.14-2.8m) | Peat formed in mires |
| Limestones | 2a | CARBONACEOUS LIMESTONE | d. grey and black | silt - f.sand | a: planar to wavy stratification | a: bivalves; c: ostracods; u: fish bone fragments | 0.3m (0.18-0.35m) | Standing water with high organic accumulation; possible marine influence |
| | 2b | CALCAREOUS SANDSTONE AND MASSIVE LIMESTONE | m. grey | v.f - f.sand | c: ripple cross-lamination, nodular bedding, planar lamination, trough cross-beds | u: roots | 0.66m (0.15-2.3m) | Shallow standing water or palustrine environment; Beginning of pedogenesis into carbonate soil |
| | 2c | NODULAR CALCRETE | m. grey | silt | a: irregular surface topography, nodular bedding; c: calcite nodules, disrupted bedding; r: siderite nodules | a: roots | 0.4m (0.25-0.7m) | Carbonate soil formed under seasonal, semi-arid climate; low sediment influx |
| Clay-rich sheets | 3a | NON-STRATIFIED GREY CLAYSTONE | m. grey | clay (some silt) | a: disrupted bedding; c: calcareous nodules; u: red/green mottles, ripple cross-lamination, thin coaly layers; r: vertical root-trace fill | a: roots, macroflora and plant fragments; c: stigmarian roots, *Calamites* stems | 0.4m (0.1-2.1m) | Hydromorphic paleosols formed in poorly drained settings |
| | 3b | LAMINATED GREY CLAYSTONE | m. grey | clay (some silt) | a: planar lamination; c: siderite nodules, thin coaly layers; r: rain prints, mud cracks, adhesion warts, calcareous concretions | a: macroflora and plant fragments; c: roots, stigmarian roots; u: bivalves, ostracods; r: arthropod trackway | 0.8m (0.2-2.0m) | Shallow, standing water bodies and wetlands with clastic influx |
| | 3c | UNCONSOLIDATED GREY CLAY | d. grey and black | clay | a: unconsolidated, disrupted bedding; c: thin coaly layers | a: plant fragments, roots | 0.5m (0.05-2.45m) | Shallow standing water with high vegetation influx; Incipient peat mires |
| | 3d | NON-STRATIFIED RED CLAYSTONE | red and m.grey | clay | a: disrupted bedding; c: red/green mottles | none | 0.75m (0.2-1.8m) | Red vertisols, likely formed in seasonal, well-drained settings |
| | 3e | LAMINATED RED CLAYSTONE | red and m.grey | clay | a: planar lamination; c: desiccation cracks, burrow traces, calcareous nodules | u: plant fragments, roots; r: tree stumps | 0.5m (0.06-1m) | Well-drained to possible lacustrine settings |

Table 2 continued…

| GROUP | FACIES # | NAME | COLOUR | GRAIN SIZE | SEDIMENTARY FEATURES | FOSSILS | THICKNESS ave(range) | INTERPRETATION |
|---|---|---|---|---|---|---|---|---|
| Silt- and sand-rich sheets | 4a | NON-STRATIFIED GREY SILTSTONE AND SANDSTONE | m.-d. grey | silt - v.f.sand | a: disrupted bedding, ripple cross-lamination, siderite concretions, calcareous concretions; u: climbing ripples, flute casts, concave-up joint sets, graded beds, vertic fabric | a: roots, macroflora and plant fragments; c: calamites stems (upright), stigmarian roots, *Lepidodendron* erect tree trunks; u: *Cordaites* leaves | 0.8m (0.15-3.9m) | Hydromorphic paleosols formed in poorly drained settings (either above or below mire or incipient mires) |
|  | 4b | STRATIFIED GREY SILTSTONE AND SANDSTONE | l.-m. grey | silt - f.sand | a: planar lamination, ripple cross-lamination; c: siderite nodules, trough cross-strata, calcareous nodules; u: adhesion warts, desiccation cracks, raindrop imprints, climbing ripples, groove casts, burrow traces, organic shale flooding horizons | a: macroflora and plant fragments, roots; c: stigmarian roots, *Calamites* stems (upright), lycopsid trees (erect), radial roots (seed-ferns); u: burrows, *Arthropleura* trackway, *Cordaites* leaves, *Pinnularia* | 1.5m (0.1-8.9m) | Shallow, standing water bodies and wetlands with clastic influx. Fluctuating water table and periodic subaerial exposure |
|  | 4c | RED SILTSTONE | d.red and grey | silt | a: disrupted bedding; c: concave-up joint sets, siderite nodules; u: mottles | c: plant fragments | 0.8m (0.7-2.5m) | Well drained soils |
|  | 4d | STRATIFIED RED SILTSTONE | red and d. grey | silt | a: planar lamination; c: calcareous concretions, desiccation cracks, rain prints; u: burrow traces, cross-lamination | u: plant fragments, tree stumps | 1.3m (0.57-1.8m) | Well drained soils |
|  | 4e | SANDSTONE SHEETS | m.-d. grey | v.f. sand | a: planar lamination; c: calcareous concretinos, wavy cross-lamination, disrupted bedding | c: roots, plant fragments, calamites fragments; u: stigmarian roots | 0.75m (0.4-1.65m) | Crevasse splays or flood sheets in well-drained settings |
| Channel fill facies | 5a | THIN CHANNEL BODIES (single storey) | m. grey | f. - m.sand | a: ripple cross-lamination, planar lamination; c: trough cross-strata, conglomerate deposits at base, groove casts; u: plane beds, calcareous concretions, desiccation cracks, rain prints, siderite nodules | a: roots; c: macroflora and plant fragments; u: tree stumps, *Calamites* stems (upright) | <2.5m (0.5-2.5m) | Smaller channels / crevasse feeders; common to poorly drained facies assemblage |
|  | 5b | THICK CHANNEL BODIES | l.-m. grey | m. - c. sand | a: ripple cross-lamination, trough cross-strata, planar lamination, multiple storeys; c: conglomerate lenses, mud clasts, plane beds, primary current lineation; u: groove casts, rain prints, desiccation cracks, siderite nodules, rill marks | c: roots; u: macroflora and plant fragments; r: tetrapod trackways | >2.5m (4.75-6.5m) | Large alluvial-distributary channels on vegetated, well-drained floodplain |

**Notes:**

| Colour Descriptions: | Grain Size Descriptions: | Sedimentary Structures and Fossil Descriptions: | Thickness Descriptions: |
|---|---|---|---|
| l: light<br>m: medium<br>d: dark | v.f.: very fine<br>f: fine<br>m: medium<br>c: coarse | a: abundant, c: common, u: uncommon, r: rare | Average thickness (range in parentheses) |

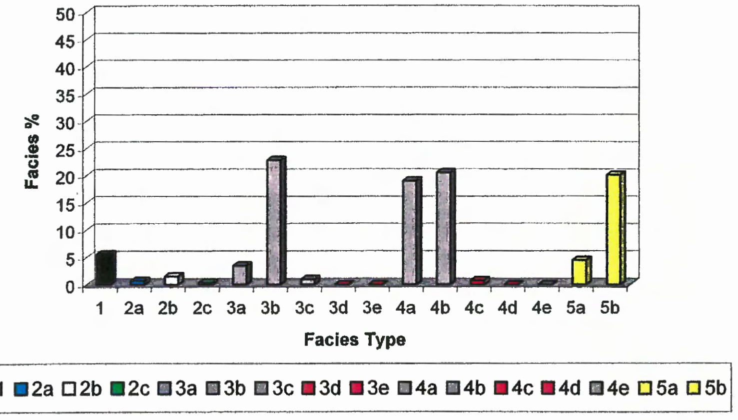


**Figure 8a - Facies proportions for Sydney Mines Formation sections at Schooner Pond. Legend explained in Table 2.**

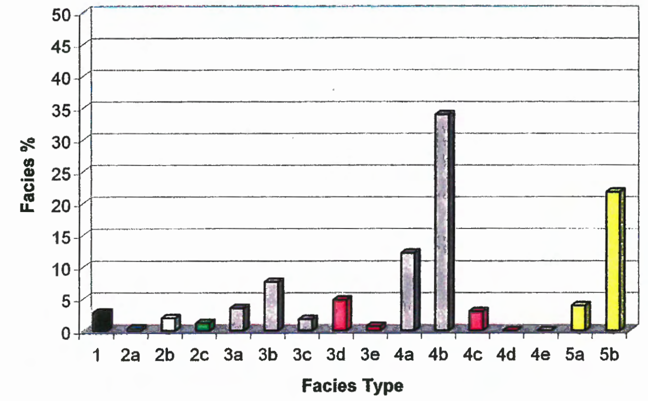


**Figure 8b - Facies proportions for Sydney Mines Formation sections at Long Beach.**

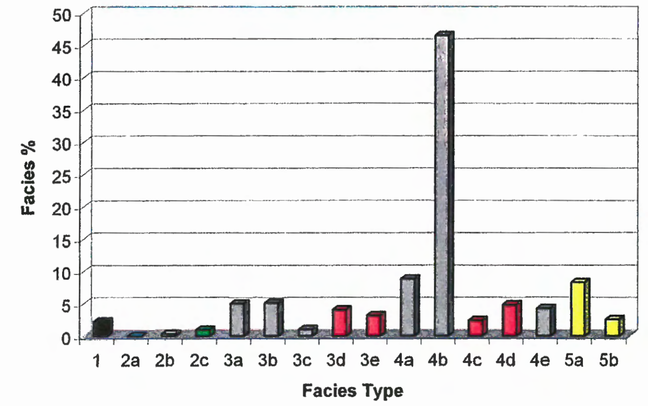


**Figure 8c - Facies proportions for Sydney Mines Formation sections at Morien South**

Figure 8 a-c. Facies Proportions of the Schooner Pond, Long Beach, and Morien South study sections.

and belong in the paleosol order Histosol (Mack et al., 1993). The coal seams are usually underlain by grey rooted seat-earths and found in association with abundant compression flora fragments and organic material. Figure 9 shows the Emery seam at Schooner Pond and Morien South. Section 2.3.3 provides a brief summary of the petrography of the Sydney Mines Formation coal seams.

The coals represent deposition in peat-forming areas (mires). The Emery, Phalen, Backpit, and Harbour coal seams are traceable across the entire Sydney Basin and aid in correlating facies packages over a large distance. Discontinuous thin coaly layers are developed locally within organic rich mudstones and shales. Inextensive coal seams probably formed in local bays or alluvial backswamps (Gibling and Bird, 1994).

### *Facies 2a: Carbonaceous Limestone*

Dark grey and black carbonaceous limestone facies form distinct layers ~30cm thick on average. These hard resistant layers stand out from the adjacent sedimentary layers (Fig. 10 a&b) and some are traceable for many kilometres across the basin. Abundant faunal concentrate layers of bivalves and ostracodes +/- fish spines define this facies, as well as secondary planar to wavy stratification. Micritic calcite is the predominant mineral present (Gibling and Kalkreuth, 1991). Figures 10c and 11b are thin section photographs of this facies from samples at Schooner Pond and Long Beach. The grain size ranges from clay to silt. This facies is commonly found either above or in close proximity to coal seams. The best correlative example of this facies in the study area is displayed above the Phalen coal seam at Long Beach, where it lies at a similar level to the fossiliferous limestones found above the Phalen seam in other sections of the Sydney Basin (Gibling et al., in press). Specific faunal identifications within this facies are

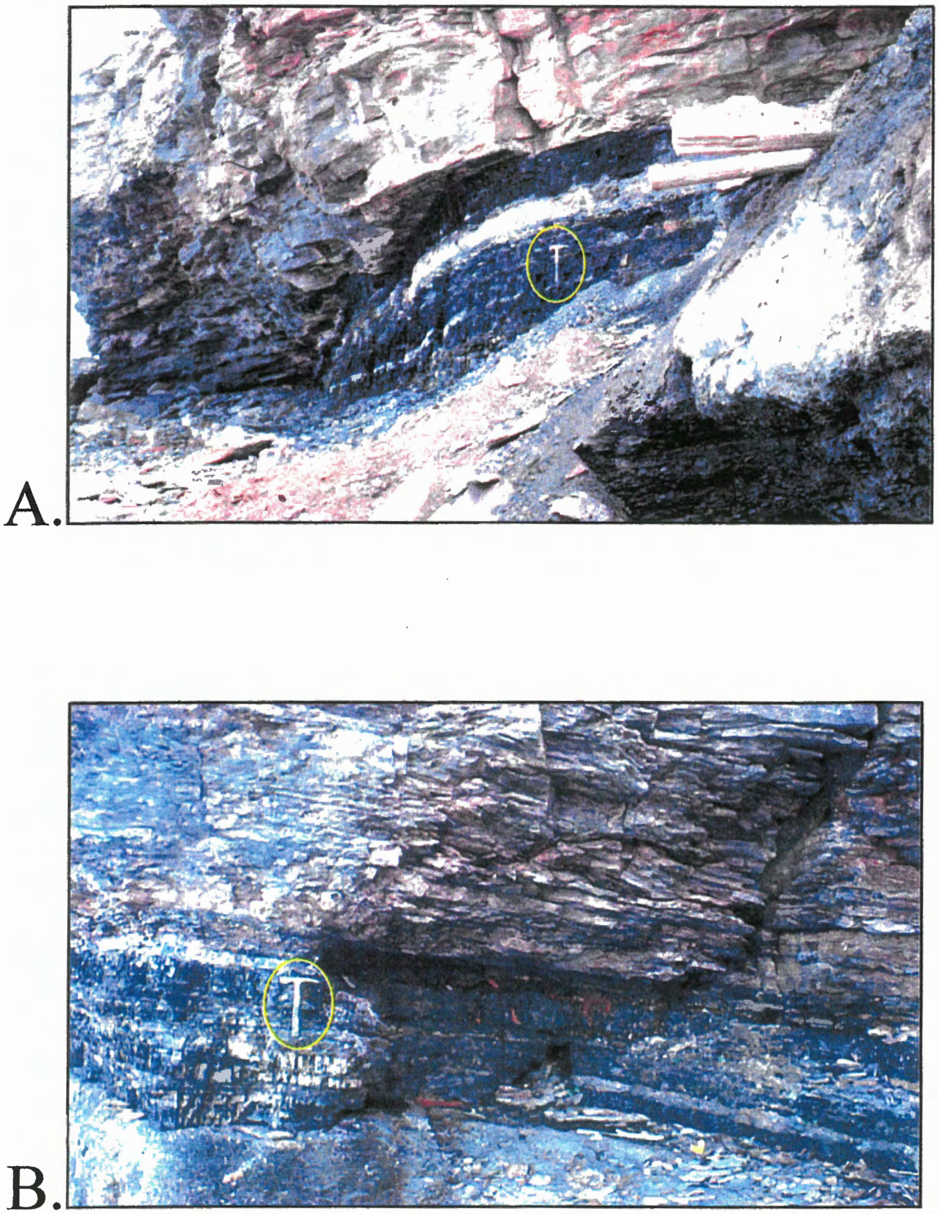


Figure 9 a & b. Photographs of the Emery coal seam (Facies 1) at Schooner Pond (A) and at Morien South (B). Hammer (circled) is ~30cm for scale.

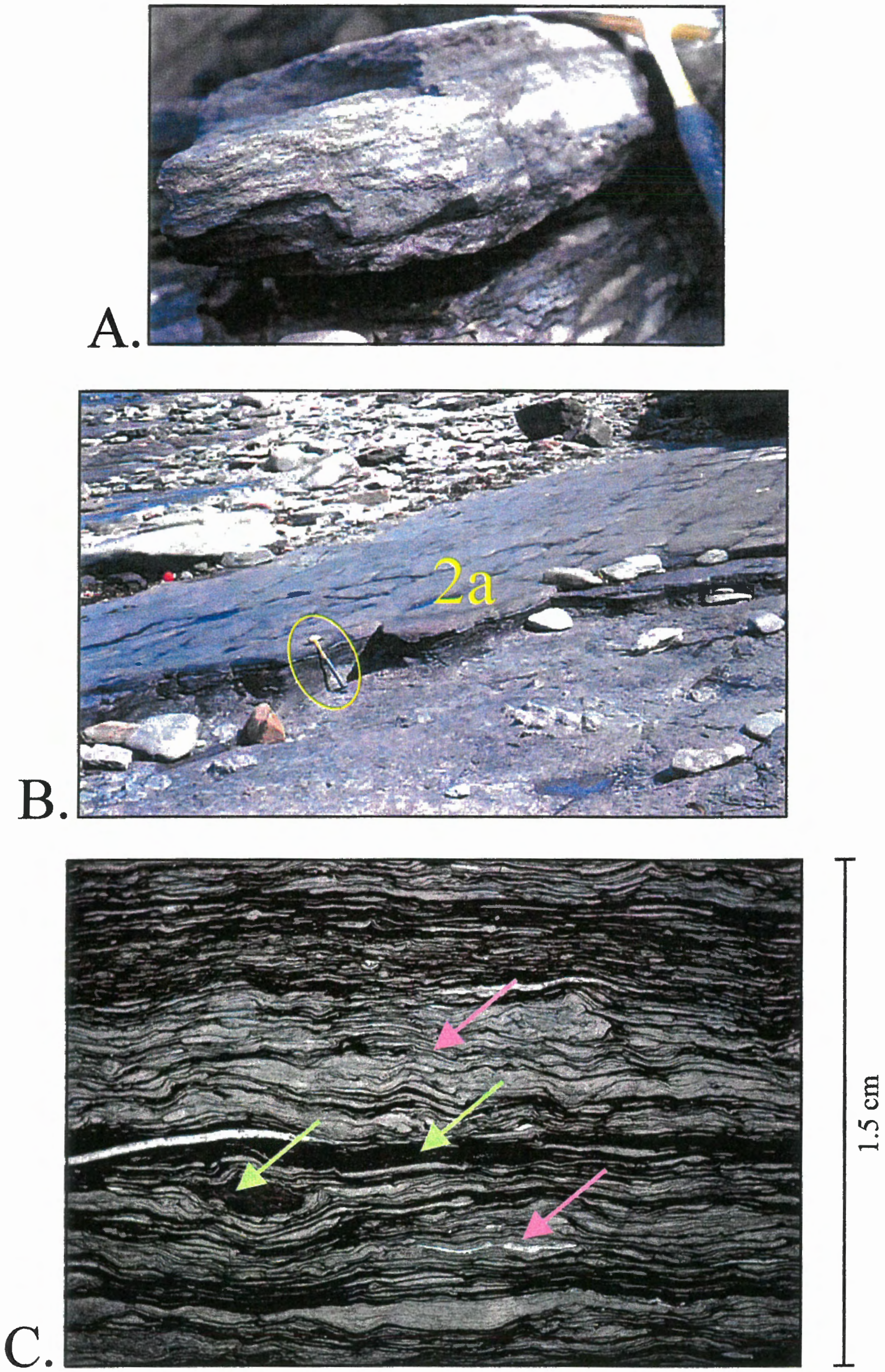


Figure 10 a-c. Carbonaceous limestone (Facies 2a) at Schooner Pond. A) Close-up photograph of limestone unit. Hammer (circled) is ~30cm for scale. B) View of resistant limestone unit extending across wave-cut platform. C) Thin section photograph of limestone with abundant bivalve fragments (pink arrow) and fine organic matter (green arrow).

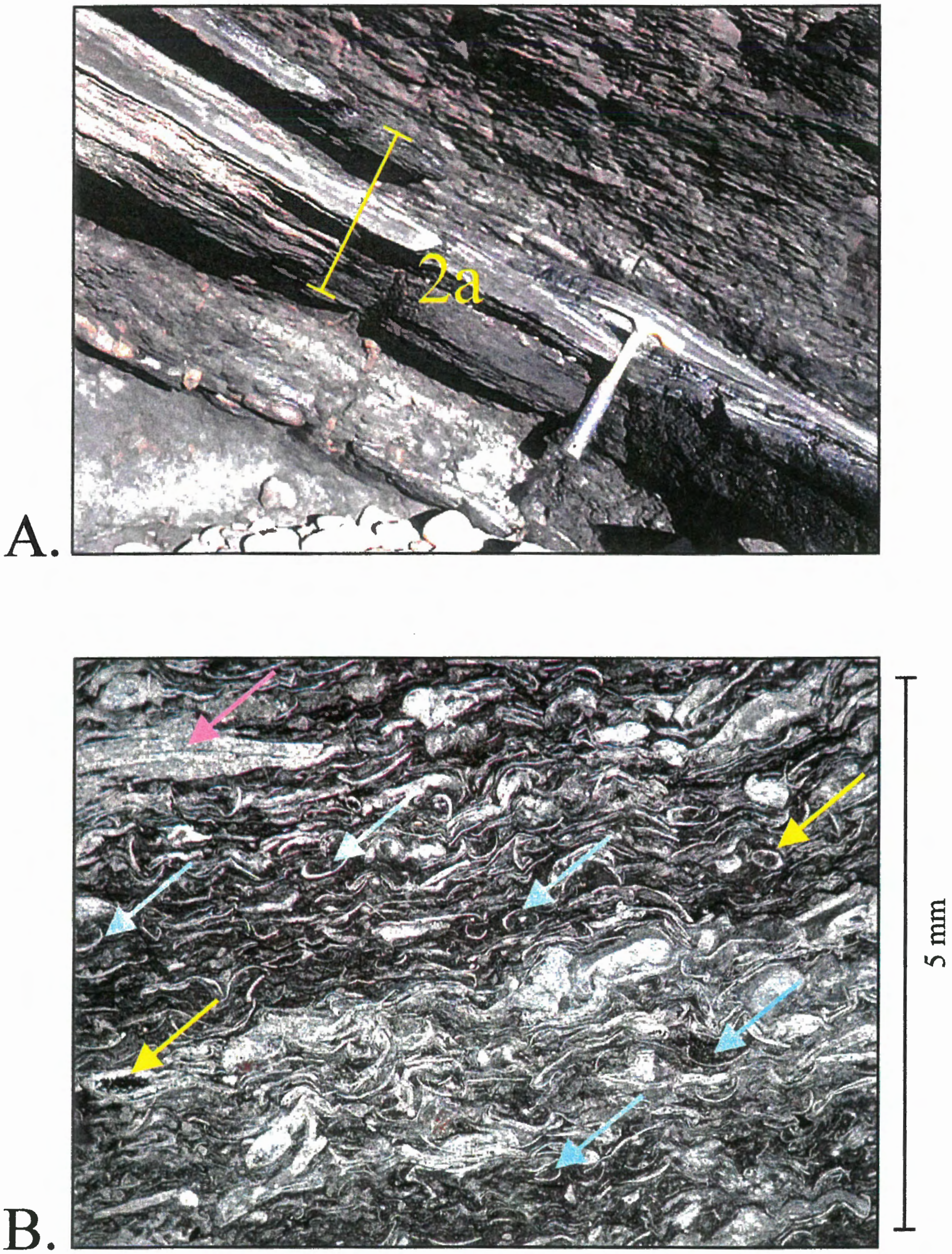


Figure 11 a & b. Carbonaceous limestone at Long Beach (Facies 2a). A) Outcrop view of limestone. Hammer is ~30cm for scale. B) Thin section photograph of bioclastic limestone with abundant single ostracod valves (blue arrows), complete two valved ostracods (yellow arrows), and long thin bivalve fragments (pink arrow).

described in Gibling and Bird (1994) and include bivalves (*Anthraconauta*, *Anthraconaia*, and *Naidites)*, ostracods (*Carbonita* and *Candona)*, estheriids, branchiopods, the serpulid worm *Spirobis*, agglutinated foraminifera and thecamoebians. Osteichthyan fish fragments (Masson and Rust, 1983, 1984) and fragments of algae representing *Girvanella*, *Garwoodia*, and *Ortonella* have also been identified (Copeland 1959; Gibling and Bird 1994; Calder 1998).

This facies represents periods when large parts of the basin were inundated, and the units probably formed in extensive brackish to freshwater bays where organic matter accumulated in condensed layers during times of minimal detrital input (Gibling and Bird, 1994). The facies likely formed in relatively deep standing bodies of water, which accounts for the fine grained and organic rich nature of the facies. This facies represents the deepest water conditions of deposition, but overlying coarsening-upward units a few metres thick suggest relatively shallow water (Gibling and Bird, 1994). Because of the dark colour and high organic content, the water bodies may have been slightly restricted and dysaerobic at times.

### *Facies 2b: Massive Limestone and Calcareous Sandstone*

This facies consists of massive medium-grey calcareous sandstone and limestone sheets, typically very fine- to fine-grained. The facies commonly displays both ripple cross-lamination and planar lamination, nodular layers of calcareous nodules, and trough cross-stratification is present but uncommon. These beds range from 0.15-2.3m in thickness and uncommonly preserve roots. They are typically ~0.66m thick on average. No other fossils were identified in this facies.

This facies is interpreted to have formed in shallow standing water bodies because of the high carbonate content and planar lamination. These limestones could also be identified as palustrine, forming under occasional subaerial exposure as indicated by roots and the nodular form. This facies is in the early stages of pedogenesis, gaining characteristics of carbonate soils (Fig. 12a).

### ***Facies 2c: Nodular Calcrete***

These hard, resistant layers display irregular surface topography partially due to the presence of large stacked calcareous nodules (Fig. 12a). The layers are typically grey with slight yellow-green weathering, and are composed of silt-sized grains. They display nodular bedding of irregular, tough, coalesced calcareous nodules (Fig. 12b). The bedding is commonly disrupted by the presence of root action. The layers are 25-70cm thick and the calcretes can be traced across parts of the basin.

These calcretes formed from the subaerial exposure and pedogenesis of the original clastic sediments. They display a vertic facbric and correspond with calcretes described by Tandon and Gibling (1997), which represent calcrete development to stage II/III of Machette (1985). The calcretes are interpreted as calcic soils that formed under a seasonal climate in well-drained and low sediment input settings.

### ***Facies 3a: Non-Stratified Grey Claystone***

Disrupted, non-stratified grey claystones are abundant in all sections. Facies 3a is composed of non-stratified medium grey claystone, locally up to 2.1 m in thickness. Ripple cross-lamination is visible in places but is not well preserved. Roots are abundant

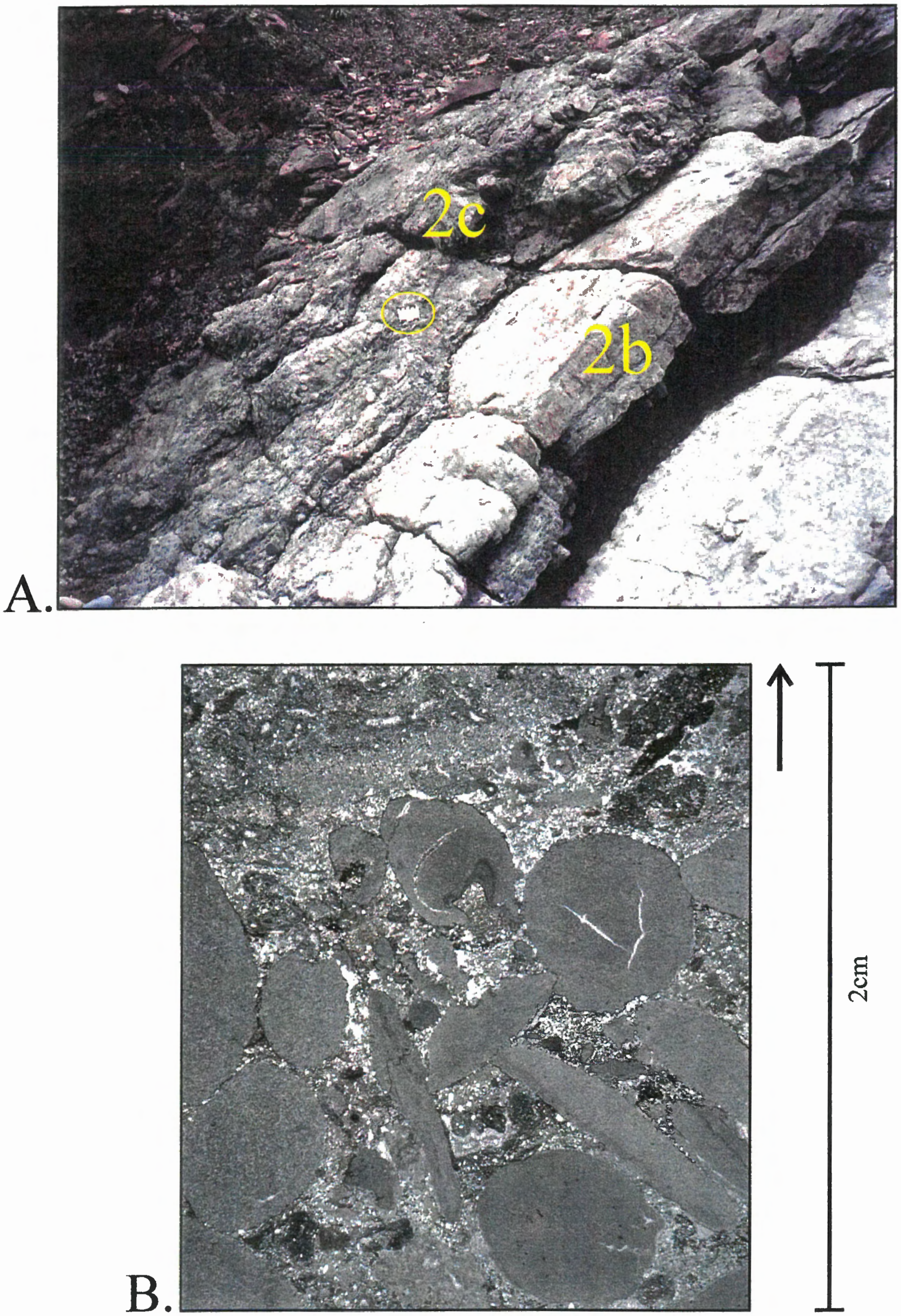


Figure 12 a & b. A) Calcrete (Facies 2c) and calcareous sandstone (Facies 2b) at Long Beach. Scale card (circled) is ~10cm. B) Thin section photograph of calcrete unit containing reworked carbonate material, transported material and silt grains.

and large stigmarian root systems are commonly preserved in the disrupted layers. Also present are thin layers of organic rich, coaly shale. *Calamites* stems are also identified. Red/green mottled layers and vertical root-trace fills are present but uncommon in the facies. Figure 13 shows a vertical root-crack fill in Facies 3a.

This facies is interpreted as hydromorphic paleosols formed in poorly drained saturated settings on a floodplain. Conditions were wet and occasionally saw subaerial conditions. Deposition occurred by crevasse splays on the delta plain and infilling of freshwater or restricted-marine bays (Gibling and Bird, 1994). Preservation of in situ *Calamites* stems in this facies supports the interpretation of disturbed, flood-prone settings, with recurrent sedimentation (Calder et al., in review).

### *Facies 3b: Laminated Grey Claystone*

This facies consists of fine-grained deposits with well-defined stratification on a millimetre-scale (Fig. 14). Siderite nodules are common within the claystone (Fig. 15) with a small proportion of calcareous concretions. Rare sedimentary structures include raindrop impressions and mudcracks. Roots, compression macroflora, and plant fragments are commonly preserved, as well as in-situ *Calamites* trunks. Bivalves and ostracodes are present but uncommon. Well-preserved tetrapod footprints were found within this claystone facies.

This facies is interpreted to have been deposited in standing bodies of water such as lakes or shallow bays exposed to clastic input, as indicated by the well-preserved stratification. However, paleosols formed locally in these poorly drained settings have a hydromorphic aspect (Gibling and Bird, 1994). Water bodies likely shallowed or dried up completely at some point, as indicated by the minor presence of mudcracks and

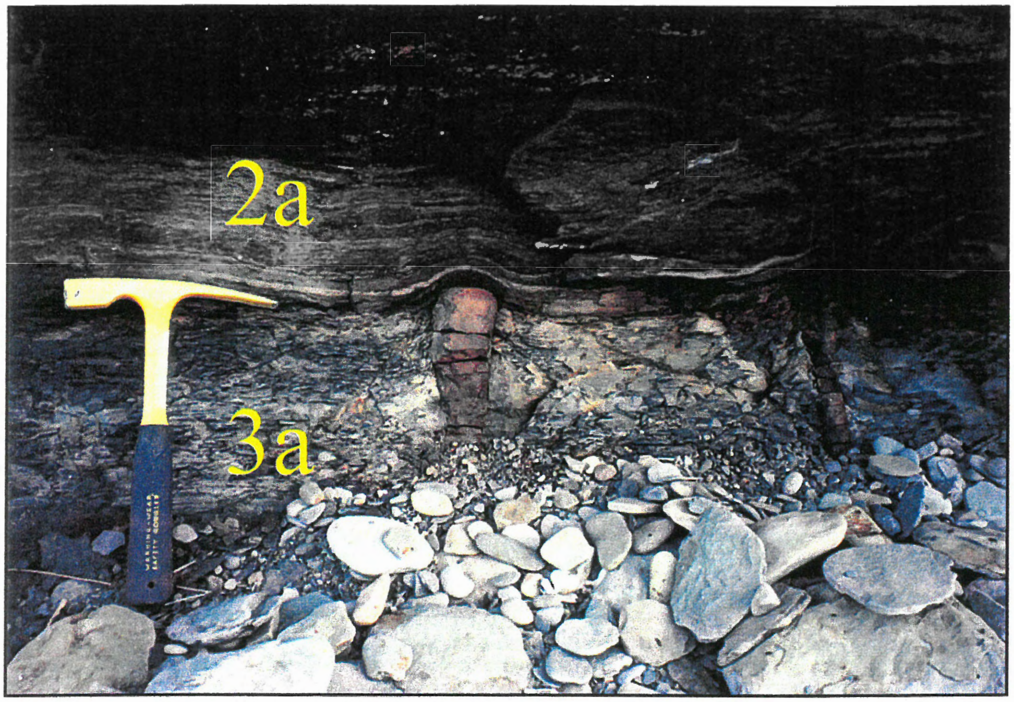


Figure 13. Non-stratified grey claystone (Facies 3a) at Long Beach with vertical root-cracks infilled by siderite. Carbonaceous limestone (Facies 2a) also pictured. Hammer is ~30cm for scale.

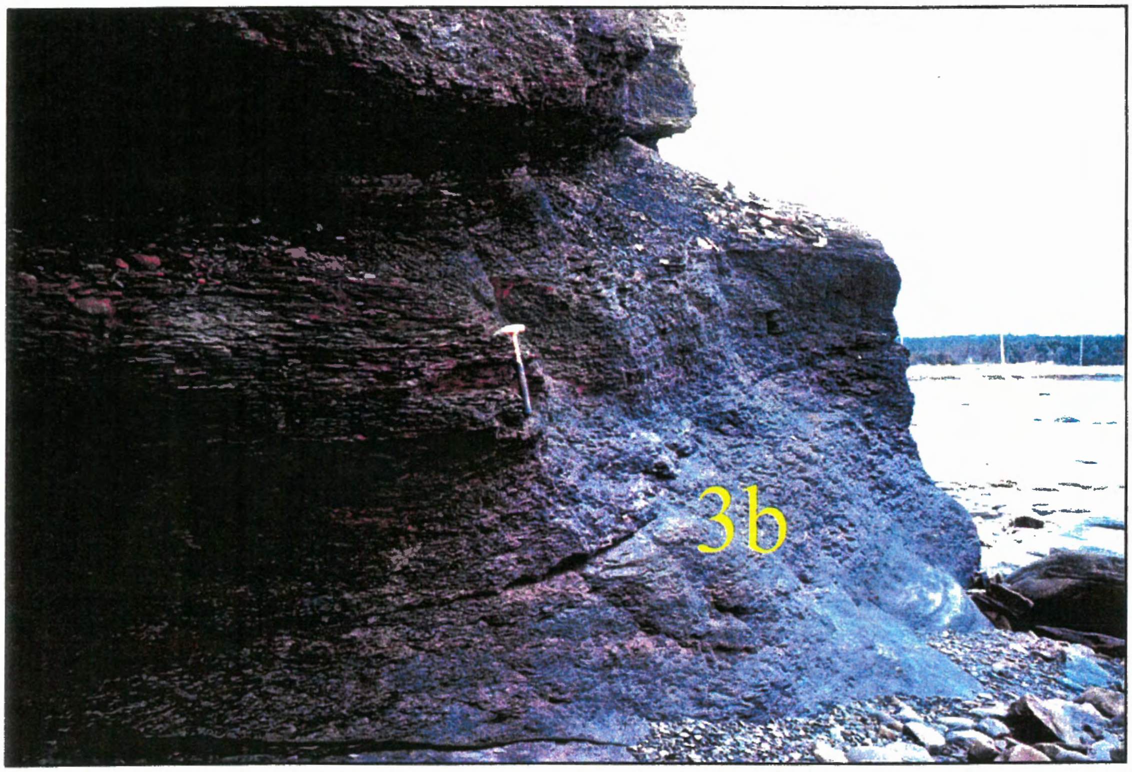


Figure 14. Laminated grey claystone facies (Facies 3b) at Schooner Pond. Hammer is ~30cm for scale.

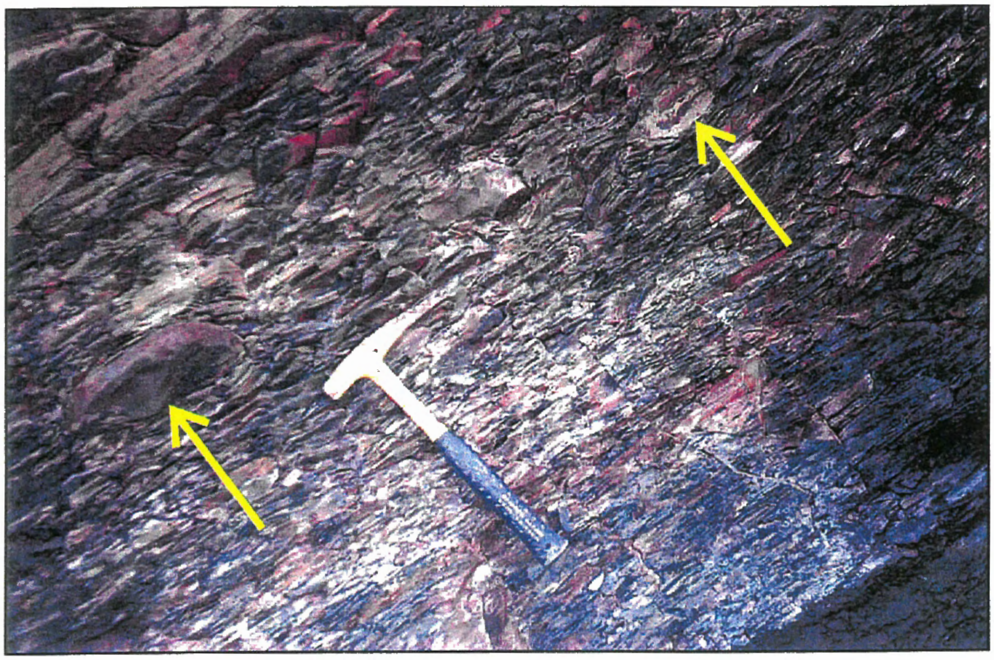


Figure 15. Laminated grey claystone (Facies 3b) at Morien South with well defined planar lamination and numerous siderite nodules (arrow). Hammer is ~30cm for scale.

rainprints. Periods of increased disturbance or sedimentation also likely occurred, indicated by the preservation of in situ *Calamites* stems in this facies. The presence of siderite nodules (Fig. 15) indicates a reducing or restricted environment. Pye (1984) described siderite cements in intertidal marsh sediments and Potsma (1982) described the formation of siderites in brackish and freshwater swamp sediments. In modern marsh sediments, the occurrence of early authigenic $Fe^{+2}$-rich carbonates, particularly siderite, suggests that anoxic conditions developed rapidly (Moore et al., 1992).

### *Facies 3c: Unconsolidated Grey Clay*

This facies consists of soft, grey, unconsolidated clay material. It is often waterlogged, poorly exposed, and very weathered in the outcrop (Fig. 16). This facies is commonly called ‘underclay’ or ‘seat earth’ as it is found mainly underneath and in association with major coal seams. It is very rich in organic material. It ranges in colour from dark to charcoal grey and consists of mainly clay sized particles, with the occasional silty mud. No sedimentary structures or stratification is preserved and coaly layers or stringers are often found cutting through the unit, possibly traces of coalified stigmarian compressions. Soft coaly fragments are also very common. It is very rich in plant material fragments, not entire preserved fossils. Woody plant debris and plant roots were also found. Very rare limey layers were occasionally found within this unit.

This unit was likely deposited in poorly drained settings similar to Facies 3a and then directly covered by layers of peat that did not always accumulate to form coal. It can also be thought of as a type of hydromorphic paleosol. It is often disrupted due to its proximity to the major coal seams and groundwater action.

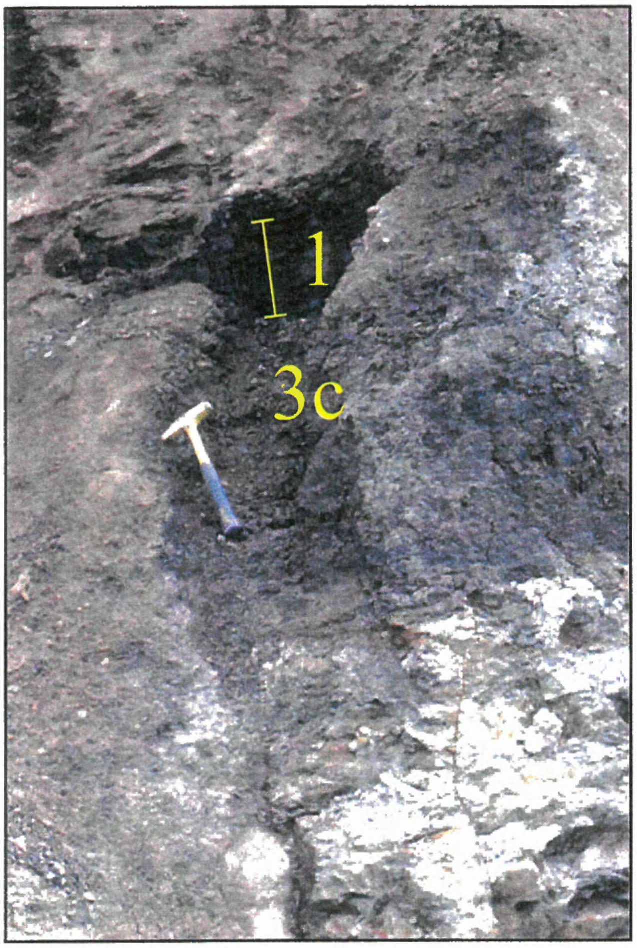


Figure 16. Pit dug at Schooner Pond to identify coal (Facies 1) and unconsolidated grey clay facies (Facies 3c). Hammer is ~30cm for scale.

### *Facies 3d and 3e: Red Stratified and Non-stratified Claystone*

Laminated red claystone layers (Facies 3e) are finely bedded and average 0.5m in thickness, ranging from 6cm to 1m (Fig. 17). Mudcracks are common at many levels throughout this facies. Calcareous nodules and burrows are also common. Although stratification is well-preserved, root traces are present within the layers but are uncommon. Plant fragments are rare and consist mainly of fragments of compression flora. Rare unidentifiable tree stumps are also present. Grey and green mottled layers are also present.

Non-stratified red claystone layers (Facies 3d) resemble the stratified red claystone strata, the major difference being the disruption of the bedding by abundant roots (Fig. 18a). Roots preserved as carbonaceous traces are abundant. These layers average 0.75 m in thickness and range from 0.2-1.8 m thick. "Onion-skin" weathering is apparent as well as red and green mottled layers that reflect reduction (green colour) linked to the former presence of organic material, including roots (Fig. 18b). No fossils other than roots were identified.

The mature paleosols represented by non-stratified red claystone resemble vertisols described from interior Australia (Rust and Nanson, 1989) where groundwater levels are generally low and the climate is strongly seasonal. Facies 3d and 3e are interpreted as well drained, calcic vertisols. These paleosols likely formed on well-drained floodplains and under seasonal climatic conditions, equivalent to the calcic, vertisol-like paleosols described in other outcrops of the Sydney Mines Formation by Tandon and Gibling (1997). The laminated strata are not as affected by root action and

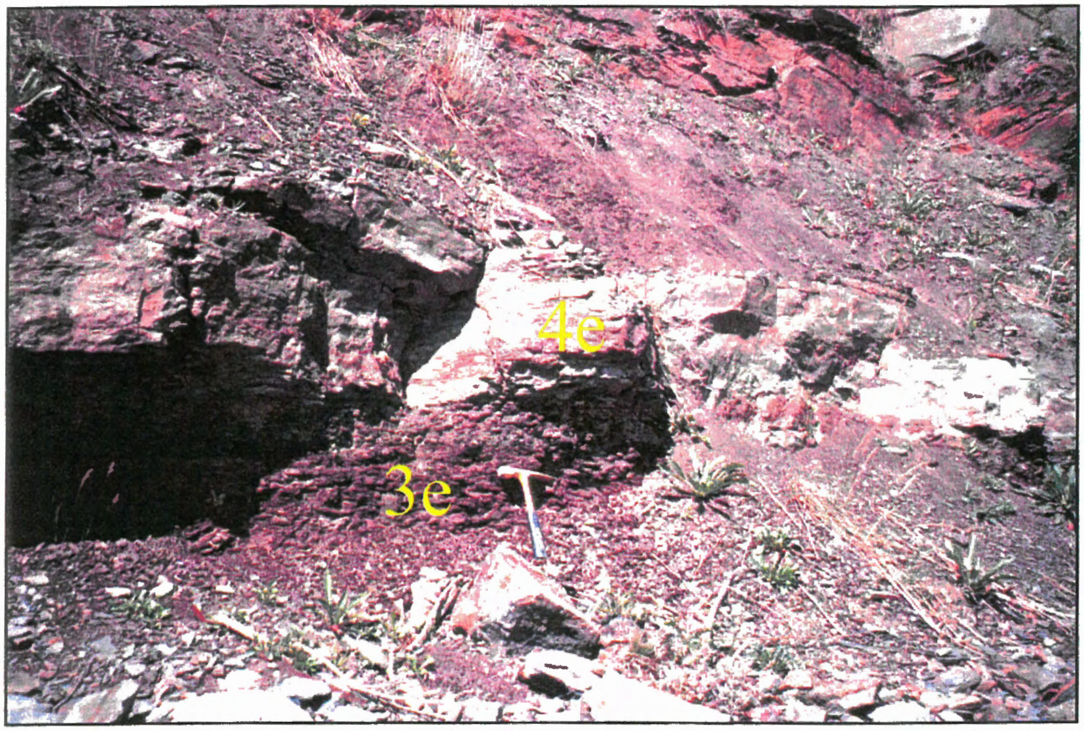
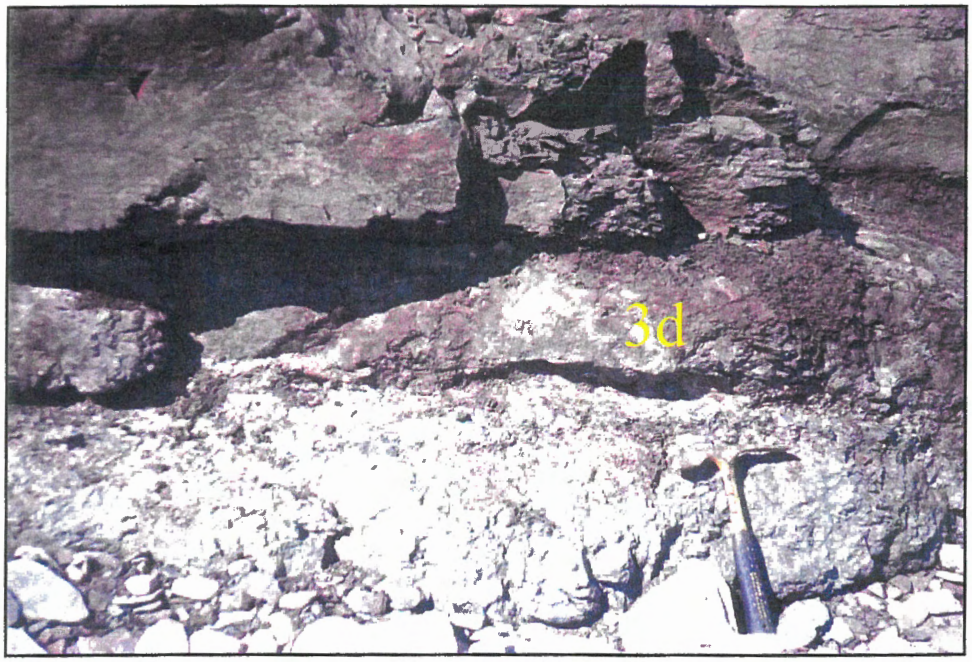


Figure 17. Laminated red claystone facies (Facies 3e) and sandstone sheets facies (Facies 4e) at Morien South. Hammer is ~30cm for scale.

A.


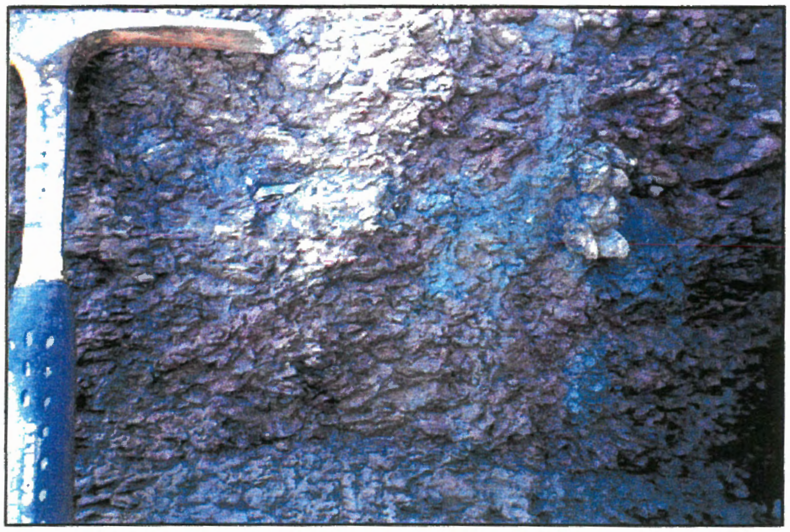
B.


Figure 18 a & b. A) Non-stratified red claystone (Facies 3d) at Morien South. Hammer is ~30cm for scale. B) Red and green mottles around root traces in Facies 3d at Morien South.

therefore may have seen a higher sediment influx and deeper water conditions allowing for the deposition of laminae, away from bioturbation processes.

### *Facies 4a: Non-stratified Grey Siltstone and Sandstone*

This facies ranges from medium to dark grey in colour and is composed of silt to very fine sand. Little stratification is preserved as it is disrupted by root action as shown in Figure 19. This facies is medium to dark grey with minor greenish layers. Units average 0.8 m thick and range from 0.15-3.9 m in thickness. Ripple cross-lamination is abundant in both the siltstone and sandstone layers with some climbing ripple sets. Graded beds and flute casts are present locally. Both siderite and calcareous nodules are common. Concave-up joint sets are present but uncommon and 'onion-skin weathering' patterns are rare.

Abundant fossil material is preserved, with fragmented plant material and roots abundant. Upright, in-situ *Calamites* stems, stigmarian root systems and lycopsid tree trunks were identified. Some foliar compression flora have been identified as *Pecopteris* sp. (foliage of tree ferns) and *Cordaites* sp. (foliage of gymnosperms).

This facies is interpreted as hydromorphic paleosols that formed in poorly drained settings (Gibling and Bird, 1994). Occurrences are probably fresh (to possibly brackish) bayfill deposits formed by advance of small deltas on the coastal plain or possibly minor crevasse splays from larger channels.

### *Facies 4b: Stratified Grey Siltstone and Sandstone*

The grey siltstone and sandstone packages range from 0.1-8.9 m in thickness and commonly form stacked coarsening upward packages ~1m thick each (Fig. 20a). This

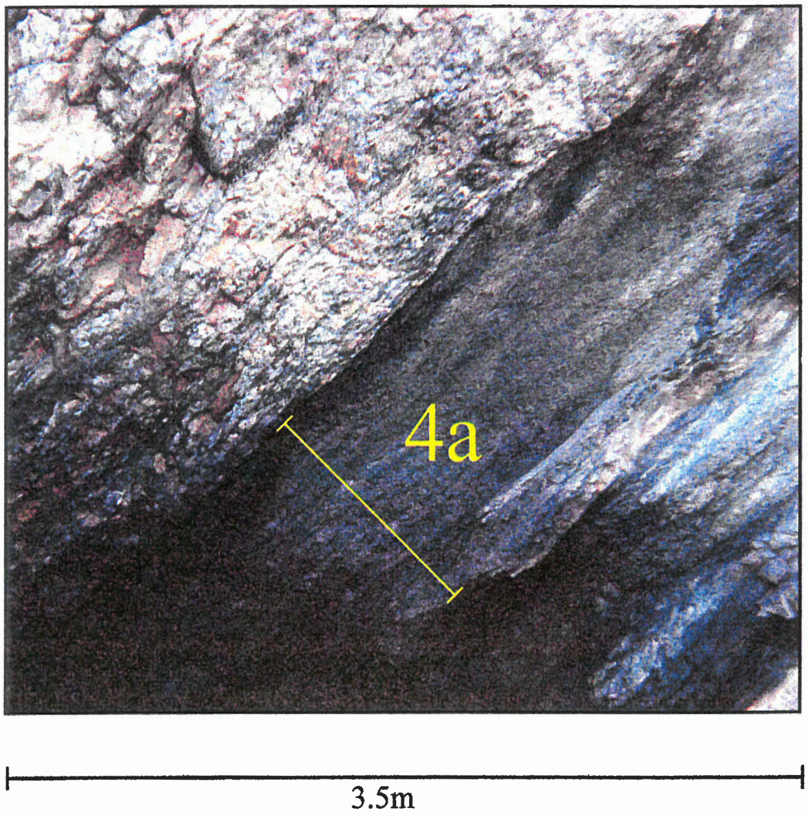


Figure 19. Non-stratified grey siltstone and sandstone facies (Facies 4a) at Long Beach.

A.

B.

Figure 20 a & b. A) Stratified grey siltstone and sandstone facies (Facies 4b) at Morien South. Hammer is ~30cm for scale. B) Ripple cross-lamination preserved in Facies 4b at Long Beach.

facies is generally light to medium grey in colour and ranges from silt to fine sand. Ripple cross-lamination is abundant (Fig. 20b), trough cross-beds and siderite nodules are common, and climbing ripple cross-sets and groove casts are uncommon. The majority of sedimentary structures observed in the study sections can be observed within this facies. Burrow traces, organic-rich shale flooding surfaces, and calcarerous nodules are also present but rare. Rare mudcracks, raindrop prints and adhesion warts were found in the laminated siltstone.

Extensive fossil biota is preserved in Facies 4b. Plant fragments are very abundant in both siltstone and sandstone layers with the best preservation generally in the finer grained sediment and in layers in close proximity to coal seams. Foliage of tree ferns (*Pecopteris* sp.), pteridosperms (*Neuropteris* sp., *Alethopteris* sp.), and gymnosperms (*Cordaites* sp.) were identified. Roots were also abundant in this facies but do not disrupt the overall stratification visible within the units. Large stigmarian root systems were also found at numerous horizons. *Pinnularia* roots were also common. Faunal traces preserved in this facies include a trackway of the huge myriapod *Arthropleura* and burrow traces. Most 'fossil forest' horizons in the sections belong to this biologically rich facies. Upright *Calamites* stems (Fig. 21a) and at least six lycopsid trees (Fig. 21b) were found at numerous levels. These findings are described in more detail in Chapter Five.

This facies is similarily interpreted as facies 4a: hydromorphic paleosols that developed in poorly drained settings (Gibling and Bird, 1994), and likely also included development under conditions with standing water bodies and repeated sediment influx. The water must have been shallow enough to support the continued growth of the forested horizons. Recurrent cycles reflect forest growth, inundation, burial, and re-

A.

B.

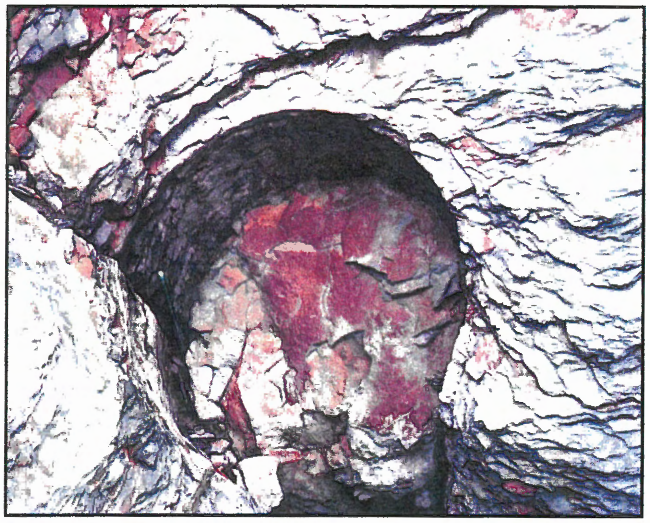


Figure 21 a & b. A) Upright in-situ grove of *Calamites* stems (arrows) preserved in Facies 4b at Morien South. Hammer is ~30cm for scale. B) Large hollowed out lycopsid trunk preserved in Facies 4b at Long Beach. Trunk diameter is 50cm.

establishment of rooted vegetation. Woody plant material probably collected at the bottom of these standing water bodies.

### *Facies 4c: Red Siltstone*

The facies is composed primarily of red siltstone with bedding disrupted by extensive root action, with minor grey siltstone layers (Fig. 22). Drab mottles, concave-up joint sets and slickensides are common, as well as siderite nodules. The beds are typically ~0.8 m thick but range up to 2.5m. Only rare, small fragments of macerated plant material were preserved.

This facies is interpreted as red vertisol-like soils that formed on well-drained floodplains. The well-developed red colour indicates oxidation of the sediment. These beds are similar to those described by Tandon and Gibling (1997) as calcic, vertisol-like paleosols with the presence of concave-up joint sets and slickensides (shrink-and-swell features) reflecting wetting and drying of the sediment formed under a seasonal climate.

### *Facies 4d: Stratified Red Siltstone*

This facies is primarily well-bedded red siltstone with minor grey siltstone, forming ~1.3 m thick packages on average (Fig. 22). Ripple cross-lamination and calcareous nodules are common. Often found are well-preserved desiccation cracks, raindrop imprints and burrow traces. Plant fragments, mainly leaves, are uncommon, as are poorly preserved lycopsid tree stumps.

This facies is typically found in association with Facies 4c and 4e. It is similarly interpreted to have formed as a red vertisol-like soil on a well-drained floodplain. The presence of mudcracks and raindrop imprints also implies shallow standing bodies of

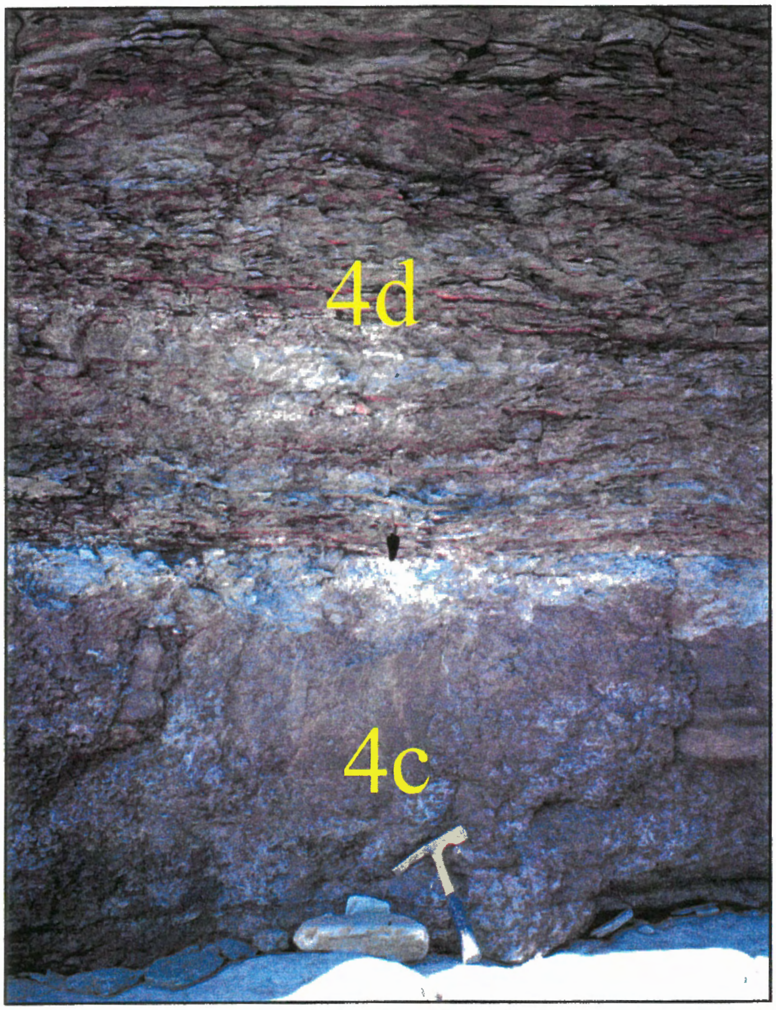


Figure 22. Red siltstone (Facies 4c) and stratified red siltstone facies (Facies 4d) at Morien South. Hammer is ~30cm for scale.

water, possibly lakes, and occasional subaerial exposure. As in facies 4c, facies 4d probably also formed under seasonal climatic conditions as recognized by Tandon and Gibling (1997).

### *Facies 4e: Sandstone Sheets*

The sheet sandstone facies is usually found in association with red claystones and siltstones (Fig. 17). The sheets are typically 0.75-1.5 m thick and stand out in the coastal exposures from the easily eroded red/grey beds on account of their medium to dark grey colour, larger grain size and greater degree of cementation (Fig. 23a). They commonly display both planar lamination and ripple cross-lamination. Some sheets have well preserved three-dimensional asymmetric ripples on the top surface of the bed (Fig. 23b). Trough cross-bedding is common, as well as root development. Calcareous nodules are common and the sandstones usually contain calcareous cement. Plant fragments are often found at the base of units. Tops of some layers contain weathered out holes where larger tree stumps (likely lycopsids) and smaller *Calamites* stems once stood, with partial siderite infilling.

This facies is interpreted as having formed by crevasse splays from major channels in well-drained settings. These sandstone beds are equivalent to the thin, distal splay deposits with reworked carbonate nodules and strong root turbation described in Gibling and Bird (1994). Fast-moving flows deposited sediment around vegetated forest horizons, presumably killing or isolating the stands, prior to the return of drier conditions.

A.

B.

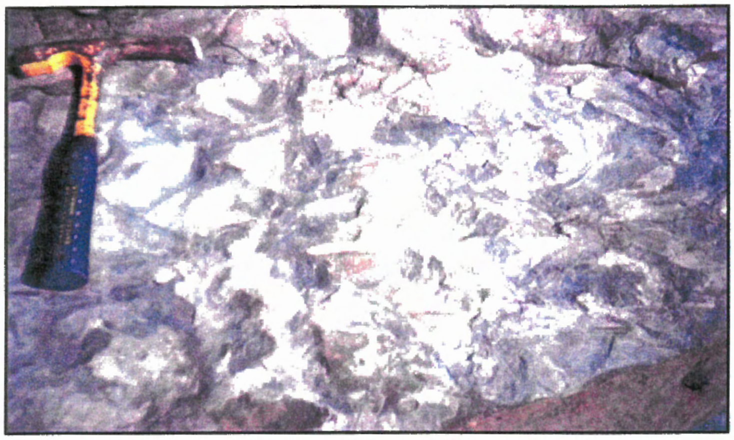


Figure 23 a & b. A) Sandstone sheets (Facies 4e) exposed at low tide on the wave-cut platform at Morien South. Hammer (circled) is ~30cm for scale. B) Well preserved three-dimensional asymmetric ripples preserved on the top surface of a unit of Facies 4e at Morien South.

### *Facies 5a and 5b: Channel Fill Facies*

Channel facies are represented by two types of channel assemblages: (1) thin channel fills (single-storey) less than 2.5 m thick dominated by ripple cross-lamination (Facies 5a) and (2) thick channel fills (multi-storey) typically 4-6 m thick, dominated by plane beds and current lineation (Facies 5b).

The thin channel fill facies (5a; Fig. 24a&b) is characterized by single storey channel fill deposits with abundant ripple cross-lamination and also planar lamination. These thin channel fills are typically fine- to medium- grained with coarser pebbles at the base. Sharp basal erosional contacts, trough cross-beds, and conglomerate lag deposits are common near the bases and at some levels within the basal fill. Groove casts and siderite nodules are also common. Mudcracks and rainprints were identified in finer-grained layers within the channel bodies. Roots are commonly found at the tops of the channels, often associated with stigmarian root systems and woody plant fragments. Lycopsid tree stumps and upright *Calamites* stems are present locally.

Facies 5b consists of coarser, thicker, multi-storey channel fill deposits (Fig. 25) of medium- to coarse-grained and pebbly sand. Plane beds with current lineation are abundant (Fig. 26) as well as trough cross-beds and ripple cross-lamination. Sharp erosional bases cut through the layers below. Conglomerate lenses at the base are common, with mud rip-up clasts. Groove casts, rill marks, and siderite nodules are found within the fills, as well as rare rain prints and mud cracks. Root action was intensive, mainly at the top of the channels, and plant fragments, both leaves and woody stem material, can be found within the channel fills. A tetrapod trackway was identified in one of the larger channel bodies and is described in Chapter Five. There are also some

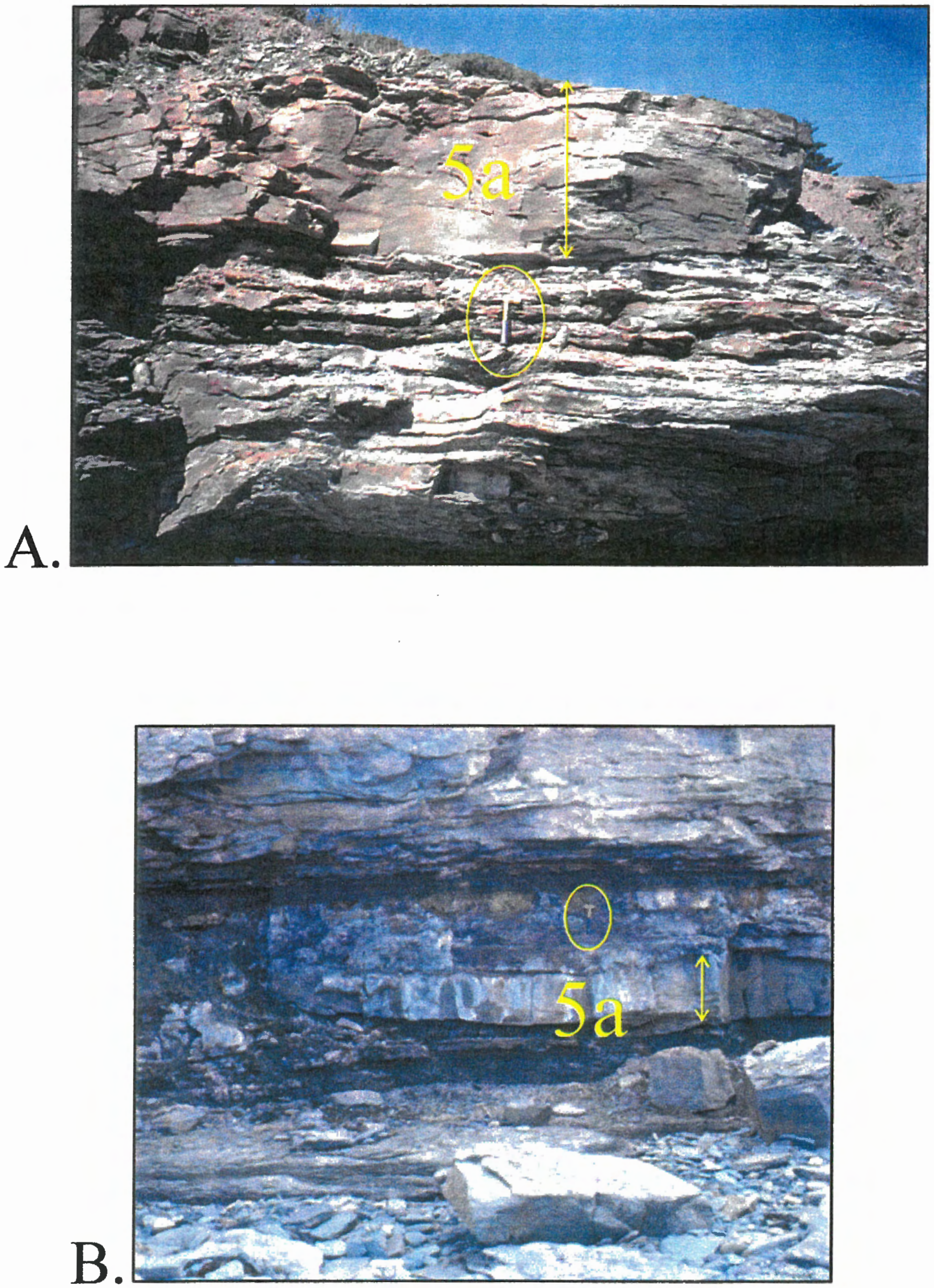


Figure 24 a & b. A) Thin channel fill (Facies 5a) dominated by ripple cross-lamination at Morien South. Erosional base is not as pronounced as in B. Hammer (circled) is ~30cm for scale. B) Thin channel fill (Facies 5a) at Schooner Pond.

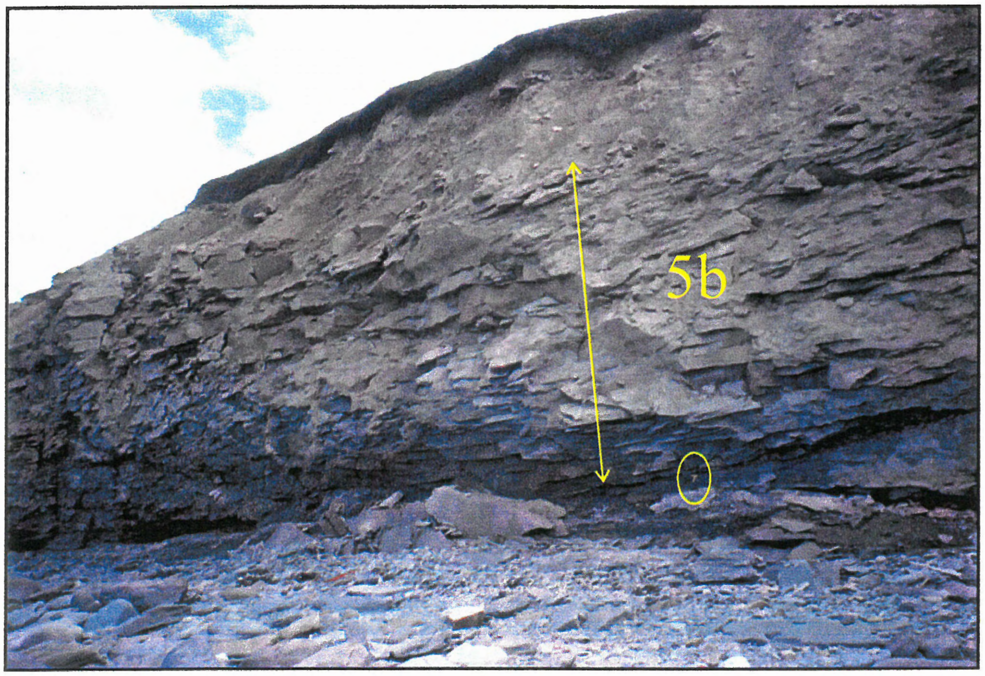


Figure 25. Thick, multi-storey channel fill (Facies 5b) at Schooner Pond. Total thickness of this channel is 8.4m. Hammer (circled) is ~30cm for scale.

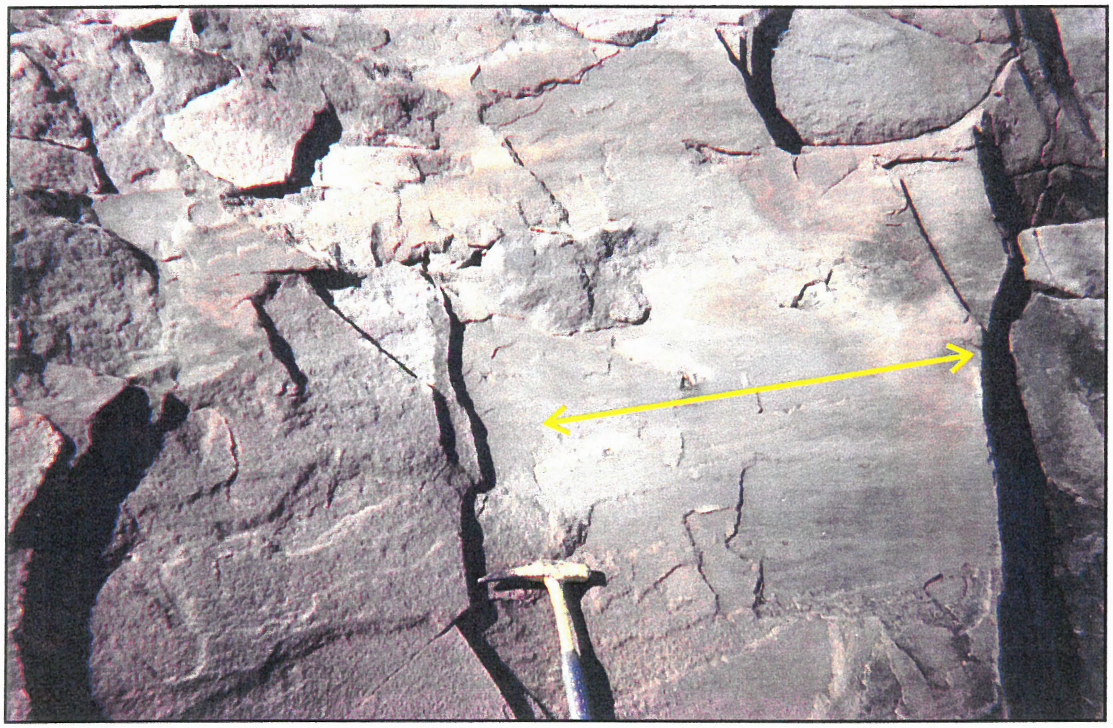


Figure 26. Plane beds with primary current lineations preserved within Facies 5b channel body at Long Beach. Hammer is ~30cm for scale. Arrow indicates trend of current direction.

channel bodies larger than 2.5 m thick which may be distributaries with dominant troughs. These channel bodies are interpreted as alluvial or deltaic distributary and meandering channels on a well-drained, vegetated alluvial plain. There is evidence for both lower (mainly Facies 5a) and upper flow regime (Facies 5b) conditions. Smaller channels may also be associated with more local crevasse splays.

### 3.2 Facies Assemblages

The facies recognized in the lower Sydney Mines Formation closely resemble the bayfills and distributary channels of modern shelf-phase deltas such as the Mississippi, but have been described as 'coastal plain deposits' because their three-dimensional form is unknown (Gibling et al., in press). Evaluation of facies observed resulted in the designation of two dominant facies assemblages within the Morien Bay strata: the *poorly drained coastal plain facies assemblage* and the *well-drained alluvial plain facies assemblage*. These assemblages have been documented across the Sydney Basin.

Definition of the 'coastal plain' within the Sydney Mines Formation can be debated. Calder (1998) questioned the use of aquatic fauna in determining marine affinities and examined the case for truly freshwater conditions for the Sydney Mines Formation. Only during the Visean are true open marine connections and related fauna recognized in the Carboniferous basin-fill of Nova Scotia. Thus, evidence used in the past to support marine connections within the Sydney Mines Formation may be inconclusive and inferred marine beds likely developed well inland. This is a fundamental issue and subsequent interpretations need careful consideration, discussion and use of references.

Marine evidence during Morien Group deposition is indicated by the presence of high-sulphur coals (Hacquebard and Donaldson, 1969) and glaucony (Batson and

Gibling, 2002). Faunal concentrate beds contain abundant bivalves and ostracods, but open-marine faunal elements such as goniatites have not been identified (Gibling et al., in press). Agglutinated foraminifera (principally *Ammobaculites*, *Ammotium*, and *Trochammina*) have been extracted from the shale and siltstone (Wightman et al., 1994). The foraminiferal assemblages resemble those of modern coastal marshes and estuaries where they indicate marine influence but also tolerance to periodic reduced salinity (Scott et al., 1991).

Thus, as evidence for marine influence at many levels is uncertain, this thesis will use a ‘coastal plain’ facies assemblage designation, with the understanding that a range of salinities likely occurred within this ‘coastal plain’ setting from fresh water to restricted marine. A freshwater to brackish depositional environment is implied and less saline influences apply landward towards red bed zones (Gibling et al., in press).

The facies associated with the poorly drained coastal plain facies assemblage are (1) coal, (3a) non-stratified grey claystone, (3b) laminated grey claystone, (4a) non-stratified grey siltstone and sandstone, (4b) stratified grey siltstone and sandstone, (2a) carbonaceous shale, and (5a&5b) channel bodies. The facies associated with the well-drained alluvial plain facies assemblage are (3e&3d) red stratified and non-stratified claystone, (4c) red siltstone, (4d) laminated red siltstone, (4e) sandstone sheets, (2b) massive limestone, (2c&2d) nodular calcrete, and (5a&5b) channel bodies. The aggregate percentage of these two facies assemblages in vertical sections at Schooner Pond, Long Beach, and Morien South is shown in Figure 27. The values from each study area are slightly different. Schooner Pond has the highest measured percentage of poorly drained coastal plain strata at 71%, while Long Beach has 61% and Morien South is much lower

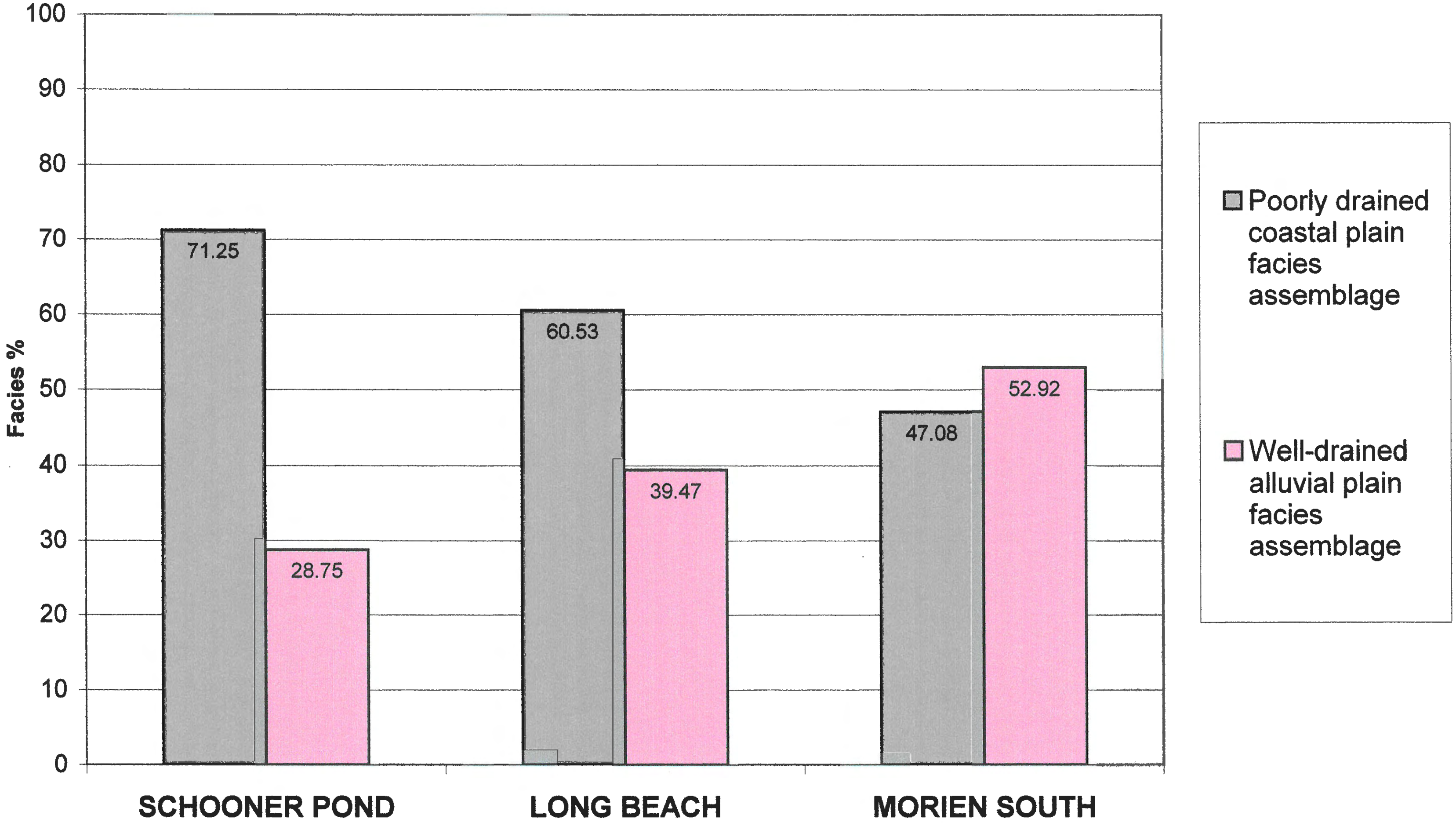


Figure 27. Poorly drained coastal plain versus well-drained alluvial plain facies assemblage representation at Schooner Pond, Long Beach and Morien South

at 47%. The amount of well-drained alluvial plain facies appears to increase as you move south towards the basin margin (towards the Morien South section). Morien South has 53% well-drained alluvial plain facies strata whereas Long Beach measured 39% and Schooner Pond only 29% well-drained alluvial plain facies. There also appears to be a higher sand content in the well-drained facies assemblage, perhaps due to increased water flow on the alluvial plain, versus the muddier and finer-grained material deposited in standing bodies of water on the poorly drained coastal plain.

The total thickness of each facies represented within the two facies assemblages was calculated. Certain facies are present in both assemblages but in different proportions. Figure 28(a-c) shows the distribution of the well-drained alluvial plain facies at all three sections. At Schooner Pond, thick dryland channel body deposits are the most abundant facies (Facies 5b) followed by minor percentages of laminated grey claystones (Facies 3b), thin channel splays (Facies 5a), and non-stratified grey siltstone and sandstone (Facies 4a). As a relatively small thickness (28.75m) of strata was measured and assigned to the well-drained alluvial plain facies assemblage at Schooner Pond, these results are somewhat biased by the presence of only three channel bodies totaling ~12 m. At Long Beach, the most abundant facies is also facies 5b, thick dryland channel body deposits. A range of facies almost equally comprise the next most abundant category, including stratified grey siltstone and sandstone (Facies 4b), non-stratified red claystone (Facies 4d) and grey siltstone and sandstone (Facies 4a), and red siltstone (Facies 4c). At Morien South, facies 4b is predominant. Thinner channel body deposits of facies 5a are the next most abundant facies. There is an increase in abundant red bed facies (Facies 3d,

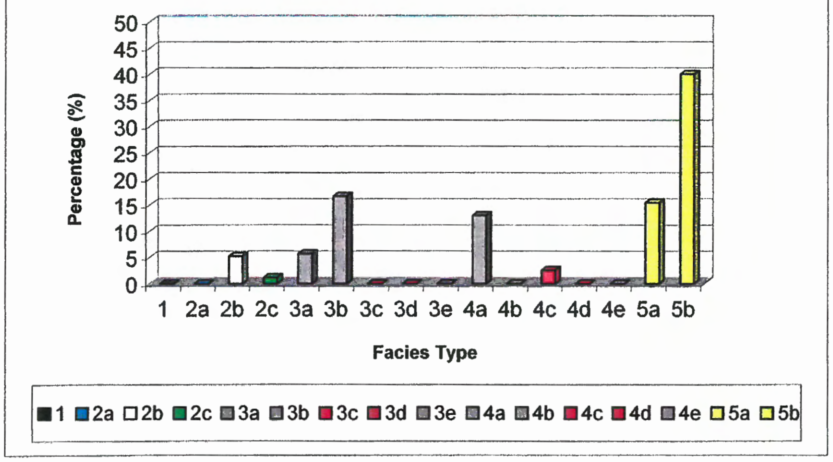


Figure 28a. Well Drained Alluvial Plain Facies Assemblage at Schooner Pond

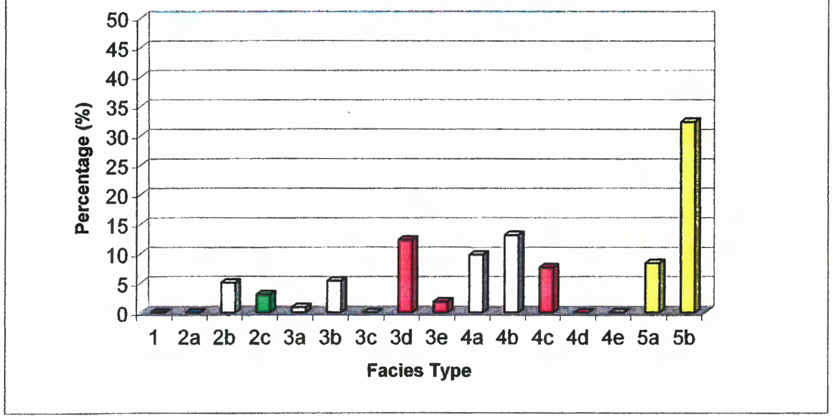


Figure 28b. Well Drained Alluvial Plain Facies Assemblage at Long Beach

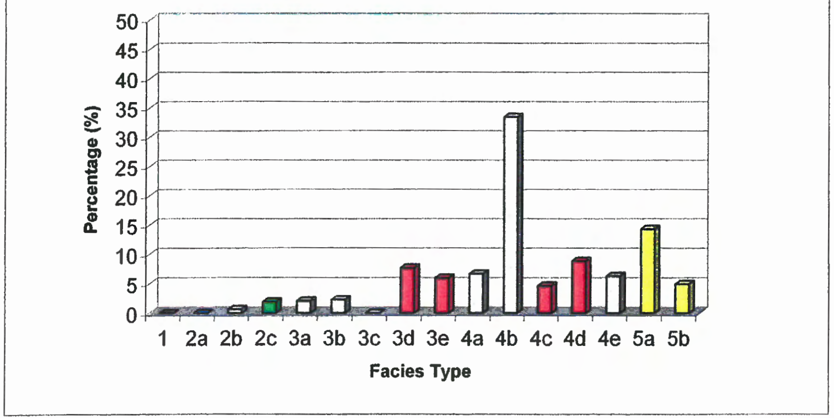


Figure 28c. Well Drained Alluvial Plain Facies Assemblage at Morien South

Figure 28 a-c. Well drained alluvial plain facies assemblages at Schooner Pond, Long Beach, and Morien South.

3e, 4c, & 4d) at Morien South versus Long Beach and Schooner Pond. The distribution of nodular calcrete (Facies 2c) is similar at all three sections (1.2-3.1%), but highest by a slight amount at Long Beach.

Figure 29(a-c) shows the distribution of facies within the poorly drained facies assemblage at Schooner Pond, Long Beach and Morien South. The distributions are similar, with over 45-60% of strata represented by facies 4b (stratified grey siltstone and sandstone) at Long Beach and Morien South, and 29% at Schooner Pond. The next most predominant facies are non-stratified grey siltstone and sandstone (Facies 4a), laminated grey claystone (Facies 3b), and non-stratified grey claystone (Facies 3a) at all three sections. Approximately 10-15% of the coastal plain facies at the Schooner Pond and Long Beach sections are represented by channel body deposits (Facies 5a and 5b). Theremaining facies present each represent values less than 5% of the total strata. Coal deposits (Facies 1) represent 5-8 % of the coastal plain facies.

### 3.3 Stratigraphic Sections

A complete stratigraphic column was created for each of the Schooner Pond, Long Beach, and Morien South outcrop sections. The total stratigraphic thickness measured was 73 m at Schooner Pond, 159 m at Long Beach, and 104 m at Morien South, combining for a total thickness of 337 detailed metres of strata in this study. Within this thickness, 235 units were identified with 58 at Schooner Pond, 96 at Long Beach and 81 at Morien South. An additional section of strata was measured at Long Beach, from the Boutilier to Harbour seam. As the goal of the study was mainly the Emery to Phalen coal seam interval, this section of strata was not documented in as fine detail nor shown in the sequence stratigraphic analysis. All three stratigraphic columns

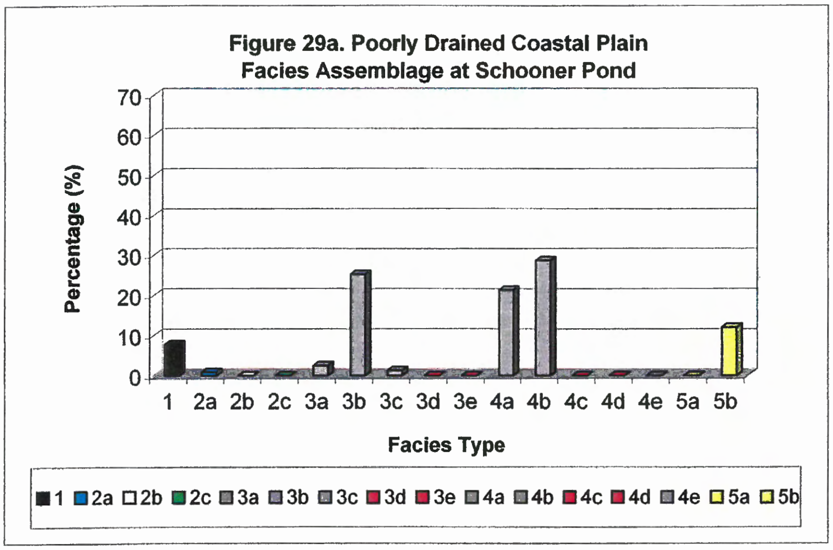


Figure 29a. Poorly Drained Coastal Plain Facies Assemblage at Schooner Pond

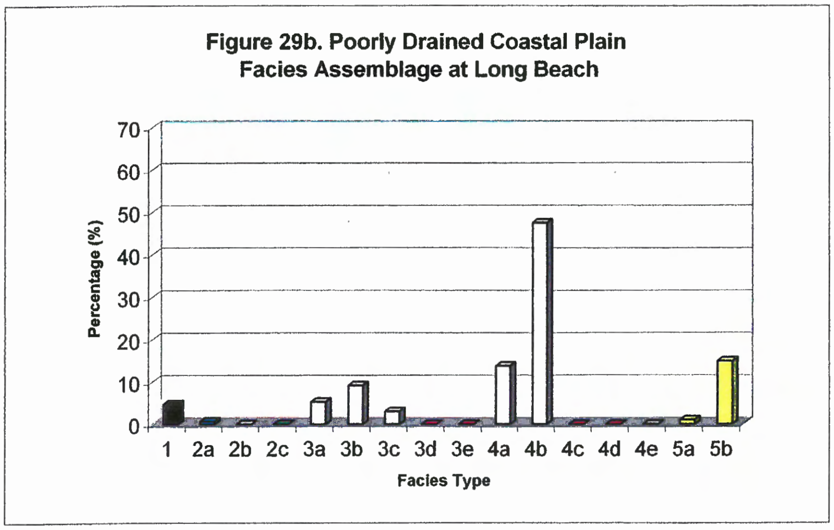


Figure 29b. Poorly Drained Coastal Plain Facies Assemblage at Long Beach

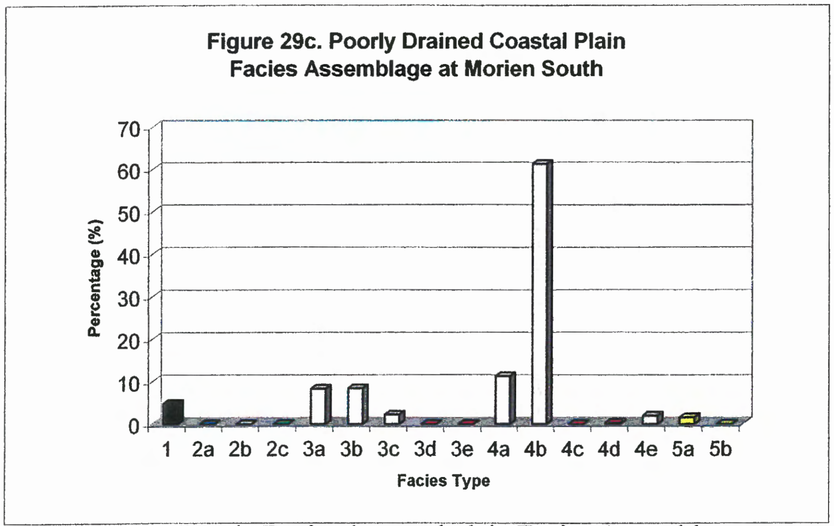


Figure 29c. Poorly Drained Coastal Plain Facies Assemblage at Morien South

Figure 29 a-c. Poorly Drained coastal plain Facies Assemblage at Schooner Pond, Long Beach, and Morien South.

are plotted together in Figure 30. Each stratigraphic column describes the lithology, grain size, sedimentary structures and fossils of the strata found along the study sections. Figure 30 also displays the legend explaining symbols used on the stratigraphic sections in Chapters 3 and 4. In Section 4.2, these same columns are shown again during the sequence stratigraphic analysis.

## 3.4 Paleocurrent Analysis

### *3.4.1 Previous Work and Theory*

Paleocurrent directional data can be collected from sedimentary structures in order to obtain information on the direction of current flow at the time of deposition. Flow conditions largely determine the external geometry of bedforms which in turn determine their preserved internal structure (Allen, 1968). Observing cross-bedding in both modern and ancient sediments shows that the maximum dip of a foreset bed is parallel or subparallel to the direction of the average local current direction, recognizing that minor secondary or eddy currents may display marked deviation from this trend (Potter and Pettijohn, 1977). In trying to reconstruct paleoenvironments, interpretations of current direction and sediment transport can be vital to basin analysis, sediment source analysis and paleotopography. Sedimentary structures that can be used for unidirectional indicators include cross-bedding, ripple marks (asymmetric), flute marks and imbrication. The two principal cross-bedding end members are tabular bodies with planar contacts (planar cross-strata) and trough-shaped bodies with curved basal contacts (trough cross-strata) (Potter and Pettijohn, 1977). Ripple marks form chiefly in granular materials at the sediment interface in response to a moving fluid, either air or water, and along with cross-bedding are probably the two most widely recognized and studied unidirectional

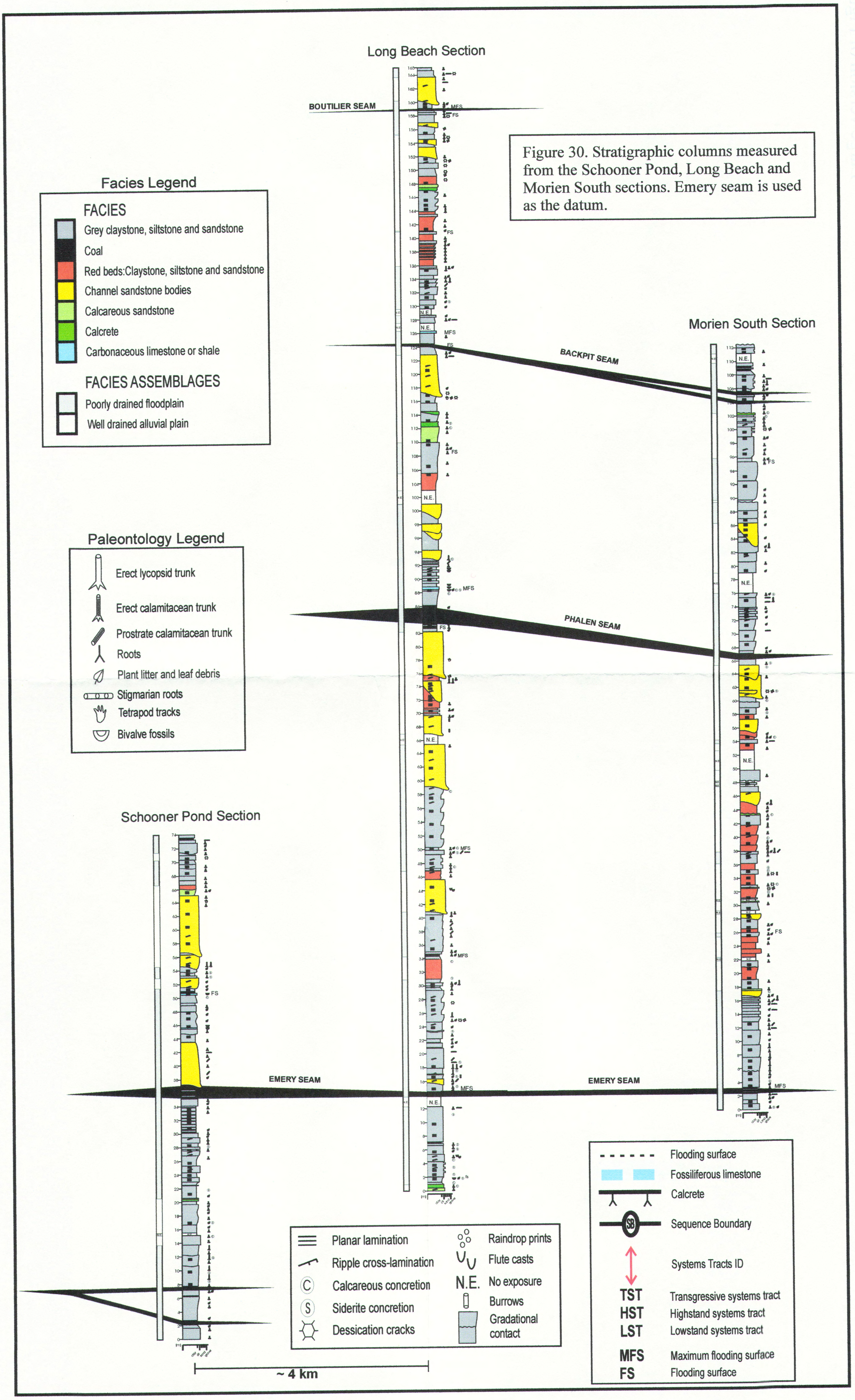


Figure 30. Stratigraphic columns measured from the Schooner Pond, Long Beach and Morien South sections. Emery seam is used as the datum.

sedimentary structures (Potter and Pettijohn, 1977). For bidirectional or trend indicators, primary current lineation, groove casts, and symmetric ripples can be utilized. Paleocurrent interpretation can occur at the outcrop level or on a basin-wide scale.

Rose diagrams provide a circular histogram or graphical representation of current direction. Calculating the vector mean of the paleocurrent values can yield an accurate estimate of the average flow direction. Rose diagrams and vector means were calculated from paleocurrent measurements at Long Beach, Schooner Pond and Morien South and are discussed in detail in Section 3.4.3. Rose diagrams for the overall paleoflow measurements were also created. Rose diagrams constructed in this study are computed with a constant area grid or non-linear frequency scale, as described in Nemec (1988). Vector means are not reported or shown with rose diagrams where datasets show polymodal form or strongly divergent modes that would render a statistical analysis meaningless.

Most previous studies in the basin utilized a much larger number of observations than this study and also made comparisons on a basin-wide scale. Gibling et al. (1992) documented a northeasterly paleoflow in the Sydney Mines and South Bar Formation, based on 357 measurements of trough cross-strata from wave-cut platforms. Low overall paleoflow variability was found in the South Bar Formation (Gibling et al., 1992), consistent with its braided-fluvial origin (Rust et al., 1987; Rust and Gibling, 1990). Higher strata show a consistent northeasterly paleoflow (Gibling et al., 1992). In the Sydney Mines Formation, a relatively high overall paleoflow variability was observed (Gibling et al., 1992), also consistent with its meandering-fluvial origin (Gibling and Rust, 1987; Rust et al., 1987). Gibling et al.'s (1992) northeastward paleocurrent direction for the region is broadly similar to the orientation of a number of syncline axes, including the Morien syncline. Very few measurements in Gibling et al.'s (1992) study of the Sydney Mines Formation are from the Morien Bay area.

### *3.4.2 Paleocurrent Data*

Paleoflow estimates are based on 114 measurements from the three study sections. Appendix 1 contains detailed information on the paleocurrent measurements collected. At Long Beach, 73 measurements of ripple cross-lamination (41%), primary current lineation (30%), cross-bedding, including both planar- and trough cross-strata (24%), and groove casts (6%) were collected. At Schooner Pond, 27 measurements of cross-bedding (63%), ripple cross-lamination (30%), and primary current lineation (7%) were collected. At Morien South, 14 measurements of cross-bedding (36%), ripple cross-lamination (29%), primary current lineation (21%) and groove casts (14%) were collected. These measurements were taken from both channel sandstone bodies (Facies 5a&5b) and interfluvial floodplain material.

The majority of measurements from all three sections were from cross-bedding (37%), which included planar- and trough cross-strata, and ripple cross-lamination (34%). Three-dimensional exposures of cross-bedding were the desired sedimentary structure in order to accurately determine the sense of paleocurrent direction (azimuth), not just the trend. Twenty-four percent of the paleocurrent measurements were from current lineation and only five percent derived from groove casts. Thus, 71% of the paleocurrent analysis was from unidirectional current indicators and only 29% from bidirectional current indicators.

Few paleocurrent measurements were collected at the Morien South section. This alone could be a major source of error as the rose diagram produces a biased view with low numbers of measurements. In the interfluvial material, cross-bedding displays a northward direction of paleoflow (vector mean of 358°) (Fig. 31a). In the channels there is a less dominant direction (Fig. 31b). The vector mean is 132° (SE), but the rose shows a polymodal distribution. This may be due to the fact that there are only four measurements in this data set and we are seeing a non-representative display of paleocurrent trend. Overall, the unidirectional current indicators at Morien South display a northward paleoflow (vector mean of 001°) (Fig. 31c). Bidirectional indicators in channel bodies recorded a vector mean of 011° which is close to the overall paleocurrent direction established with the unidirectional indicators (Fig. 31d).

Interfluvial materials at Schooner Pond show a distribution of unidirectional paleocurrent data that is almost trimodal and not in accordance with the channel bodies (Fig. 32a). The channel bodies at Schooner Pond have a polymodal distribution with a generally northerly paleoflow and vector mean of 029° (NNE) (Fig. 32b). A rose diagram of all unidirectional data from Schooner Pond, however, displays no strong single paleoflow direction (Fig. 32c). Very few bidirectional measurements from channel measurements were taken at Schooner Pond, and this dataset is not likely to be representative. The vector mean is 148/328° (Fig. 32d), transverse to directions recorded by cross-bedding and ripple cross-lamination within the channel bodies. A possible explanation for this could be the sinuosity of the channels, overbank splays, or variations in paleoflow within a channel, due to a variety of factors such as current eddies.

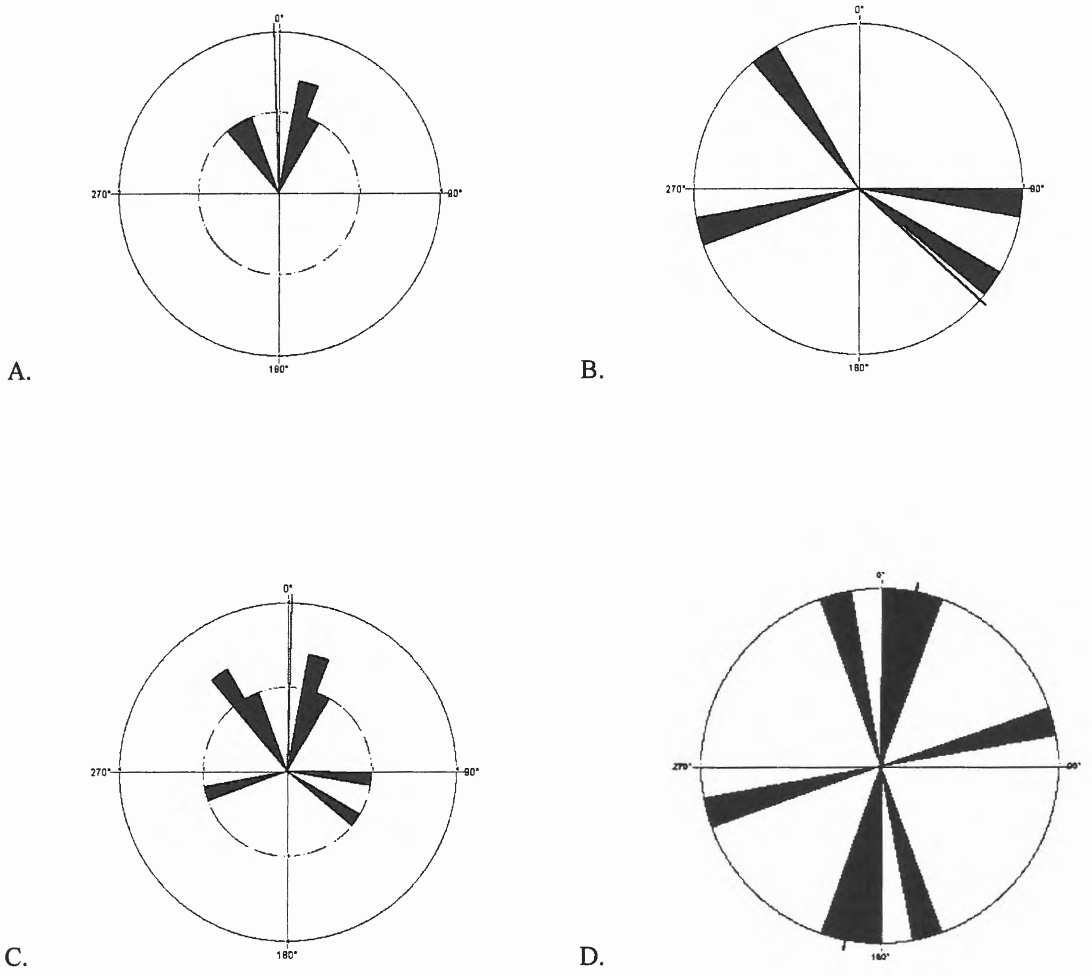


Figure 31a-d. Paleocurrent rose diagrams from directional data from Morien South. A) Unidirectional data from interfluvial material (n=5). B) Unidirectional data from channel bodies (n=4). C) Unidirectional data rose diagram from all strata at Morien South (n=9). D) Bidirectional data from primary current lineation in channel bodies at Morien South (n=4). All plots in this and following figures are equal-area/non-linear frequency scale as described by Nemec (1988). Solid line marks the vector mean of the data.

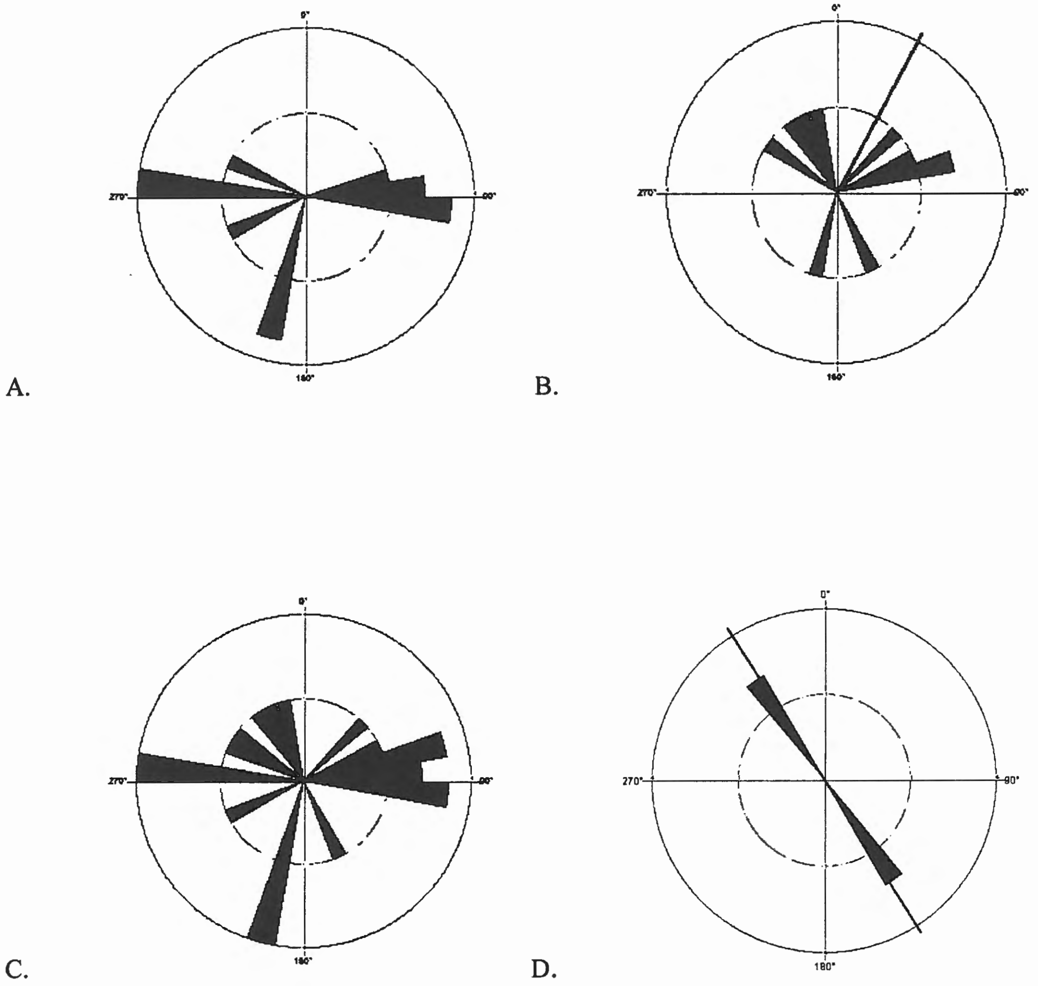


Figure 32a-d. Paleocurrent rose diagrams from directional data measured at Schooner Pond. A) Unidirectional data from interfluvial material (n=15). B) Unidirectional data from channel bodies (n=10). C) Unidirectional data rose diagram from all strata at Schooner Pond (n=25). D) Bidirectional data from primary current lineation in channel bodies at Schooner Pond (n=2). Refer to Figure 31 for additional details.

The bulk of paleoflow data in this study come from the Long Beach section. Unidirectional paleocurrent data from interfluvial strata show a somewhat bimodal distribution with prominent NE and SW modes (Fig. 33a). Unidirectional current indicators from the channel bodies indicate a strong north-northwest paleoflow preference with a vector mean of 334°, with outliers orthogonal to the vector mean (Fig. 33b). Interfluvial paleoflow appears orthogonal to the dominant flow within the channel bodies, in accord with a hypothesis of flow from channels onto floodplains on either side of the channel line. Figure 33c displays the paleocurrent information from all unidirectional data at Long Beach. The major channel bodies appear to have a NW paleoflow, while the interfluvial material follows this direction slightly but mostly at 90° angles to the channel bodies, flowing off on either side.

Bidirectional data from Long Beach display a bimodal distribution (Fig. 33d). The vector mean is 054° or northeastward but has low statistical significance. The majority of these measurements are from plane beds, created by higher velocity flows than those that formed cross-strata in large channel systems (Facies 5b). In larger channels, the flow power can be greater and the sedimentary structures are developed under upper regime flow. The larger the structure and flow power, the greater its paleocurrent significance and the less its variance (Potter and Pettijohn, 1977). The rose diagram in Figure 33d indicates paleoflow trends that are parallel to the main channel modes and to the floodplain flows.

Long Beach paleoflow measurements are not in direct accordance with the predominant northeasterly paleoflow determined by Gibling et al. (1992) for the Sydney Basin as a whole. There seems to be a different local trend in paleoflow recorded here,

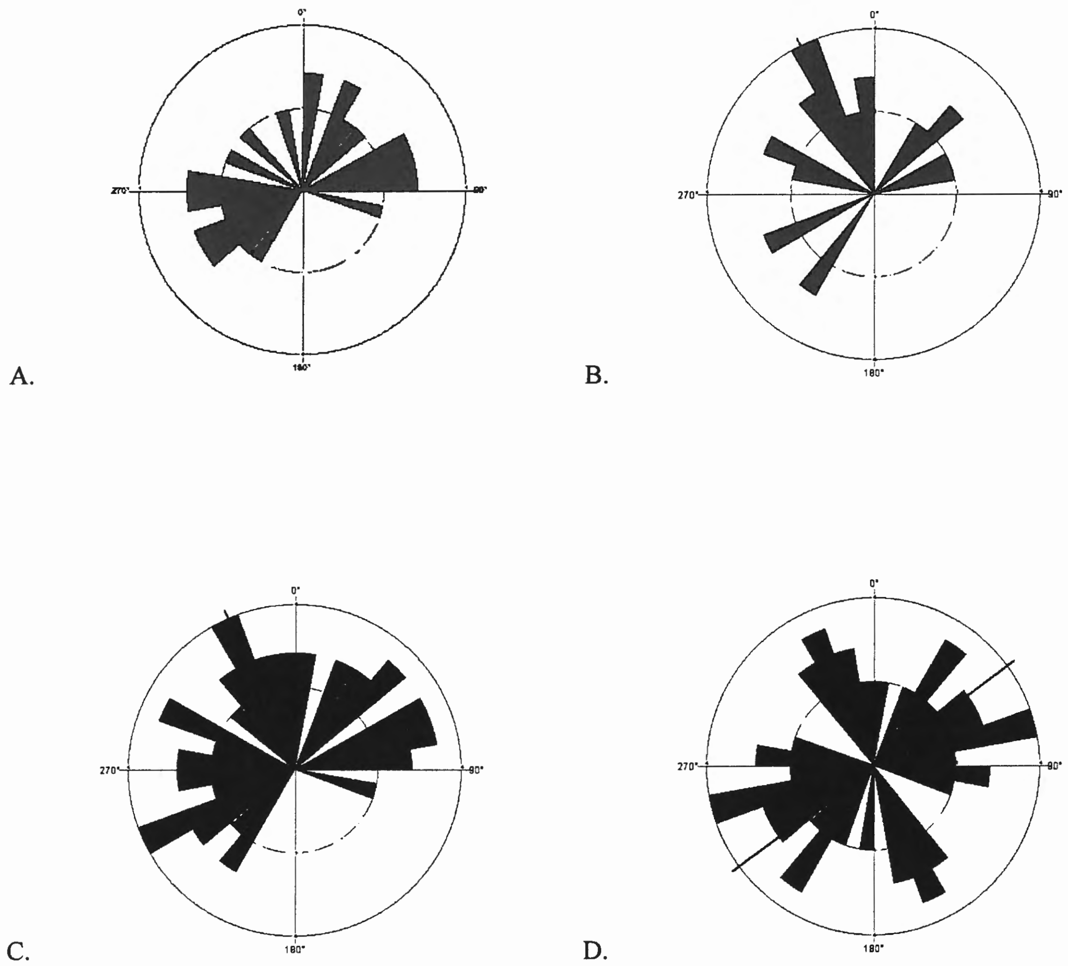
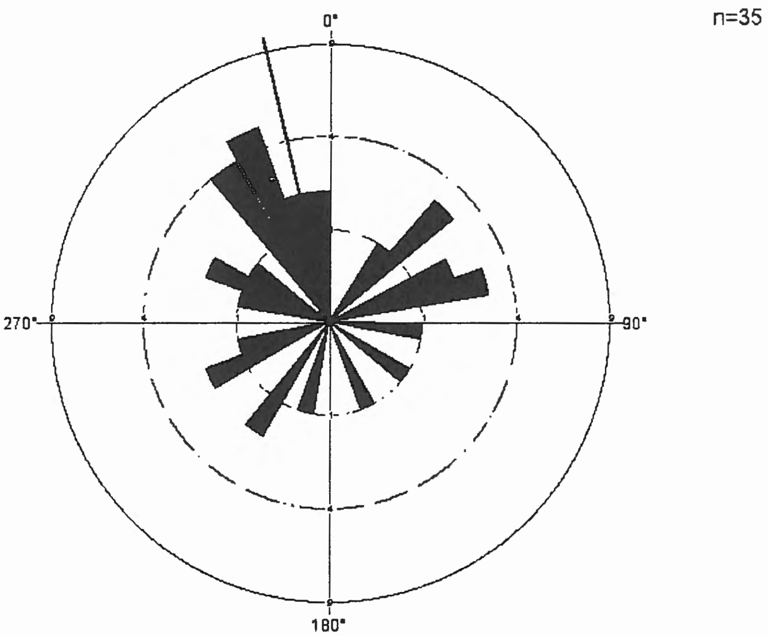


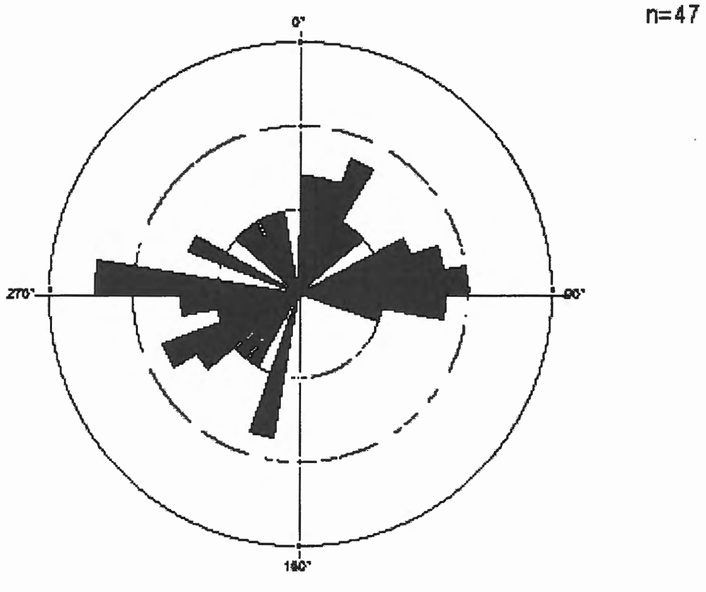
Figure 33a-d. Paleocurrent rose diagrams from directional data from Long Beach. A) Unidirectional data from interfluvial material (n=27). B) Unidirectional data from channel bodies (n=21). C) Unidirectional data rose diagram from all strata at Long Beach (n=47). D) Bidirectional data from primary current lineation and groove casts at Long Beach (n=26). Refer to Figure 31 for additional details.

one that is more north-northwestward than northeastward, suggesting central basinal drainage west of the study sections.

The measurements of unidirectional data from channel bodies in all three sections were plotted on a single rose to summarize their overall paleocurrent direction (Fig. 34a). These measurements are from 15 individual channel bodies. Eight channel bodies yielded measurements at Long Beach, with one to three paleoflow measurements per channel body, the exception being one channel body with seven measurements. At Schooner Pond, measurements were obtained from four channel bodies with two to three paleoflow measurements per channel body. At Morien South, three channel bodies were measured with one to two paleoflow measurements per channel body. Thus, the dataset is somewhat spread out between the three sections and not dominated by numerous measurements from only one or two channel bodies. The vector mean paleoflow direction is 347° (NNW). The vector mean paleocurrent direction for the interfluvial strata from all three study sections is 335° (Fig. 34b), with several modes but with paleoflow broadly orthogonal to the channel mode. Figure 35 shows channel-body data plotted as one data point per body, with all unidirectional data averaged for each body. Although a strong scatter is observed, ten out of 15 measurements lie in the two northerly quadrants, with strong modes into the syncline axis (NW) and sub-parallel to the syncline axis (NE). Figure 36 shows four roses for unidirectional channel body data on a geological map of the Morien Syncline. The vector mean paleocurrent direction at each study section can be summarized as follows: 029° (ENE) at Schooner Pond, 001° (N) at Morien South and 333° (NNW) at Long Beach. This variance in paleocurrent direction may in part reflect



A.



B.

Figure 34a-b. Paleocurrent rose diagrams from Schooner Pond, Morien South, and Long Beach. A) Unidirectional data from 15 channel bodies (8 at Long Beach, 4 at Schooner Pond and 3 at Morien South); n=35. B) Unidirectional data from interfluvial material (n=47). Refer to Figure 31 for additional details.

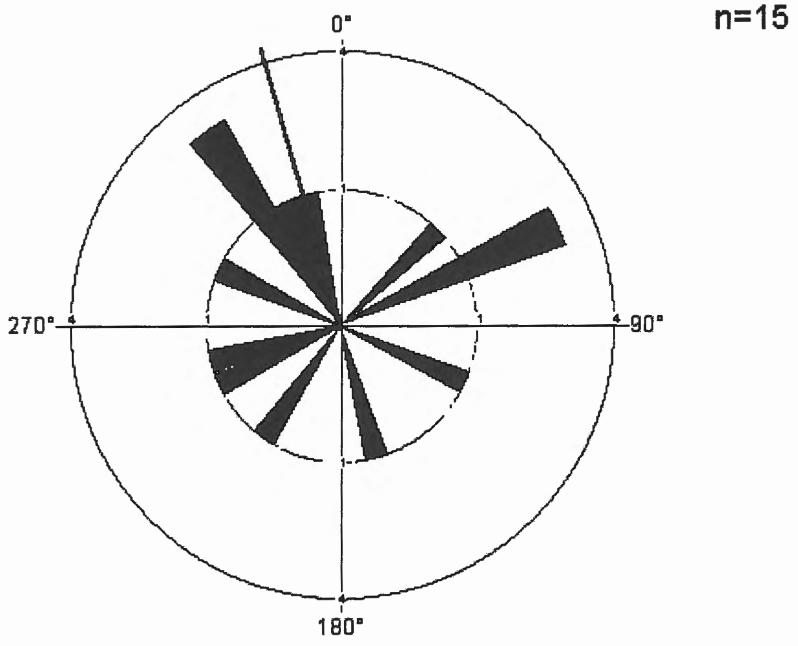


Figure 35. Paleocurrent rose diagram of channel-body data plotted as one data point per body with all unidirectional data averaged for each body. 15 channel bodies were sampled from all study sections. Refer to Figure 31 for additional details.

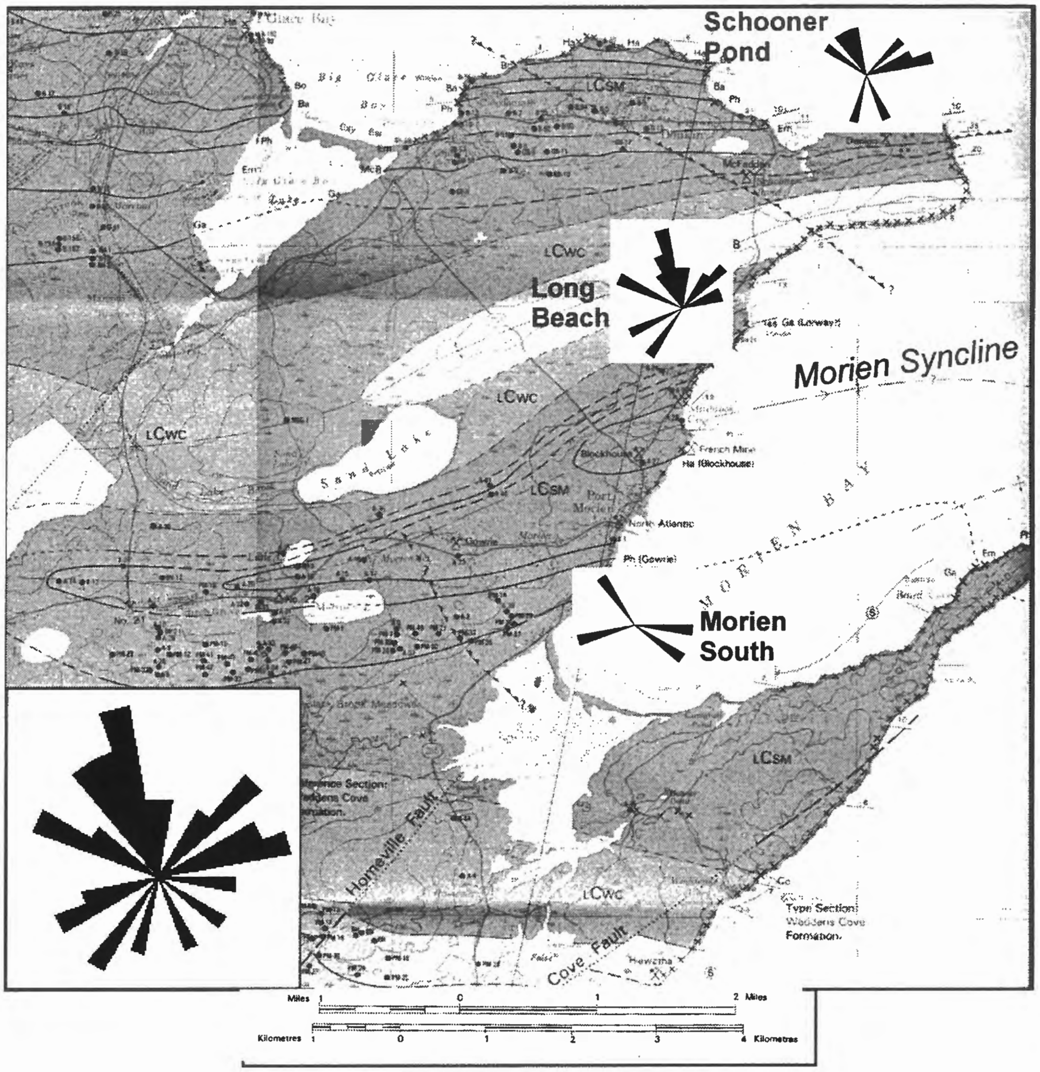


Figure 36. Paleocurrent rose diagrams of unidirectional data from channel bodies at each section plotted on geological map of the study area. Inset rose diagram is of combined unidirectional data from all the channel bodies. See text for details on sample number (n) and statistics. (Geological map from Boehner and Giles, 1986).

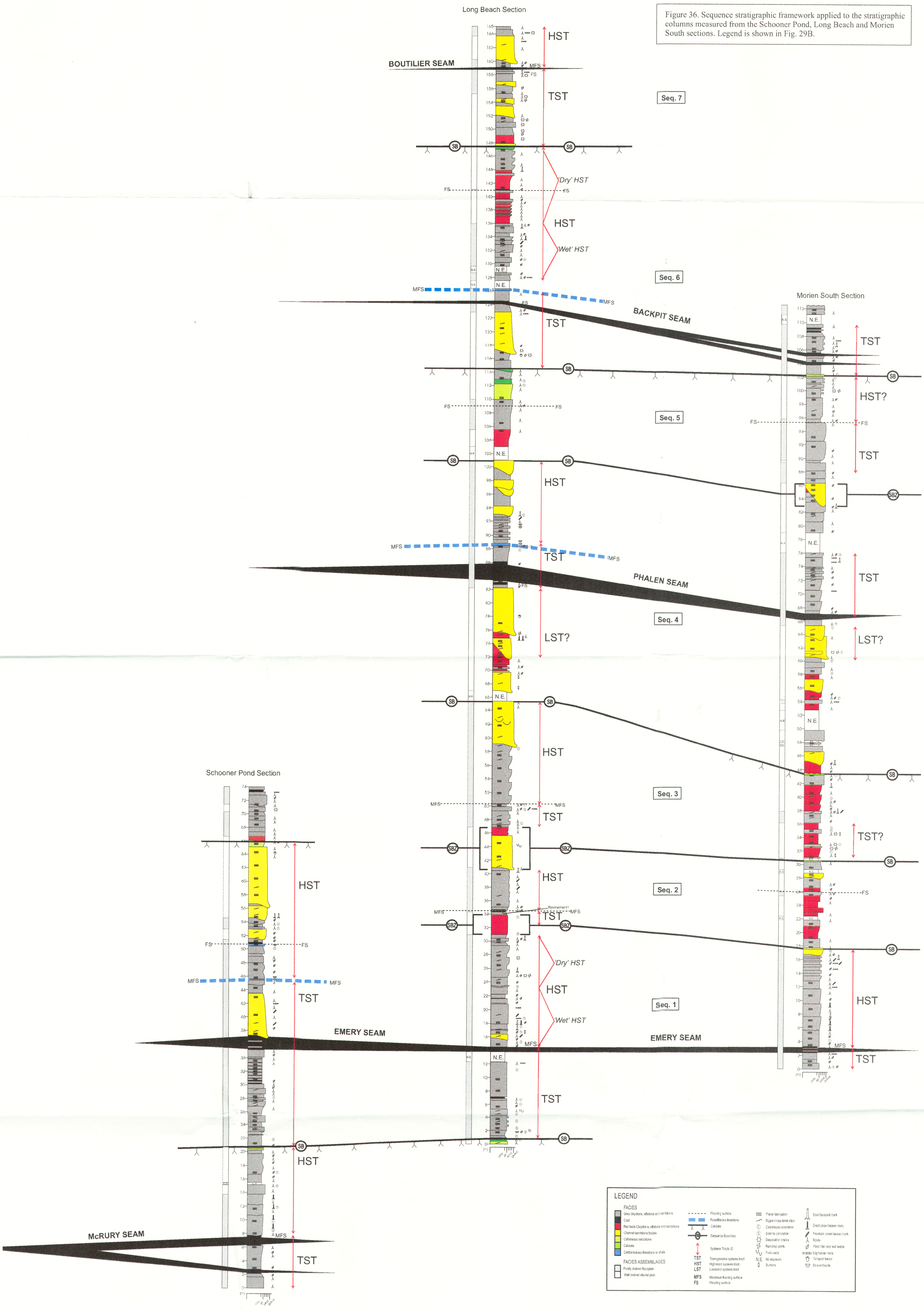


Figure 36. Sequence stratigraphic framework applied to the stratigraphic columns measured from the Schooner Pond, Long Beach and Morien South sections. Legend is shown in Fig. 29B.

deposition within a meandering-fluvial paleoenvironment for some parts of the Morien Bay system, as previously proposed for the Sydney Mines Formation (Gibling et al., 1992).

Paleoflow direction estimates from the three study sections suggest a sediment source broadly to the south and/or southwest of the study area, almost orthogonal to the axis of the Morien syncline. Older Proterozoic rocks of the Avalon Terrane (Scatarie Ridge) uplifted during the Acadian Orogeny lie directly south of the study area. Scaterie Ridge (Fig. 1), which the coal measures onlap, was a prominent high during deposition (Pascucci et al., 2000). Thus, the southern source that this dataset indicates could be an upland region near the southern margin of the basin. This is in agreement with other studies in the area (Dondale, 2001). Dondale (2001) also proposed that a northward paleoflow aids in understanding the higher sandstone abundance on the southern limb of the syncline. The syncline may have acted as a major depocentre for river drainage and sediments during this time, with flow into the depositional area from the south, merging with axial NE flow. The Morien South section has a large proportion of red beds compared to the other two study sections and this southern part of the study area was probably better drained (an upland), consistent with the expectations from paleoflow indicators. Paleochannel features have been a historic mining problem in the Sydney Basin and their prediction may prove viable to future underground mining and mine safety in this region.

# Chapter 4: SEQUENCE STRATIGRAPHY

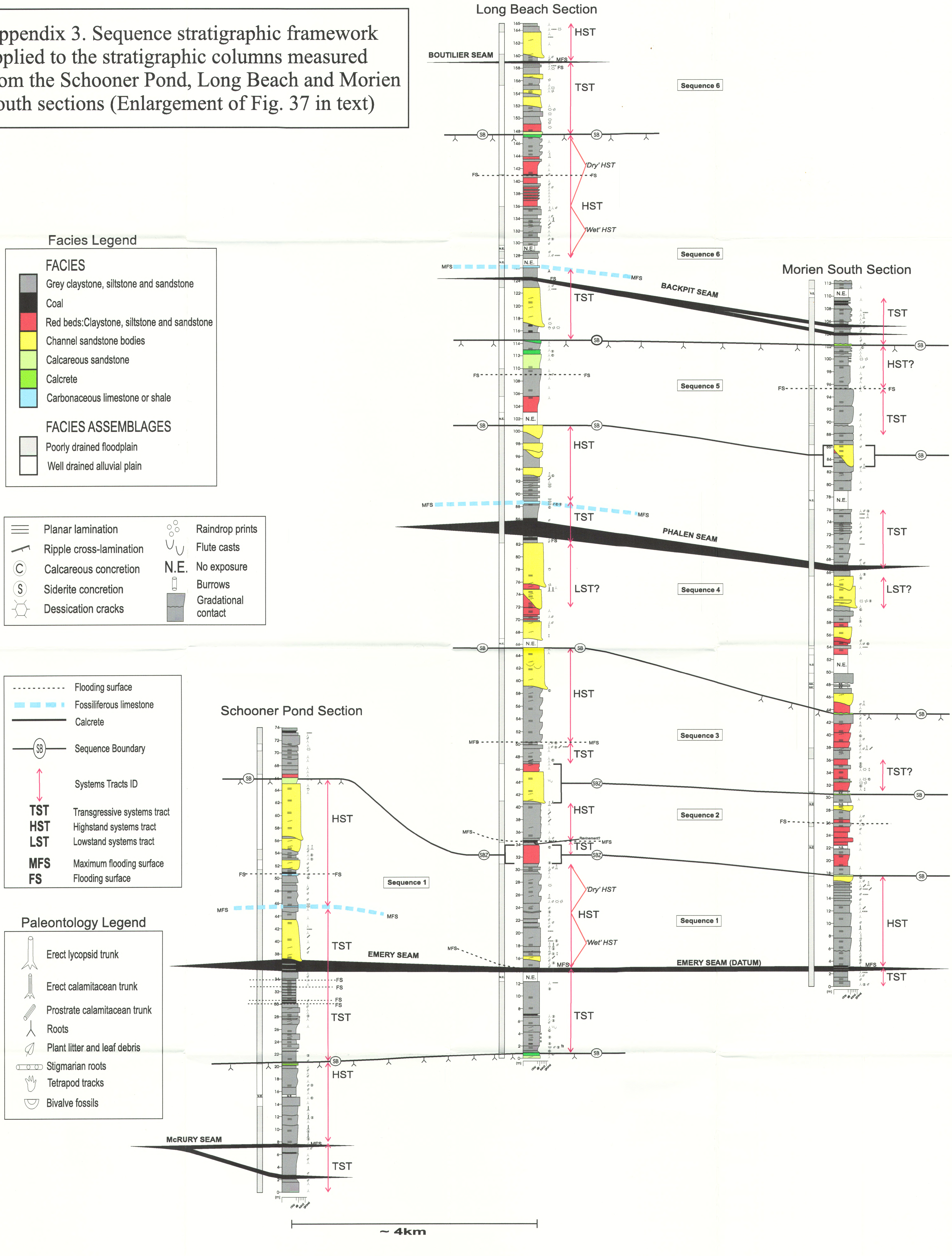
A major part of this thesis involved the application of sequence stratigraphy to the Morien Bay exposures. Figure 37 displays the sequence stratigraphic framework applied to this study's three stratigraphic columns and it is included in a larger print-out as Appendix 3. This chapter first reviews principles of sequence stratigraphy and terminology relevant to the study area. The exposures allowed several issues to be addressed in unusual detail: recognition of sequence boundaries in non-marine strata; recognition of flooding and maximum flooding surfaces; and distinction between highstand and falling stage systems tracts. All three of these issues involve recognition of key surfaces, and they are discussed in detail in dedicated segments of the text. The development of seven sequences across the study area is then presented in detail, drawing on the Long Beach, Morien South and Schooner Pond stratigraphic sections. Basin-wide comparisons and trends are discussed following the sequence analysis at Morien Bay.

## 4.1 Sequence Stratigraphy: An Introduction

### *4.1.1 Definitions for a marine/coastal context*

Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner et al., 1988, 1990; Vail, 1987). The first ideas of sequences can be traced back to the work of Sloss et al. (1949) but these ideas only became popularized and widely used after the advent of seismic stratigraphy (Vail et al, 1977, 1984, 1991; Sloss, 1988; Van Wagoner et

Appendix 3. Sequence stratigraphic framework applied to the stratigraphic columns measured from the Schooner Pond, Long Beach and Morien South sections (Enlargement of Fig. 37 in text)



al., 1990; Christie-Blick and Driscoll, 1995). Present models are primarily two dimensional with few assumptions about three dimensional effects (Martinsen and Helland-Hansen, 1995). However, a reliable sequence stratigraphic study requires integration of all available data types and consideration of the architecture in three dimensions (Martinsen and Helland-Hansen, 1995).

Sequence stratigraphy allows for the ability to potentially predict and model sedimentary successions and stratigraphic packages. Evolving sequence stratigraphic techniques allow for greater understanding and higher resolution of both outcrop and subsurface strata on local to regional scales. Sequence stratigraphy has been extensively applied to littoral and shallow marine strata and less extensively to non-marine strata.

Christie-Blick and Driscoll (1995) described the following three different frameworks used in sequence stratigraphy: i) the classic depositional sequence stratigraphy produced by Exxon in the 1970s and 1980s, ii) genetic sequence stratigraphy, and iii) allostratigraphy. This thesis builds upon on the theoretical scheme of sequence stratigraphy first developed by the Exxon group (Van Wagoner et al., 1998; Posamentier and Vail, 1988; Posamentier et al., 1988). Depositional sequence stratigraphy is different from genetic sequence stratigraphy in terms of how the depositional units are defined and measured. Depositional sequence stratigraphy uses the depositional sequence, a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Mitchum et al., 1977; Van Wagoner et al., 1990; Christie-Blick 1991). In Galloway's (1989) genetic stratigraphic framework, the genetic stratigraphic sequence is bounded by intervals of sediment starvation. These correspond with times of maximum flooding and their significance is quite different from that of subaerial erosion surfaces (Christie-Blick and Driscoll, 1995). Boundaries are located within more-or-less continuous successions, sometimes with no distinct surfaces present, limiting the resolution of maximum flooding surfaces and high resolution subsurface studies (Christie-Blick and Driscoll 1995). Allostratigraphic units are defined and identified on the basis of bounding discontinuities (Christie-Blick and Driscoll, 1995) and nomenclature is not always applicable where a bounding unconformity passes laterally into potentially unidentifiable correlative conformity (Baum and Vail, 1988).

Regardless of definition chosen, the fundamental unit of sequence stratigraphy is the sequence. For depositional sequences, the type chosen for use in this study, unconformities are a crucial part of its bounding surfaces. An unconformity is a surface separating younger from older strata, along which there is evidence of subaerial erosion, truncation (and in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated (Van Wagoner et al., 1988). A conformity is a bedding surface separating younger from older strata along which there is no evidence of erosion (either subaerial or submarine) or non-deposition, and along which no significant hiatus is indicated (Van Wagoner et al., 1988).

In the depositional sequence model, sequences are typically composed of parasequences, which may be further grouped into parasequence sets with specific stacking geometries. Parasequences are defined as relatively conformable successions of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces (Van Wagoner et al., 1990). They can be bounded above or below by sequence boundaries. Parasequences have been identified in coastal plain, deltaic, tidal, estuarine and shelf environments (Van Wagoner et al., 1990). Identification of non-marine, alluvial equivalents of parasequences have not yet been reliably accomplished and may be impossible (Shanley and McCabe, 1994). Most siliciclastic parasequences are progradational, resulting in upward shoaling of facies (Van Wagoner et al., 1988, 1990). Parasequences are best developed in shallow marine sediments and their boundaries (flooding surfaces) may be excellent chronostratigraphic markers (Mitchum and Van Wagoner, 1991).

A flooding surface is a surface separating younger from older strata, across which there is evidence of an abrupt increase in water depth (Van Wagoner et al., 1988). Minor erosion and nondeposition generally accompanies the deepening, and a minor hiatus may be indicated (Van Wagoner et al., 1988). In non-marine strata, deepening may not necessarily be a feature of flooding surfaces, as these flooding surfaces may represent widespread areal transgressive events. Flooding surfaces tend to be planar, with little topographic relief and have a correlative surface in the coastal plain and on the shelf (Van Wagoner et al., 1988, 1990).

Type I and Type II sequences can be identified in the rock record on the basis of (1) the systems tracts present on either side of the sequence boundaries and (2) the type of sequence boundary present. A Type I sequence boundary is characterized by subaerial exposure and erosion associated with stream rejuvenation (the presence of incised valleys), a downward shift in coastal onlap and a basinward shift in facies (Van Wagoner et al., 1988). These sequence boundaries form when the rate of eustatic fall is greater than the rate of basin subsidence at the depositional shoreline break, thus producing a relative fall in sea level at that position (Van Wagoner et al., 1988). These sequences can be produced in modern environments: Boyd et al. (1989) found that the late Wisonsinan-Holocence Mississippi River has deposited a Type I sequence that includes lowstand, transgressive, and highstand systems tracts in the northern Gulf of Mexico.

Type II sequence boundaries are marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional shoreline break, yet do not have the subaerial erosion associated with stream rejuvenation as in Type I sequences (Van Wagoner et al., 1988). This type of sequence is thought to form when the rate of eustatic fall is less than the rate of basin subsidence at the depositional shoreline break (Van Wagoner et al., 1988). Type I sequences contain lowstand, transgressive and highstand systems tracts whereas Type II sequences are composed of shelf-margin, transgressive and highstand systems tracts, which are explained below.

Sequences can be subdivided into systems tracts (Fig. 38). These are defined as a linkage of contemporaneous depositional systems (Brown and Fisher, 1977) where depositional systems are defined as three-dimensional assemblages of lithofacies (Fisher and McGowen, 1967). Van Wagoner et al. (1988, 1990) recognized four main systems tracts: lowstand, shelf-margin, transgressive and highstand systems tracts. More recent studies follow these definitions and also propose additional systems tracts, such as the falling stage systems tract of Plint and Nummedal (2000). Christie-Blick and Driscoll (1995) described the subdivision of sequences into systems tracts as being based on the phase lag between transgressive and regressive cycles and the development of corresponding sequence boundaries. Van Wagoner et al. (1988) noted that the terms highstand and lowstand do not imply a distinct period of time or position on a eustatic cycle (or relative change in sea level).

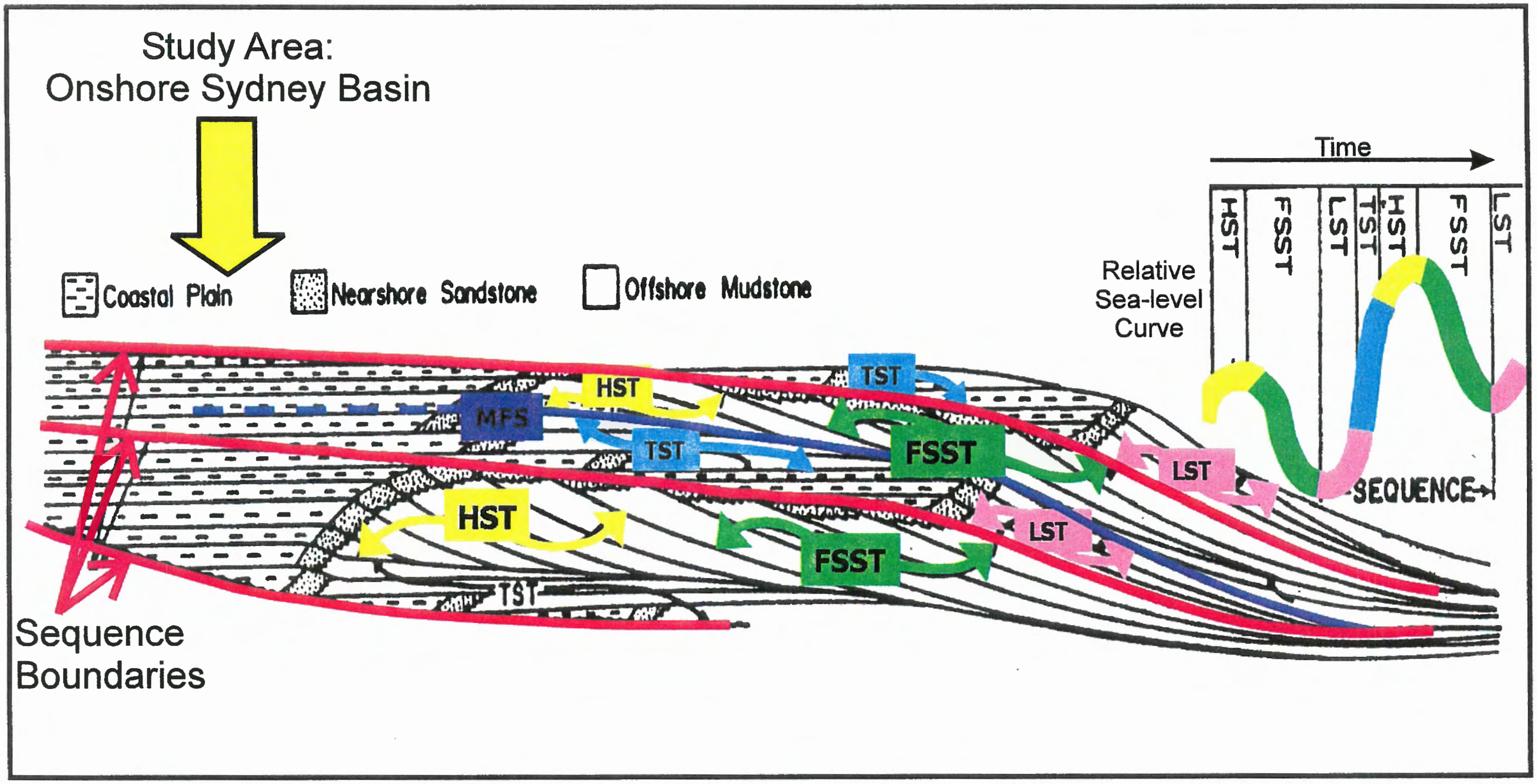


Figure 38. Stacking pattern of systems tracts, sequence boundaries and maximum flooding surfaces. Corresponding relative sea-level curve is on the right. HST - Highstand Systems Tract. FSST - Falling Stage Systems Tract. LST - Lowstand Systems Tract. TST - Transgressive Systems Tract. MFS - Maximum Flooding Surface. Large yellow arrow indicates relative lateral position of the onshore Sydney Basin strata and resulting potential non-representation of various systems tracts and surfaces. Modified from Plint and Nummedal (2000).

The lowstand systems tract is the lowermost systems tract if it lies atop a Type I (erosive/unconformable) sequence boundary. If the sequence boundary is of Type II (non-erosive/conformable), the lowermost systems tract is called the shelf-margin systems tract. The top of the lowstand systems tract is the transgressive surface: the first significant marine-flooding surface across the shelf within the sequence (Van Wagoner et al., 1988).

The transgressive systems tract is initially the first flooding event after the maximum lowstand regression (Wright and Marriott, 1993). It is the middle systems tract, characterized by "one or more retrogradational parasequence sets. These parasequences onlap onto the sequence boundary in a landward direction and downlap onto the transgressive surface capping the LST in a basinward direction. The top of this systems tract is a downlap surface, a marine-flooding surface onto which toes of prograding clinoforms (a seismic signature) in the overlying highstand systems tract downlap" (Van Wagoner et al., 1988). A change from retrogradational to aggradational parasequence sets is observed at this surface. It represents the time of maximum extent of aquatic facies and is termed the maximum flooding surface. Often it includes a condensed section (Loutit et al., 1988), a facies consisting of thin hemipelagic or pelagic sediments deposited at very slow rates as parasequences step landward and the shelf is starved of terrigenous sediment. If it forms a condensed section it is deposited during the time of the latest transgressive to early highstand systems tract. Condensed sections often contain the greatest abundance and diversity of aquatic fauna within the sequence (Van Wagoner et al., 1990) due to their relative enrichment as a consequence of reduced sediment supply.

The highstand systems tract is deposited during the highest relative sea level, when the rate of relative sea level rise slows and eventually reverses (Wright and Marriott, 1993). It is the uppermost systems tract and is characterized by "parasequences that onlap onto the sequence boundary in a landward direction and downlap onto the top of the transgressive or lowstand systems tracts in a basinward direction. Commonly one or more aggradational parasequence sets are succeeded by one or more progradational parasequence sets with prograding clinoform geometries" (Van Wagoner et al., 1988). Most deposits in the highstand systems tract were deposited during relative sea level rise (Plint and Nummedal, 2000)

Plint and Nummedal (2000) proposed that the HST be subdivided into a shortened HST (from its original concept) and a falling stage systems tract. Their work in siliciclastic ramp settings suggests that deposition during relative sea level fall produces a distinctive stacking geometry and relationship to sequence boundary formation they called the falling stage systems tract (FSST, Fig. 38), a logical counterpart to the transgressive systems tract formed during maximum rates of relative sea level rise. Plint and Nummedal (2000) consequently state the need for a new systems tract (FSST) that corresponds to the time between the onset of relative sea level fall and sea level lowstand. Various studies have addressed this similar problem with varied terminology (forced regressive wedge systems tract, Hunt and Tucker, 1992; forced regressive systems tract, Helland-Hansen and Gjelberg, 1994), yet arrived at similar conclusions. Hunt and Tucker (1992) proposed the forced regressive wedge systems tract (FRWST), to include both shelf and deep water strata deposited between the onset of relative sea level fall and relative sea level lowstand, with the lower boundary termed the "basal surface of forced regression" (equivalent to the original depositional sequence boundary of Posamentier et al. (1992)), and the upper surface a sequence boundary definition.

The FSST is characterized by "offlap, lies above the (revised) highstand and below the lowstand systems tracts. The lower boundary is interpreted to correspond in time with the start of relative sea level fall. In seismic profiles, the upper boundary of the FSST is characterized by renewed onlap of overlying strata onto the sequence boundary. The stacking pattern in the FSST is one of forestepping higher order parasequences and is produced during a phase of relative sea level fall" (Plint and Nummedal, 2000). The process driving the formation of the FSST is that of forced regression (Plint, 1991; Plint and Norris, 1991; Posamentier et al., 1992).

Formation of the FSST and examples from the geological record are documented in Plint and Nummedal, (2000). Introducing this new systems tract significantly changes how system tracts are defined because the emended highstand systems tract now terminates at relative sea level highstand, and the FSST is deposited during relative sea level fall (Plint and Nummedal, 2000). Key issues here include what type of surface might separate these two systems tracts, what degree of diachroneity such surfaces might show, and how to recognize them. In this study recognition of the falling stage systems tract was attempted, but proposed falling stage strata are identified with a question mark on diagrams, due to the ambiguity of their bounding surfaces. In several sequences, highstand systems tract deposits were subdivided into 'dry' and 'wet' components that reflect upward passage into red and grey dryland facies. These may represent falling sea level prior to the formation of the sequence boundary. The 'dry' HST deposits may in fact represent the closest one can postulate as true falling stage deposits.

### *4.1.2 Sequence stratigraphy in non-marine settings*

Shanley and McCabe (1994) provided perspectives on the sequence stratigraphy of continental strata and noted that sediment supply is generally a more complex variable for non-marine environments than in the marine realm, due to proximity to the source area. Climatic and tectonic effects on sediment supply are easily observed. The fact that the major controls of climate, tectonism, and eustasy are only somewhat independent, and that a change in one parameter will likely cause changes in the others, is also more readily apparent in continental strata (Shanley and McCabe, 1994).

Changes in relative sea level significantly affect stratigraphic base level in marginal and shallow marine settings, but the impacts for continental strata are not as widely known and agreed upon. In the lower coastal plain, the concept of a graded fluvial profile has been used to approximate an equilibrium surface between erosion and sediment preservation (Mackin, 1948), thereby linking changes in relative sea level to patterns of fluvial aggradation and degradation (Shanley and McCabe, 1994). Controls on sediment supply and relative changes in base level interact in the lowermost parts of a fluvial system to produce alluvial successions (Blum, 1994). The accommodation space available for sediment accumulation on a floodplain is controlled by the elevation of the channel, its bankfull depth (Wright and Marriott, 1993), and the sedimentation rate of the floodplain. Floodplain deposits cannot build up above the bankfull level, which is ultimately controlled by the local base level (Wright and Marriott, 1993). Shanley and McCabe (1994) stated that in the lower coastal plain, a change in relative sea level (eustasy and subsidence) will be the major factor in controlling stratigraphic base level for fluvial systems, whereas further inland, the effect of a change in relative sea level becomes diminished. Climate and source area uplift become more important controls on stratigraphic base level here. However, determining the exact relationship between changes in stratigraphic base level and fluvial aggradation or degradation is not easy. The delivery of large amounts of sediment to a shoreline or continental shelf probably reflects not only base level lowering, but uplift of the sediment source area (Schumm, 1993) and possibly relative seasonality, greatest during climatic minima (Cecil, 1990). Wright and Marriott (1993) regard the highest rates of accumulation (maximum alluvial sedimentation) as taking place during the TST rather than late HST, thus fluvial deposits are more likely to accumulate during times when adequate accommodation allows the system to store sediment.

In lacustrine settings, lake levels act as local base level and exert a fundamental control on lacustrine and adjacent fluvial stratigraphy, much as marine and coastal strata respond to changes in relative sea level (Shanley and McCabe, 1994). Periods of fluvial incision and aggradation near the lakeshore may correspond closely with lake levels, with the correlation decreasing as distance from the lacustrine shoreline decreases.

In interior basins, recognition of alluvial sequence boundaries is almost entirely due to changes in alluvial stacking patterns (Shanley and McCabe, 1994). Paleosols can also aid in recognition of sequence boundaries as they reflect periods of subaerial exposure. Maximum flooding surfaces were recognized in subsurface and outcrop data sets by condensed sections that may be extensively burrowed or bored. In alluvial strata however, Shanley and McCabe (1994) state that the period of maximum flooding is represented by the invasion of tidal processes into areas formerly dominated by purely fluvial processes. As comparatively fewer sequence stratigraphic models have been applied to continental strata than marine strata, further applications of sequence stratigraphy will likely result in the development of better correlation and predictions of the location and nature of fluvial and eolian reservoirs (Shanley and McCabe, 1994).

### *4.1.3 Accommodation, Climate, and Supply as controls on sequences*

Stratigraphic sequences are affected by both eustatic and tectonic changes in relative sea level. Schlager (1993) proposed that climatic change be recognized as an additional control. Shanley and McCabe (1994) also studied the role of climate on sediment supply and architecture and concluded that changes in climate can affect vegetation and rainfall, which in turn affects erosion, sediment source, and discharge not only in the sedimentary basin but also in the highlands that source fluvial drainage systems. They also found from studies of Quaternary fluvial systems that the time scales over which river systems respond to climatic and environmental changes are substantially less than that required for even fourth-order (0.1-0.2 m.y.) and fifth-order (0.01-0.02 m.y.) cycles of stratigraphic base level change. Cecil (1990) showed evidence of such response to climate change in this time frame. Thus, in alluvial sections showing no independent evidence for marine and/or lacustrine influences, genesis of persistent bounding disconformities may be unrelated to relative changes in base level, even though the stacking pattern of the alluvial succession may reflect variations in stratigraphic base level (Shanley and McCabe, 1994). It was concluded that fluvial responses to changes in stratigraphic base level are complex and partly depend on upstream controls on discharge and sediment supply.

Sea level and sediment supply have been identified as equally important factors in transgressions and regressions (Schlager, 1993). Sequences in fluvatile continental basins are removed from sea-level induced changes in accommodation and many must have formed by changes in the rate and pattern of supply (Schlager, 1993). According to Schlager (1993), the most important factor in recognizing sea level cycles is the subaerial exposure of marine sediments at the sequence boundary. Other minor factors include downstepping of shelf breaks and characteristic patterns of the spacing of time lines within sequences. Evidence proposed as not diagnostic for sea-level falls are siliciclastic shoaling upward sequences from inner shelf deposits via beaches to alluvial plains. The systems tract model and its interpretation in terms of sea level change, presented by Schlager (1993), is valid only if variations in sediment supply are small and sea-level controlled variations in accommodation dominate the system. It is assumed that the system always builds to base level and thus the system tracts are controlled by the balance of two rates: the rate of change in accommodation and the rate of sediment supply. In this model, the rate of change in accommodation is controlled by sea level, and the rate of sediment supply is controlled largely by environmental factors, thus variations in supply can substitute for sea-level driven variations in accommodation (Schlager, 1993). Certain features cannot be generated by changes in supply, such as exposure of marine sediment along a sequence boundary and the downstepping shelf surface of the lowstand wedge because these features require a negative change in accommodation (Schlager, 1993).

Two important points from Schlager's (1993) work were that (1) changes in sediment supply can have an equally large effect on sequence geometry as changes in accommodation, and (2) due to changes in supply, environmental factors that are independent of sea level can generate stratigraphic sequences. Schlager (1993) proposed that an estimate of the magnitude of supply effects in the sequence record can be obtained from observing the regional variation in depositional systems on the present-day sediment surface of the Earth.

### *4.1.4 High Frequency Sequences*

High frequency cyclicity in carbonate rocks has long been recognized. Mitchum and Van Wagoner (1991) use sequence stratigraphic concepts to show three-fold cyclicity in less widely recognized siliciclastic rocks with frequencies within the range of Milankovitch cycles, possibly the result of global eustasy. Third order (1–10 m.y.) sequence boundaries observed on a global basis have been plotted and dated on cycle charts by Haq et al. (1988) where one sequence is interpreted to form during one eustatic cycle. As resolution techniques of sequence stratigraphy improve, the recognition of higher order sequences is possible. High frequency sequences most commonly occur with fourth-order cyclicity or fifth-order cyclicity (Boyd et al., 1989). Assuming a frequency based approach, these frequencies are similar to those of parasequences in third order sequences and thus fourth- and fifth-order cyclicity may be expressed as parasequences or high-frequency sequences (Mitchum and Van Wagoner, 1991).

Mitchum and Van Wagoner (1991) produced a complex relative curve of sea-level change that is the composite result of the superposition of cycles by the hierarchical stacking of several eustatic cycles of differing frequencies. They conclude that (1) High frequency sequences commonly occur in basins where the sedimentation rate was very high and subsidence was low (If subsidence was low, minor eustatic falls would more likely be represented as relative falls and, if subsidence was high, small high frequency falls of sea level are less likely to be represented as relative falls); and (2) High-frequency sequences are most recognizable in basins with high depositional rates, enabling the preservation of minor sea level fluctuations. This is assuming eustasy is the main control at this scale. Tectonic uplift could mimic eustatic falls if coincident with sediment supply changes at smaller or shorter scales. Cyclicity is present in all stratigraphic units yet the recognition of it depends on the scale of measurement, and understanding of the facies within the rocks. The response of the basin would be quite different if there were no marine record present.

## 4.2 Recognition of Sequence-Related Features in the Morien Sections

### *4.2.1 Sequence Boundaries*

Depositional sequence boundaries are key stratigraphic surfaces that need to be recognized in lithologic sections in order to recognize sequences and apply principles of sequence stratigraphy. A key method in interpreting stratigraphic surfaces in some work is through the use of seismic profiles which provide large amounts of data in areas such as offshore regions, where outcrop exposure is not possible. Recognizing sequence boundaries in seismic sections may prove to be difficult, as individual horizons may become unresolvable with the limited scale and quality of the data. Thus being able to recognize these surfaces in multiple outcrop exposures can permit refinement of the true nature of these surfaces.

A sequence boundary is formed when relative sea level rise begins to slow, stabilize, and then fall on the coastal plain. A surface of subaerial exposure and erosion is generated in landward by this relative fall in sea level. Key indicators for (Type I) sequence boundaries are large paleovalley fills with strong channel incision. In the ‘interfluve’ environment, sequence boundary recognition is difficult as the sedimentation and accomodation rate influences the type of horizon preserved. In areas of minor to no sedimentation, single well-defined calcretes (calcareous paleosols) can form in semi-arid climates, indicating a lack of sedimentation over a long period of time. In areas of higher sedimentation, vertisol-type paleosols several metres thick would likely be preserved, reflecting the gradual addition of new sediment and reworking into the soil profile.

The majority of sequence boundaries identified in the study sections could be called Type II sequence boundaries as no major incision (incised valleys) or erosion surfaces were observed. Type I sequence boundaries can be found in other parts of the Sydney Mines Formation and are recognized with large paleovalley fills (up to 30m thick) (Batson and Gibling, 2002). For this reason, it is not assumed that all sequence boundaries in the three study sections are of Type II. The concept of the Type II boundary was created for predominantly marine strata and its definition does not make it applicable in all sequence stratigraphic analyses. In non-marine to coastal plain strata, shelf-margin deposits are unlikely to be observed, a key indicator of Type II boundaries. Also, lowstand deposits can be incorporated into the sequence boundary layer, not preserved, or even not present in some parts of the study sections as it is too proximal.

Working with coastal plain or alluvial plain facies often presents other recognition problems as these boundaries do not present similar signatures on all parts of the coastal plain. It can be hard to trace the correlative conformity of the sequence boundary distally and the time gap of the unconformity can lead to temporal imprecision. Finally, there could be multiple unconformities (e.g. channel cuts) making identification of regionally significant boundaries difficult. As a result, three types of sequence boundaries are defined and recognized in the Morien Bay sections (Fig. 39):

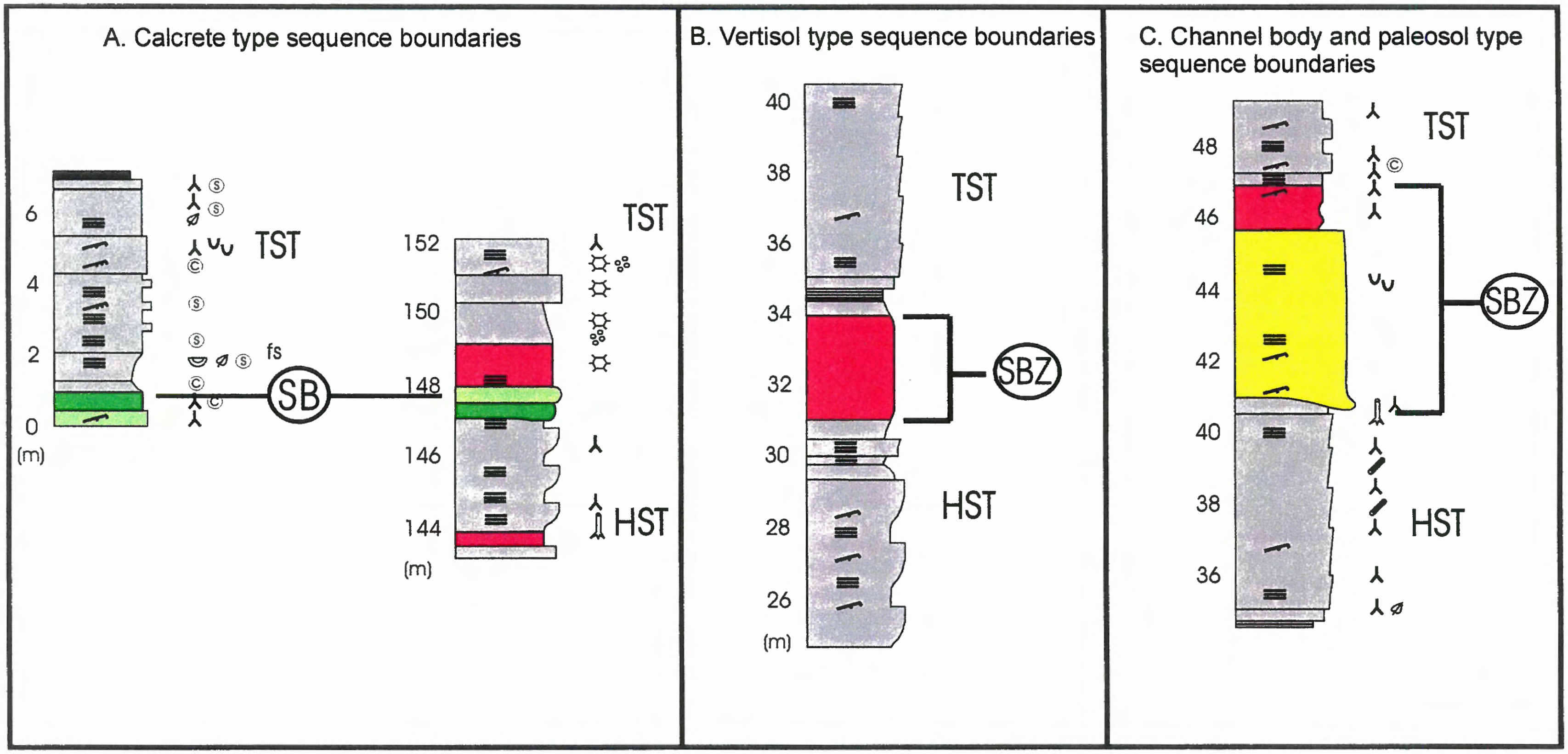


Figure 39a-c. Types of Sequence Boundaries Recognized in the Morien Bay Sections.

### *A. Calcrete type sequence boundaries*

The first type of sequence boundary is represented by thick, distinct calcrete horizons (Fig. 39a). The calcretes are commonly found above calcareous sandstone layers that display less extensive calcareous soil development than the calcrete layers (Fig. 40). Sedimentation was minimal during formation of these layers. Well-defined calcretes are commonly observed in the study sections especially at Long Beach, and some layers can be correlated between sections. In other parts of the basin, these calcretes have been recognized and correlated across distances of up to 30 km (Gibling et al., in press). This type of sequence boundary is the easiest to recognize in the study section due to the distinctiveness of the sedimentary layer in outcrop. The calcretes are found as single distinct layers or are overlain by packages of dryland red mudstone (Fig. 39a). The top surface of the calcrete is generally considered to mark the sequence boundary (Fig. 40), as it represents the topmost preserved strata on the former coastal plain, below which soil is expected to have developed and deepened progressively. The calcrete type sequence boundaries are typically the easiest to use for regional correlation.

### *B. Vertisol type sequence boundaries*

The second type of sequence boundary is represented by thick, vertisol-type paleosols, up to several metres thick where sediment was being supplied to the interfluves at greater rates (Fig. 41). As no single surface is recognizable as the 'exact' sequence boundary level, this study terms these units as representing sequence boundary 'zones' (Fig. 39b). A number of sequence boundary zones were identified in the study sections. The thick rooted paleosols are typically red in colour and have well preserved concave-up joint sets. The sequence boundary zones are more problematic and less distinct in outcrop

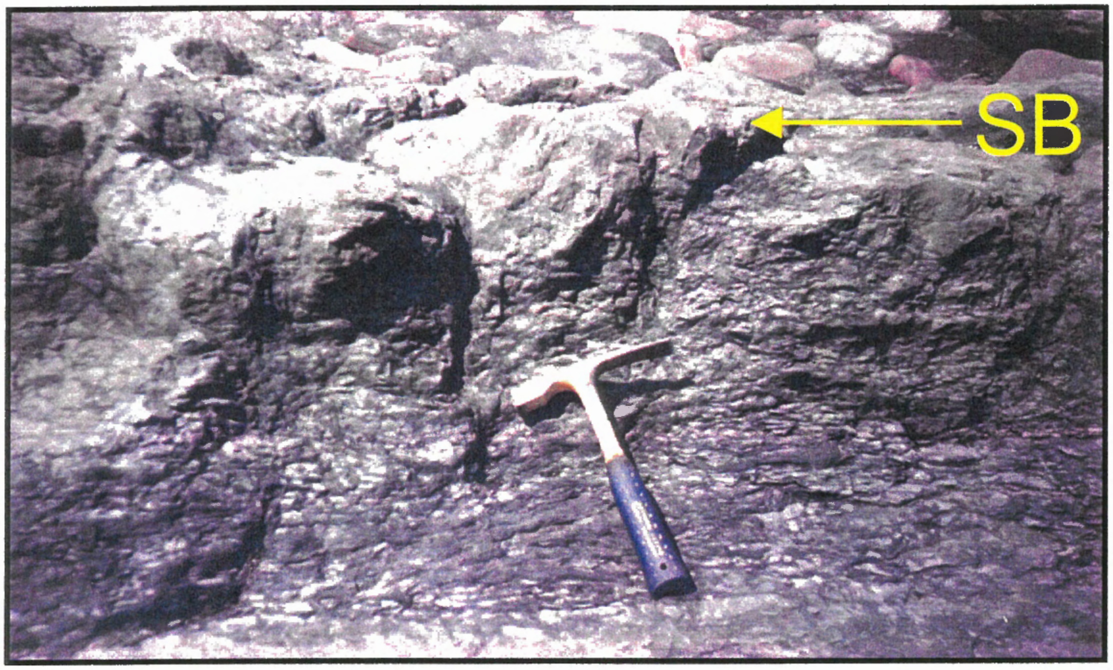


Figure 40. Calcrete and underlying soil profile development on beach outcrops at Morien South. This layer represents the sequence boundary (SB) at the base of Sequence 3. Hammer is ~30cm for scale.

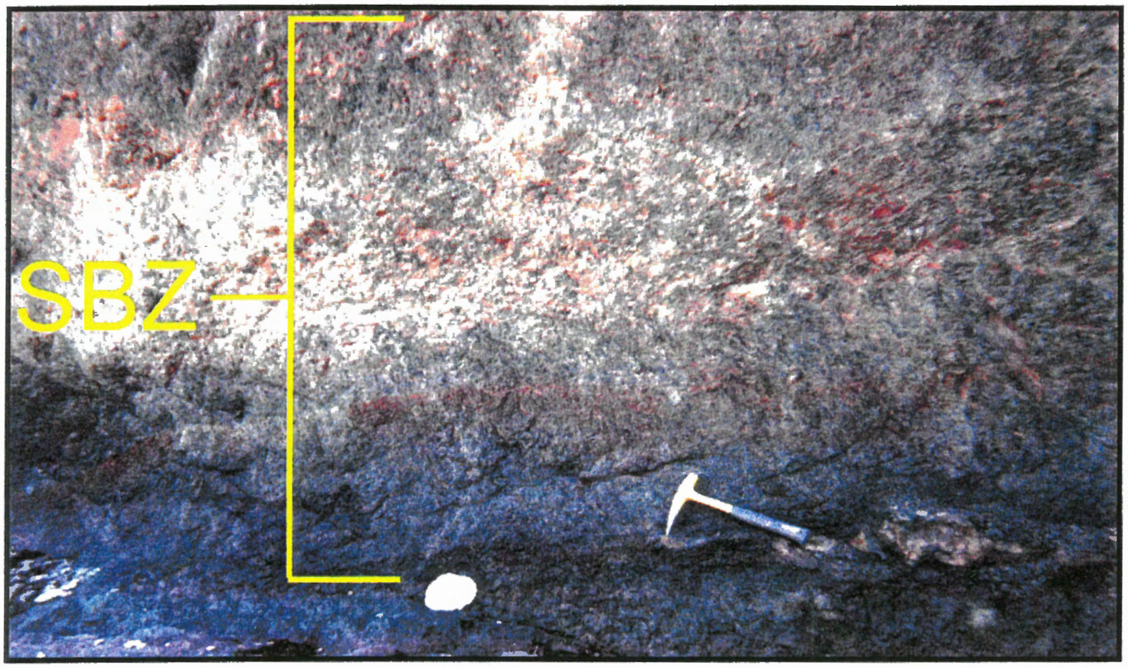


Figure 41. Thick vertisol-type paleosol at Long Beach (Sequence 2). This layer represents a sequence boundary zone (SBZ) as not one specifc horizon is easily identified as the sequence boundary surface. Hammer is ~30cm for scale.

and thus more difficult to accurately correlate through the sections. Although the zones are typically only a few metres thick, this thickness may constitute a significant proportion of sequences that may be as thin as 12 m.

*C. Channel body and paleosol type sequence boundaries*

The third type of sequence boundary is represented by channel bodies or small paleovalley fills and floodplain deposits of dryland type. Large, extensive paleovalley fills are not present in the study sections but can be identified in eastern parts of the Sydney Basin (Batson and Gibling, 2002). Thus, the third type of sequence boundary is channel bodies and/or smaller paleovalley fills found in association with stratal packages of dryland redbeds, indicating a strong change in sedimentation accompanied by paleosol formation (Fig. 39c). A single sequence boundary layer can be difficult to identify here. Where in some places a major erosive channel base can be identified at the base of the dryland strata, this can be taken as the sequence boundary level. However in most instances channel bodies are thin and intercalated with red mudstones. Persistent sedimentation for a long period is assumed and a sequence boundary zone terminology is applied. These types of sequence boundaries are more complex as a distinct gap in sedimentation is not apparent, and they are not easily correlated across large distances. Details on specific sequence boundaries and their characteristics are discussed in Section 4.3.

### *4.2.2 Flooding Surfaces*

Flooding surfaces are some of the easier horizons to identify in outcrop due to certain defining characteristics. Flint et al. (1995) studying coal measures in the United

Kingdom found that regional correlations suggest that thick coal seams are time-correlative to significant flooding surfaces at the coeval coastline. The 'marine bands' of the classic Westphalian 'Coal Measures' of England may be regarded as flooding surfaces or condensed sections, with several being good candidates for maximum flooding surfaces (Flint et al., 1995). In the Barataria Basin, Kosters and Suter (1993) observed thick peats of high organic content immediately landward of the shoreline of maximum transgression (the landward extent of the MFS). As groundwater is recharged into the delta plain during a rise in relative sea level, standing bodies of fresh water can be created in interlobe basins, a prerequisite to the formation of peats (Kosters and Suter, 1993).

A maximum flooding surface refers to the surface of deposition at the time the shoreline is at its maximum landward position (ie. the time of maximum transgression) (Posamentier and Allen, 1999). These surfaces are generally readily identifiable within cyclic sedimentary successions and potentially form good stratigraphic markers for regional correlations (Galloway, 1989). The maximum flooding surface is a key stratigraphic surface and is commonly a condensed horizon with an unusually thin sedimentary record representing a relatively long period of time (Walker, 1992). Within the study area and the Sydney Basin, maximum flooding horizons are represented by distinct, thin faunal-concentrate limestone layers. These layers tend to cap the thicker coal seams, indicating the maximum extent of the flooding waters. They are rich in bivalve and ostracod fossils as well as fish fragments and reworked shell fragments (Fig.11a). These beds form excellent regional stratigraphic markers within the Sydney Basin sections. The most extensive maximum flooding surface recognized in the study

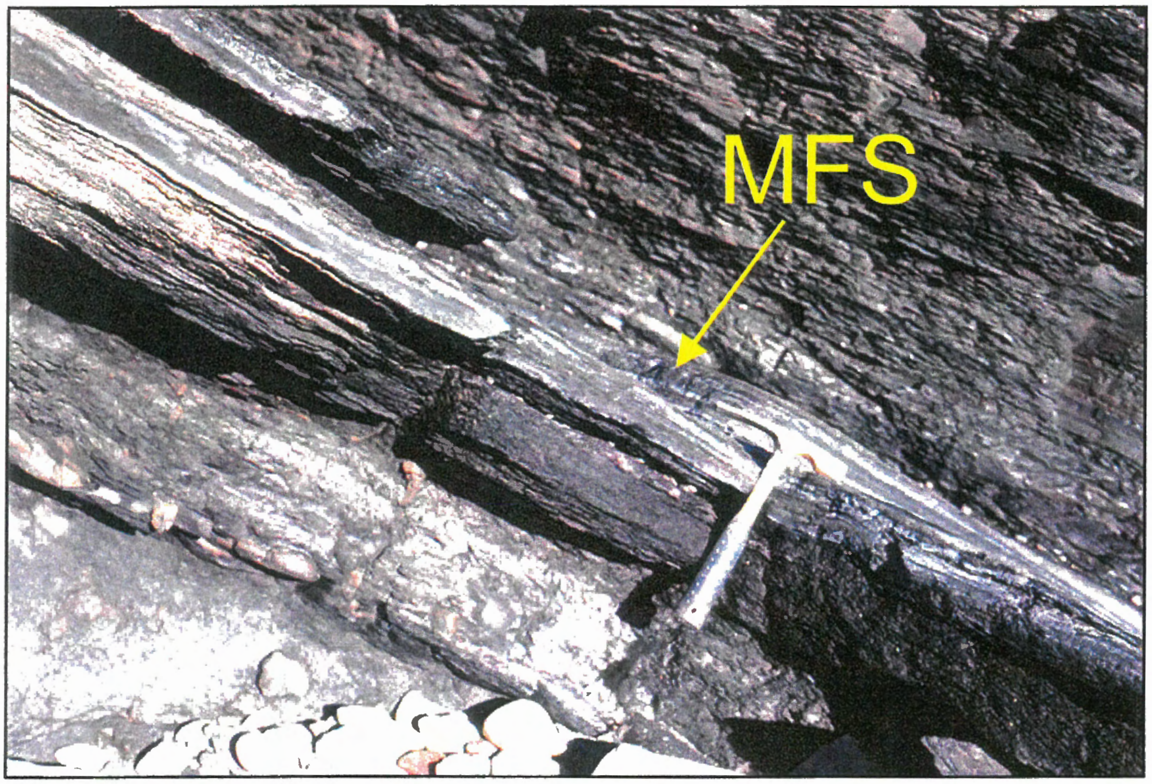


Figure 42. Maximum flooding surface identified at Schooner Pond section. This fossiliferous limestone layer (Facies 2a) is rich in bivalve and ostracod remains and has well developed planar to wavy stratification. This 18cm thick unit is easily identifiable in the cliff and extends into the low tide zone on a wave-cut platform. Hammer is ~30cm for scale.

sections lies above the Backpit seam and is identified at Long Beach, and is 0.25 m in thickness. A distinct limestone marker bed was also identified in the Schooner Pond section (Fig. 42). None of these limestone horizons were found at the Morien South section, perhaps implying that it was consistently landward of the maximum transgression of the basin at this time.

Additional examples of flooding surfaces observed are thin coal or coaly shale horizons (Fig. 43). Thick, extensive, coal seams can be used to represent the maximum flooding surface where no distinct, faunal-rich limestones are present. Transgression and increased relative sea level causing ponding and higher groundwater levels up the coastal plain could create the swamp-like conditions excellent for coastal, blanket peat accumulation. Many thick coals likely formed landward of the shoreline of maximum transgression.

### *4.2.3 Systems Tracts*

Systems tracts form an integral part in the application of a sequence stratigraphic framework. The main systems tracts can be recognized in the study sections at Long Beach, Morien South, and Schooner Pond, yet not all systems tracts are preserved to the same degree. The concept of identifying systems tracts is important as it allows for prediction from one contemporaneous depositional system to another (Walker, 1992).

Systems tract terminology is not readily applied to the alluvial-plain strata where no open-marine influence is demonstrated or preserved (Gibling and Bird, 1994). Very few LST deposits were identified in the study section, but this could be due to a preservation bias and or erosion during lowstand incision. In more proximal locations, the

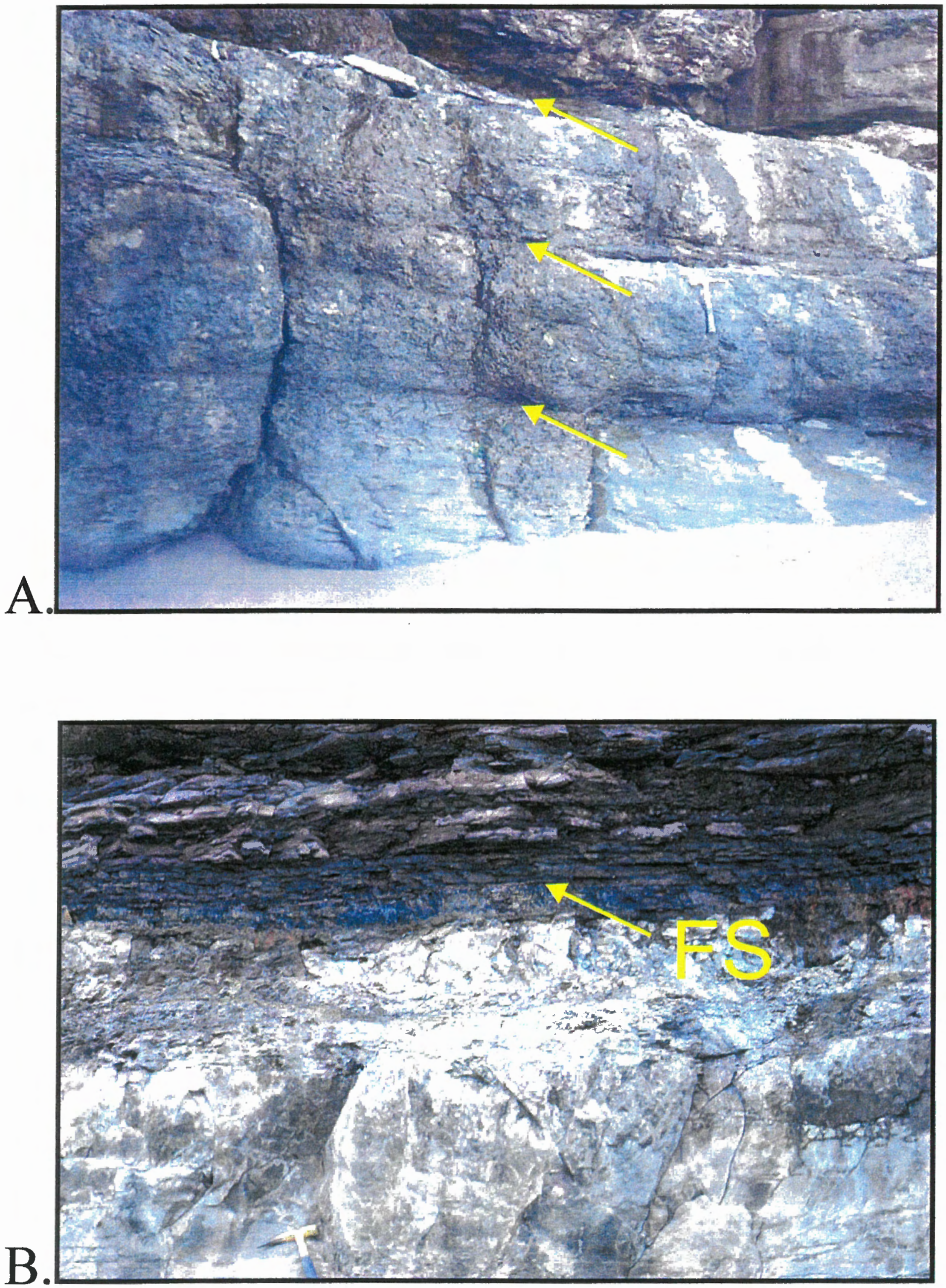


Figure 43. Flooding Surfaces (FS). A) Repeated minor flooding surfaces identified by the yellow arrows at Morien South. Hammer is ~30cm for scale. B) Unidentified coal layer at Schooner Pond also represents a flooding surface.

preservation of LST deposits is unlikely. Furthermore, it can be assumed that many lowstand horizons were incorporated into the well-developed soil or paleosol profiles and/or calcrete horizons.

The transgressive systems tract can be straightforward to identify in most sequences. It characteristically includes the deposits accumulated during transgression (an upward deepening of facies). The maximum flooding surface caps the top of the transgressive systems tract. The main coal zones of England's Westphalian coal measures fall dominantly within the transgressive systems tract (Flint et al., 1995). The economic coals of the Sydney Basin also fall dominantly within the transgressive systems tract (Gibling et al., in press). The transgressive systems tract is prominent in the Morien Bay sections. Deposits are often thick because accommodation space is high due to infilling above lowstand surfaces.

The highstand systems tract is deposited during an interval of slowing rates of sea-level rise (Posamentier and Allen, 1999). Fluvial deposition migrates farther out on the coastal plain, as the highstand systems tract continues to develop (Posamentier and Allen, 1999). Accommodation space is slowly decreasing and sedimentation style and sequences reflect this. The coastal plain is readvancing during the highstand systems tract and many channels and distributary systems are establishing themselves. Areas maintaining high accommodation space can facilitate development of fossil forests as evidenced from the majority of erect trees found within HST versus TST strata. HST deposits are well represented in the Morien Bay sections.

Greater detail on specific systems tracts and their occurrence in each sequence is provided in the following section. Because strata in the McRury to Emery coal seam interval are poorly exposed, sequence numbering commences just below the Emery seam. Emphasis on sequence designation and correlation is placed predominantly on the Long Beach and Morien South sections. As the Schooner Pond section is much shorter than the other two and represents less of the study interval, it is difficult to assign sequence designations and its use for sequence stratigraphic analysis is fairly incomplete. Initial correlations are made with the sequence boundary of Sequence 1 and below the Emery seam but that is as far as sequence designation is proposed for Schooner Pond as there are some consistency problems.

## 4.3 Sequence Architecture of Studied Sections

### *Sequence 1 (31m)*

The sequence (Figure 44) commences with a distinctive 0.96 m nodular calcrete with a well-developed vertic fabric and large sub-spherical calcareous nodules at Long Beach. This layer is interpreted as the sequence boundary. The sequence boundary is not visible at Morien South as cliff outcrops begin there approximately 2m below the Emery coal seam. It is overlain at Long Beach by ~11m of grey, laminated siltstone, containing siderite and (less commonly) calcareous concretions, ripple cross-lamination and plant fragments. A road cut through the cliff creates a gap after which the Emery coal seam becomes visible. This seam is at least 0.65m thick at Long Beach whereas it has split into three thinner coal seams interbedded with fossiliferous grey mudstones at Morien South (and Schooner Pond).

The maximum flooding surface is placed at the top of the Emery seam at Long Beach and at the top of the thickest leaf of the Emery seam at Morien South. These horizons are chosen to best represent the maximum landward extent of flooding or

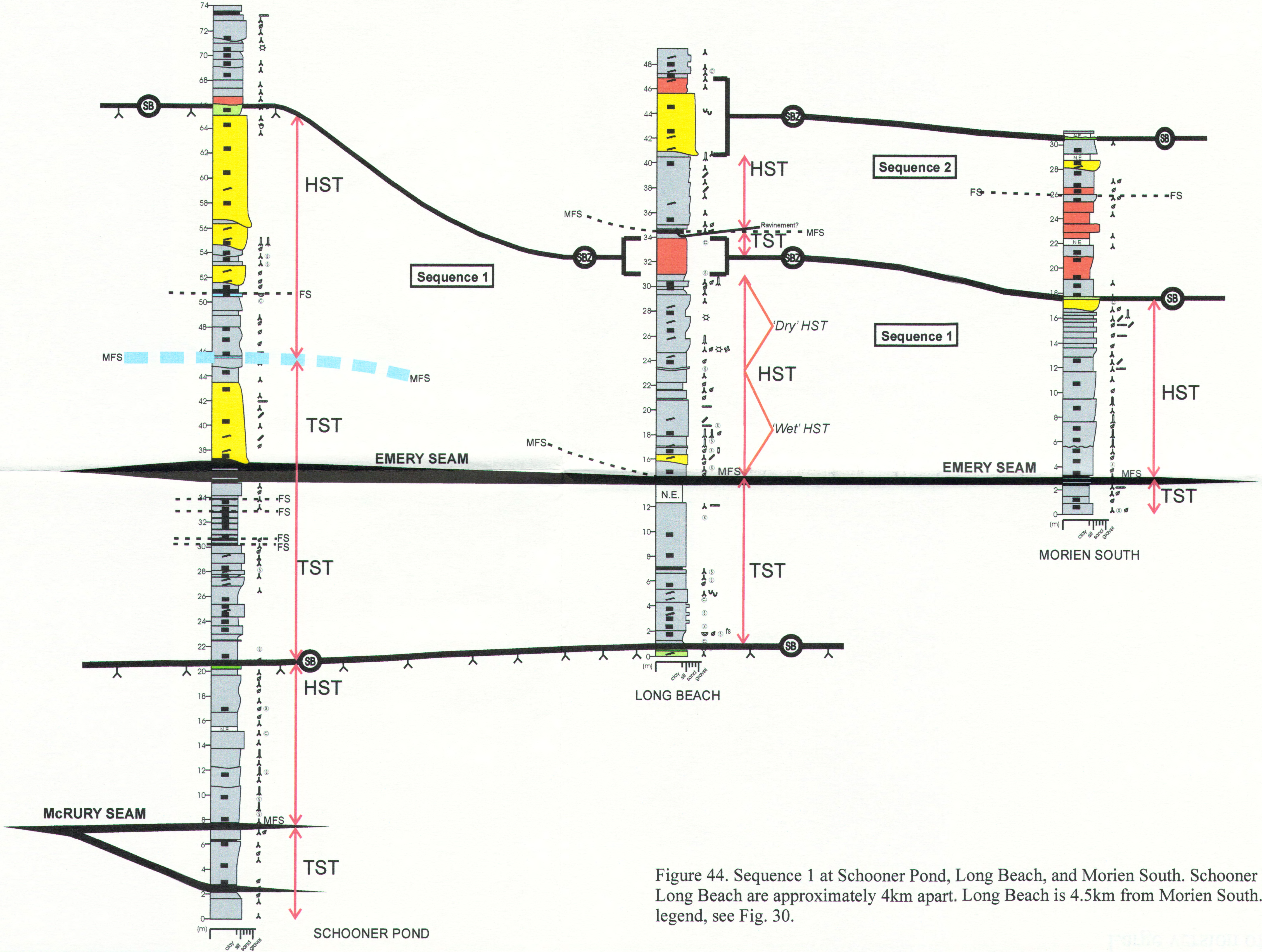


Figure 44. Sequence 1 at Schooner Pond, Long Beach, and Morien South. Schooner Pond and Long Beach are approximately 4km apart. Long Beach is 4.5km from Morien South. For legend, see Fig. 30.

transgressive conditions achieved during this cycle. However, no distinctive faunal-concentrate level marks this position, and peat was not succeeded by open-marine conditions. The Emery seam is highly split across the Sydney Basin and averages 2.69% sulphur and 9.5% ash (Hacquebard and Donaldson, 1969). This seam has been the thinnest coal mined within the Sydney Coalfield (Hacquebard, 1998). The TST below the maximum flooding surface at Long Beach is fairly thick and includes two major leaves of the Emery seam. Minor flooding surfaces are represented by thin coaly layers. At Morien South the TST present is fairly thin but this is only due to the limited exposure in outcrop.

The HST is 16m thick at Long Beach and can be characterized by two sub-components: 'wet' vs 'dry' HST. Overlying the Emery seam are ~8m of fossiliferous grey siltstones and sandstones. These beds contain some of the best-preserved plant compression fossils found within the study sections. These beds also contain numerous prostrate and in situ *Calamites* logs, in-situ lycopsid trunks, and numerous large stigmarian roots. Siderite nodules are also common within these rooted units. The lower 8m are considered 'wet HST', with evidence for a consistently high groundwater table, likely present still from the effects of the past transgression. Characteristic bayfill or poorly drained setting indicators such as siderite nodules, stigmarian roots and *Calamites* and lycopsid flora abound in these units. The upper 8m of 'dry HST' consists of strata quite different from that of the 'wet' HST. It still consists mainly of coarsening-up grey sandstone units, yet poorly-drained or waterlogged features are not observed. Instead, desiccation cracks and raindrop impressions are preserved at several levels. Minor plant fossil material is preserved and better drainage conditions are inferred. The boundary between 'wet' and 'dry' HST is taken at a prominent erosion surface marked by a lag of reworked siderite nodules, at 23m at Long Beach. Due to its limited exposure and unusual position, this surface is not considered a potential sequence boundary.

At Morien South, the 14m HST commences with 10m of coarsening-up packages, with abundant in situ *Calamites*, stigmarian roots, plant fossil material, and in situ lycopsid trees. The floral record is more extensive and easily noticed here than at Long Beach, likely due to a larger presence of laminated siltstones and mudstones. These laminated strata indicate calmer water conditions and a less disturbed environment during deposition, promoting plant material accumulation and organic preservation. Numerous fossil forest horizons are preserved at Morien South. Within a 13m interval, three extensive *Calamites* horizons and two lycopsid fossil forest horizons are preserved. The uppermost 6m is dominated by thinner alternating sandstone and shale units with more prominent stigmarian roots and prostrate *Calamites*, perhaps indicating a less conducive environment for extensive fossil forest preservation. No signs of drying conditions are found in the HST deposits at Morien South to correspond with those at Long Beach. The whole HST package here appears to represent numerous poorly drained, vegetation-rich swamps and bays, possibly in part due to raised water tables and local ponding still present from the transgression. As repeated fossil forest horizons are observed, conditions conducive to extensive plant growth and preservation persisted and plant species continued to re-colonize with the repeated flooding of their habitat.

At Schooner Pond, a similar calcrete level to Long Beach was picked to represent the sequence boundary. It is overlain by 14m of grey laminated mud- and siltstone packages. Numerous rooted horizons and plant fragments are found in these packages as well as many coaly shale flooding horizons. The Emery Seam is quite thick at Schooner

Pond (2.03m with ~35cm shale lens 1.3m into the seam) and immediately overlain by a large channel body. This channel body has extensive rooted horizons with large stigmarian root systems. Trough cross strata and planar laminations are common as well as calamite stems. A 0.18 m thick fossiliferous limestone unit lies 1m above this channel body. It contains mostly bivalve and ostracod remains and is very well stratified with planar to wavy laminations. It is a very distinctive layer or 'marker bed' that is visible along the cliffs and extensively exposed on the wave-cut platform (Fig. 10b). Possible fish coprolites were also identified in this unit. No comparable unit at similar levels was found at Long Beach or Morien South. This unit was picked as the MFS and thus below it, a very thick TST is preserved. (However, assigning this as the MFS involves having a major channel body within the TST atop the coal, while at Long Beach coeval post-Emery deposits are considered HST at an equivalent level). Above this layer are numerous flooding horizons and again another limestone layer. It is similar to the 'marker bed' described above but contains more black coaly shale material and thin coal stringers. It is interpreted as a major flooding surface but not the maximum. After the maximum transgression, as the relative sea level dropped, it may have paused or risen slightly again, resulting in an additional organic-rich horizon, before regression set in again. A fossil forest horizon is identified at 55m and at least four large lycopsid trunks or their remains were preserved in the cliff face. The minor channel sandstone above this unit appears more as a succession of troughs, having to form around the standing trunks. Above this, drier conditions are apparent and a large, dryland channel body possibly makes up the rest of the HST. Minor conglomerate is observed at the base of the channel, with alternating levels of planar- and trough-cross strata as you go up the unit. Near the top of this unit a set of tetrapod trackways was located in 1998 (Gibling, 2000 pers. comm.). The top of the unit is extensively rooted and grades into a calcareous siltstone, closely resembling the calcretes represented elsewhere in the section.

### *Sequence 2 (13-15m)*

The sequence boundary at Long Beach is placed within a 3m package of unstratified red siltstone containing calcareous concretions and well developed concave-up joint sets (Figure 45). These joint sets are indicative of the shrinking and swelling action of the clay minerals within the paleosols due to changes in the water table. These features are commonly seen in regions under seasonal climatic influences. This is the first representation of a sequence boundary zone in the study sections as described in Section 4.2.1. These beds are similar to those interpreted by Tandon and Gibling (1994) as calcic, vertisol-like paleosols. No single surface can be easily identified as the sequence boundary, thus a zone is applied here. At Morien South the sequence boundary is placed at the top of a 0.95m channel body, where an extensively rooted and nodular calcareous layer of sandstone records a prominent paleosol. Similar sequence boundaries identified in the Sydney Basin by Gibling et al. (in press) suggest a break in sedimentation.

The paleosol is overlain at Long Beach by a thin 10cm coal-rich layer interpreted as a flooding surface and likely the maximum flooding level. The TST is very thin here and may be represented only by <1m of mudstone. However, the sequence boundary zone may include mud incorporated into a cumulative paleosol during the early stages of transgression, when fine sediment was stored on the floodplain. Six metres of rooted grey coarsening-up packages, rich in calamites and standing lycopsid trunks are interpreted as the highstand systems tract. An overlying large channel body cuts these wetland deposits.

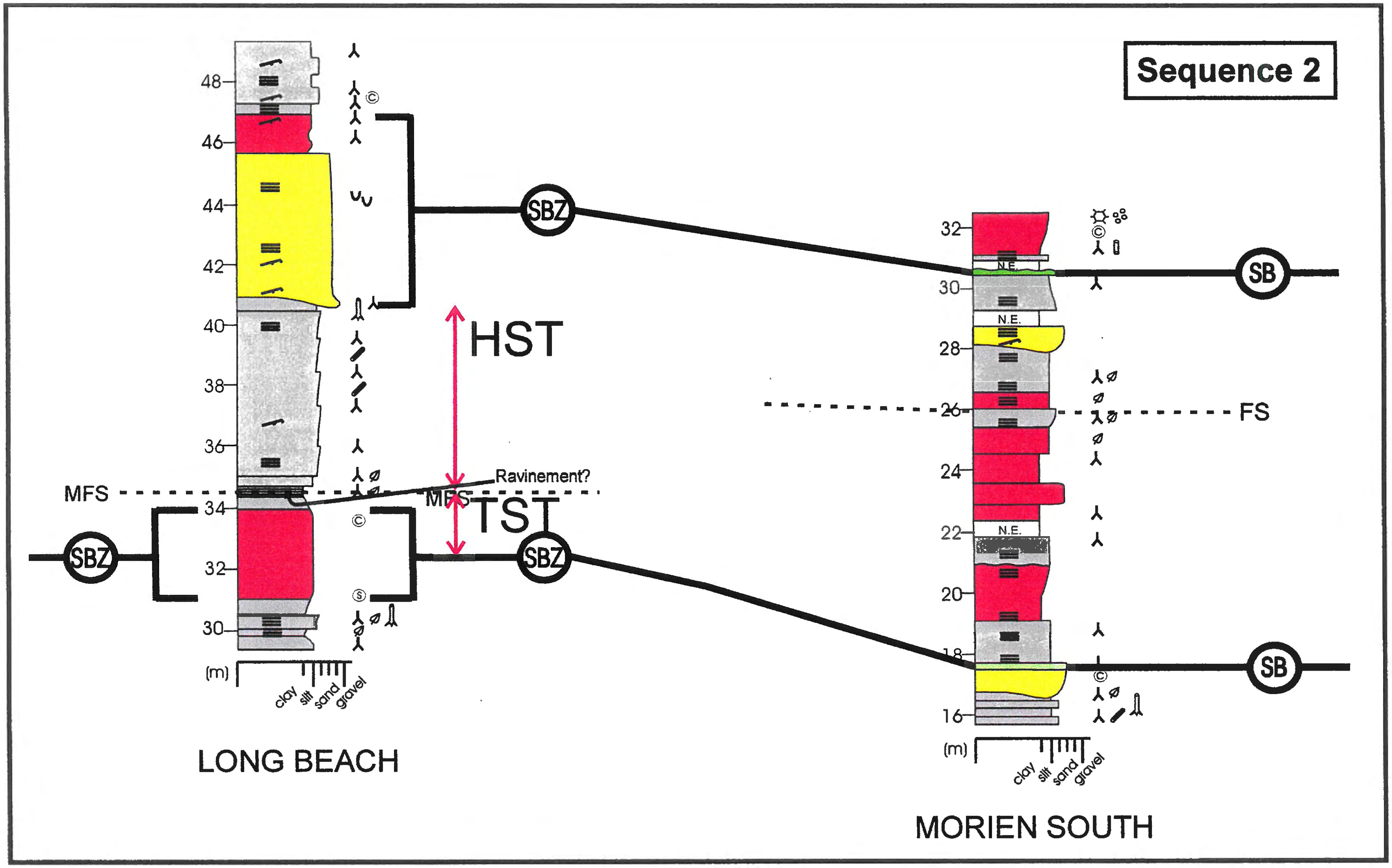


Figure 45. Sequence 2 at Long Beach and Morien South. Long Beach and Morien South are approximately 4.5km apart. For legend, see Fig. 30.

The base of the unit directly above the basal sequence boundary zone has an abrupt contact and is rich in organic debris. This horizon could possibly mark a ravinement surface that could be verified through further outcrops along strike. It is however not as convincing an example as the surface at ~23m at Long Beach.

At Morien South a different set of facies is observed above the sequence boundary. Greater than 50% of the sequence is represented by red mudstones and siltstones, with some preserving laminations while others are rooted. These layers could represent lacustrine deposits and could represent transgression in an updip, predominantly non-marine setting. They are assigned, however, to the well-drained alluvial plain facies assemblage as their overall stratal representation is not very large. These deposits could have formed in a minor, shallow lake environment. It is plausible for lakes to have formed between the larger channels tracts on a well drained alluvial plain. The upper 5m of the sequence contains two minor flooding surfaces marked by thin layers of dark organic material rich in macerated plant fragments and a minor distributary channel body. No coal is present comparable to that at LB, and the MFS cannot be identified. Thus, no individual systems tracts were identified in sequence 2 at Morien South.

### ***Sequence 3 (11-21m)***

Sequence 3 commences at Long Beach with a 4.75m channel body, overlain by 1m of red rooted mudstone (paleosol) (Figure 46). These beds are interpreted as a sequence boundary zone as no single surface is readily identified as the sequence boundary. At Morien South, the more proximal (landward?) locality, sequence 3

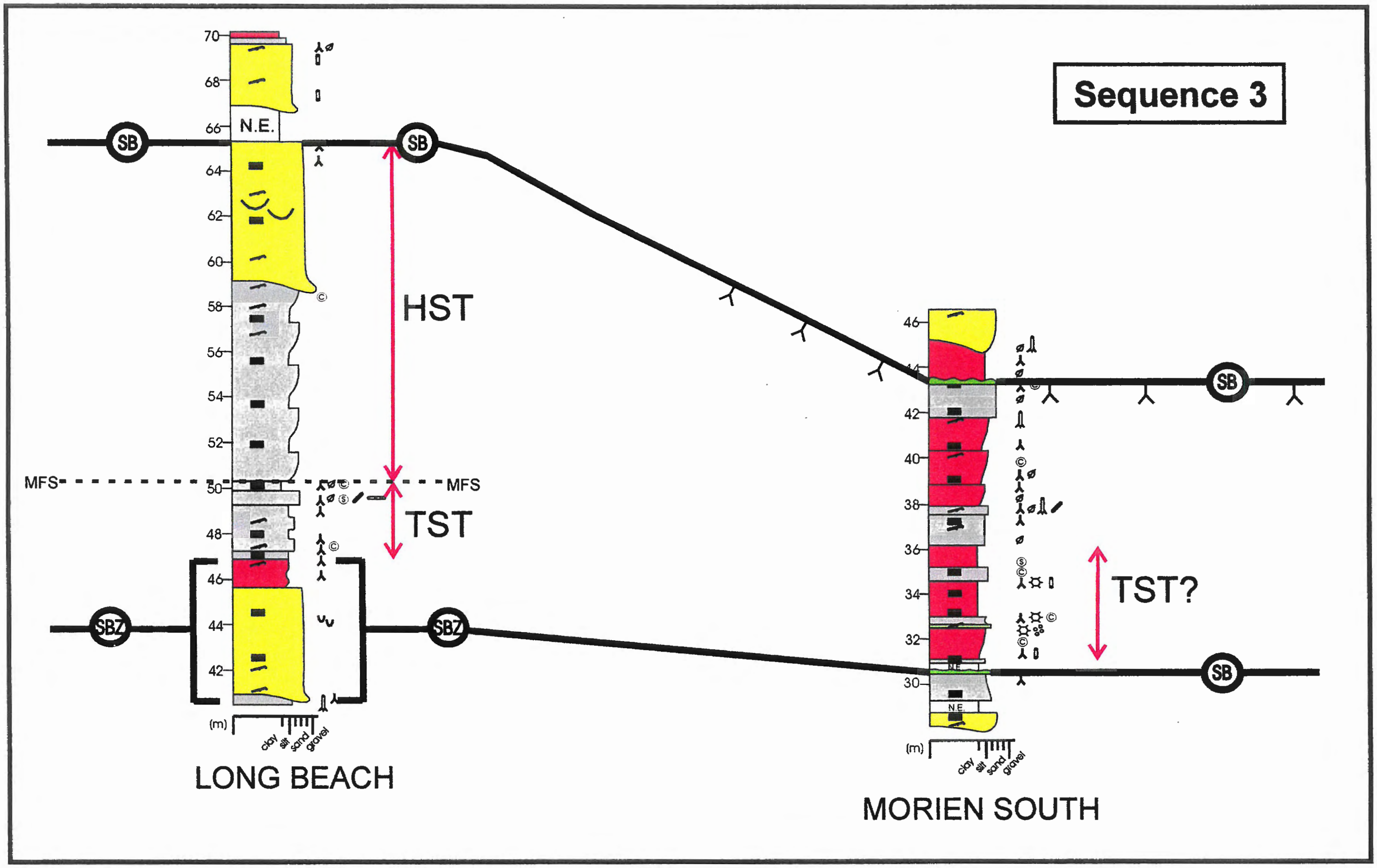


Figure 46. Sequence 3 at Long Beach and Morien South. Long Beach and Morien South are approximately 4.5km apart. For legend, see Fig. 30.

commences with a 0.32m calcrete, with the top of the rooted, calcareous nodule-rich layer selected to mark the sequence boundary.

The sequence boundary is overlain by 4m of grey rooted sandstone and mudstone with roots and scattered calcareous and siderite nodules. The transgressive systems tract at Long Beach is fairly thin (4m). A maximum flooding surface is represented by thin shaly organic-rich layers atop beds rich in stigmarian roots and calamites logs. At Long Beach a large (9m) package of laminated grey coarsening-up strata, with ripple cross-laminated sandstones is cut by a large distributary channel body that displays planar beds and trough cross strata. The upper layers of the channel body are very rooted and all signs of stratification are lost. These stacked wetland facies are assigned to the highstand systems tract.

At Morien South a thicker (6m) succession of dryland soils is interpreted as representing the TST. Alternating red beds and grey sheet sandstones contain calcareous nodules, desiccation cracks, raindrop impressions and burrows at numerous levels. These red mudstones are well laminated indicative of accumulation in standing bodies of water. The presence of standing water bodies (or lakes) is in accord with possible ponding and accommodation which would likely be present during transgression downdip of the area. Thus these units can be interpreted as the TST as they formed updip during transgression. After assigning these lower redbeds as possible TST deposits, no obvious MFS was observed at Morien South, similar to Sequence 2. Above this the beds are dominated by 4m of red coarsening-up sandstones further indicative of a lowered water table and increased stability of the landscape (or better drainage). No major rise of relative sea level or transgression is recorded here.

### ***Sequence 4 (35-38m)***

At Long Beach, the sequence boundary is placed at a calcareous nodular and rooted horizon at the top of a large distributary channel body (Figure 47). More landward at Morien South, the sequence boundary is represented by a thin rooted calcareous sandstone with a nodular top capped by ~1m of coarsening-up rooted red mudstones.

Several channel sandstone bodies dominate the sequence at Long Beach. Two styles of channel deposit are observed. In the lower half of the section, the channel bodies have prominent plane beds, washed-out dunes, and strong incision through packages of redbeds. These channels are interpreted as flashy, dryland channel bodies forming during a relative lowstand where there was greater incision of channels and a lower water table. In between these channel deposits are well-laminated red siltstones, moderately rooted and with in situ *Calamites* stems at one level. The channel bodies range from 2-5.5m in thickness. The largest channel body consists of multiple storeys and includes a well-preserved set of tetrapod trackways (further description in Section 5.4.2). Raindrop prints are found at the base of the channel and around the trackway, which also has adhesion warts and desiccation cracks present. These sedimentary structures indicate subaerial exposure and an episode of drying, perhaps seasonal dryland environment during deposition. The strong incision and high flow conditions suggest that the channels may have formed on the well drained alluvial plain at the end of base level fall and could be the closest thing to substantial LST deposits preserved at Morien Bay. It is difficult to know if these truly are lowstand deposits as strong sediment accumulation is not always associated with this period of the relative sea level cycle, which is commonly assumed to involve sediment bypass. At Morien South at a similar level there are also dryland

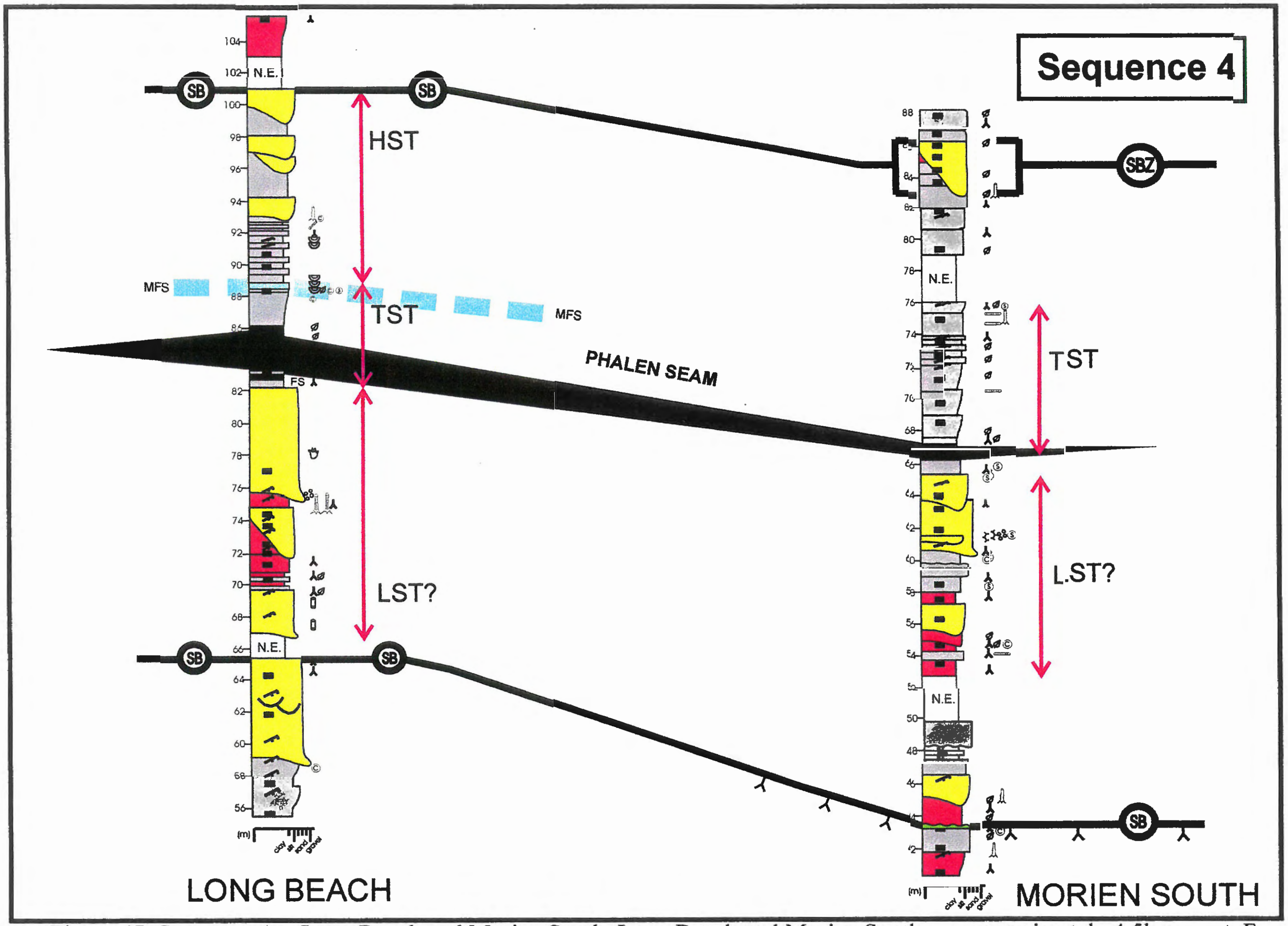


Figure 47. Sequence 4 at Long Beach and Morien South. Long Beach and Morien South are approximately 4.5km apart. For legend, see Fig. 30.

channel bodies with major erosional bases. Thicker packages of red and grey interfluve sediments are found between the channel deposits in the lower part of the section. Higher up there are more indications of drier conditions such as desiccation cracks, raindrop impressions and calcareous nodules. Thus, there are many similar characteristics to the channel systems at Long Beach and they likely formed under similar local environmental conditions. Just below the Phalen coal seam rooted grey mudstones with siderite nodules reappear as also found at the Victoria Mines section ~30km to the west (Gibling et al., in press).

A rapid transgression followed and accumulation of major peat deposits commenced. The Phalen coal is one of the Sydney Basin's main economic seams and can be up to 2.5m thick with 3.29% sulphur and 7.1% ash (Hacquebard and Donaldson, 1969; Hacquebard, 1998). Next to the Harbour seam, this seam has been the most extensively mined seam in the Sydney Coalfield with 14 different mines having been in operation (Hacquebard, 1998). At Long Beach the Phalen reaches 2.8m in thickness while at Morien South it is noticeably thinner at 0.8m thick. The base of the Phalen coal represents a major flooding surface. The Phalen seam is overlain by poorly drained floodplain deposits that consist of coarsening-up packages of fossiliferous grey mudstones (9m thick). At Long Beach, ~2m of laminated grey mudstone overlies the Phalen, capped by a prominent 0.35m fossiliferous limestone. This unit is rich in bivalves and ostracods and a similar unit at a similar level can be traced widely (Naylor et al., 1996; Gibling et al., 1999) elsewhere in the Sydney Basin. At Morien South this distinctive limestone layer is not observed, perhaps due to locally higher relief or a lesser extent of transgressive flooding recorded at a more landward locality. The limestone is overlain by poorly drained floodplain deposits, again rich in bivalves, at Long Beach. Coal forms a major part of the transgressive systems tract here with the limestone indicating the maximum flooding level. The highstand systems tract contains the second style of channel bodies and the underlying grey, poorly drained floodplain deposits. The channels represent wetland distributary channel systems and are less than two metres in thickness with ripple cross-lamination, rooted horizons and burrows.

At Morien South, repeated packages of grey siltstone rich in stigmarian roots and fossil plant debris dominate the rest of the sequence. These strata represent TST deposits with numerous stigmarian roots and plant rich levels as well as standing tree trunks. No distinct MFS is identified so it is not clear where the HST begins.

### ***Sequence 5 (13-16m)***

The sequence boundary at Long Beach is interpreted at a slightly rooted horizon atop a channel body (Figure 48). Following a gap, a 2m thick laminated red paleosol overlies the sequence boundary. At Morien South, the sequence boundary is not identifiable by one horizon but rather within a sequence boundary zone consisting of laminated red mudstones cut and capped by a large plane-bedded channel sandstone. Sequence 5 is a relatively thin sequence.

At Long Beach a thin succession of coarsening-upwards rooted and laminated grey mudstones overlies the red paleosol. At Morien South, thicker coarsening-upwards packages of laminated and rooted grey mudstones are present, ~16m in thickness. Drier conditions are indicated in the upper part of these poorly drained facies at Morien South by the presence of desiccation cracks, raindrop impressions and calcareous nodules.

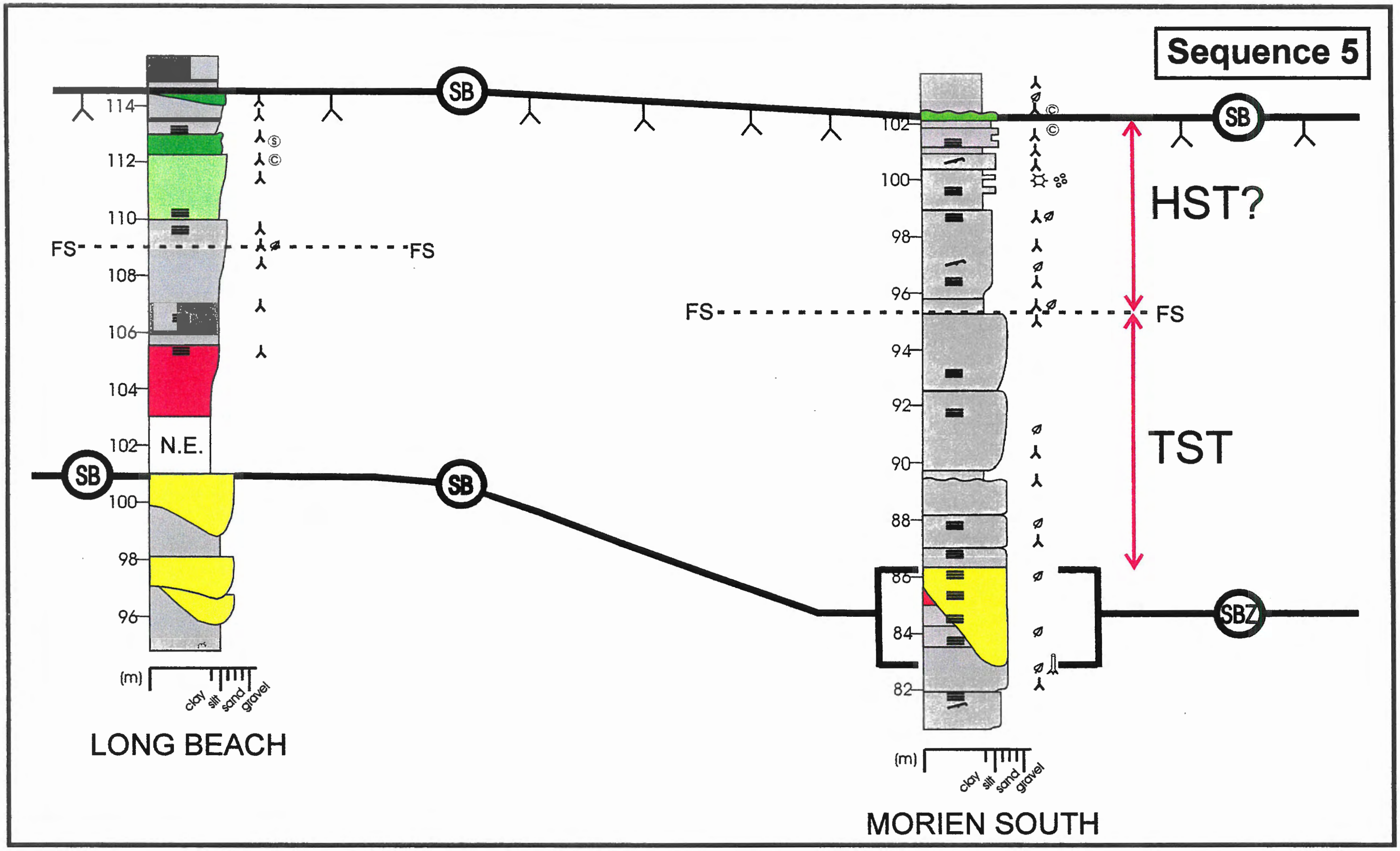


Figure 48. Sequence 5 at Long Beach and Morien South. Long Beach and Morien South are approximately 4.5km apart. For legend, see Fig. 30.

One flooding surface at Long Beach is represented by an organic-rich coaly shale layer within this unit. One similarly thin flooding surface is also observed at Morien South. If this surface is assumed to be a maximum flooding surface, TST deposits consist of the coarsening-up packages of grey muds and sandstones below this level. There are probable HST deposits as well at Morien South, though they are similar to the 'dry' HST deposits identified in Sequence 2 at Long Beach. Beyond this, characteristic system tracts identification was not possible in Sequence 5.

### *Sequence 6 (35m)*

This sequence begins with a very prominent calcrete zone (2-3m) at Long Beach which correlates with a thinner calcrete at Morien South (Figure 49). At Long Beach a 2m thick rooted calcareous sandstone is overlain by a more cemented mass of coalesced carbonate nodules. The topmost calcrete layer representing the final stable land surface is interpreted to represent the sequence boundary. This calcrete is very resistant and distinctive in outcrop.

Thin grey mudstones overlie the calcrete, and are associated with more well-drained strata at Long Beach. Here a large, dryland alluvial channel body is recorded with numerous desiccation cracks, plane beds, raindrop impressions and small tetrapod trackways. The Backpit coal lies above the dryland strata but differs in its representation from Long Beach to Morien South. Across the onshore outcrop belt of the Sydney Mines Formation, the Backpit is a single, unsplit seam up to 1.5m thick (Gibling et al., in press) averaging 1.9% sulphur and 5.9% ash (Hacquebard, 1998). At Morien South, the seam has split into at least two leaves with thick shale partings between them. Exploratory wells 5-10km offshore from this area recorded two closely spaced leaves (White et al.,

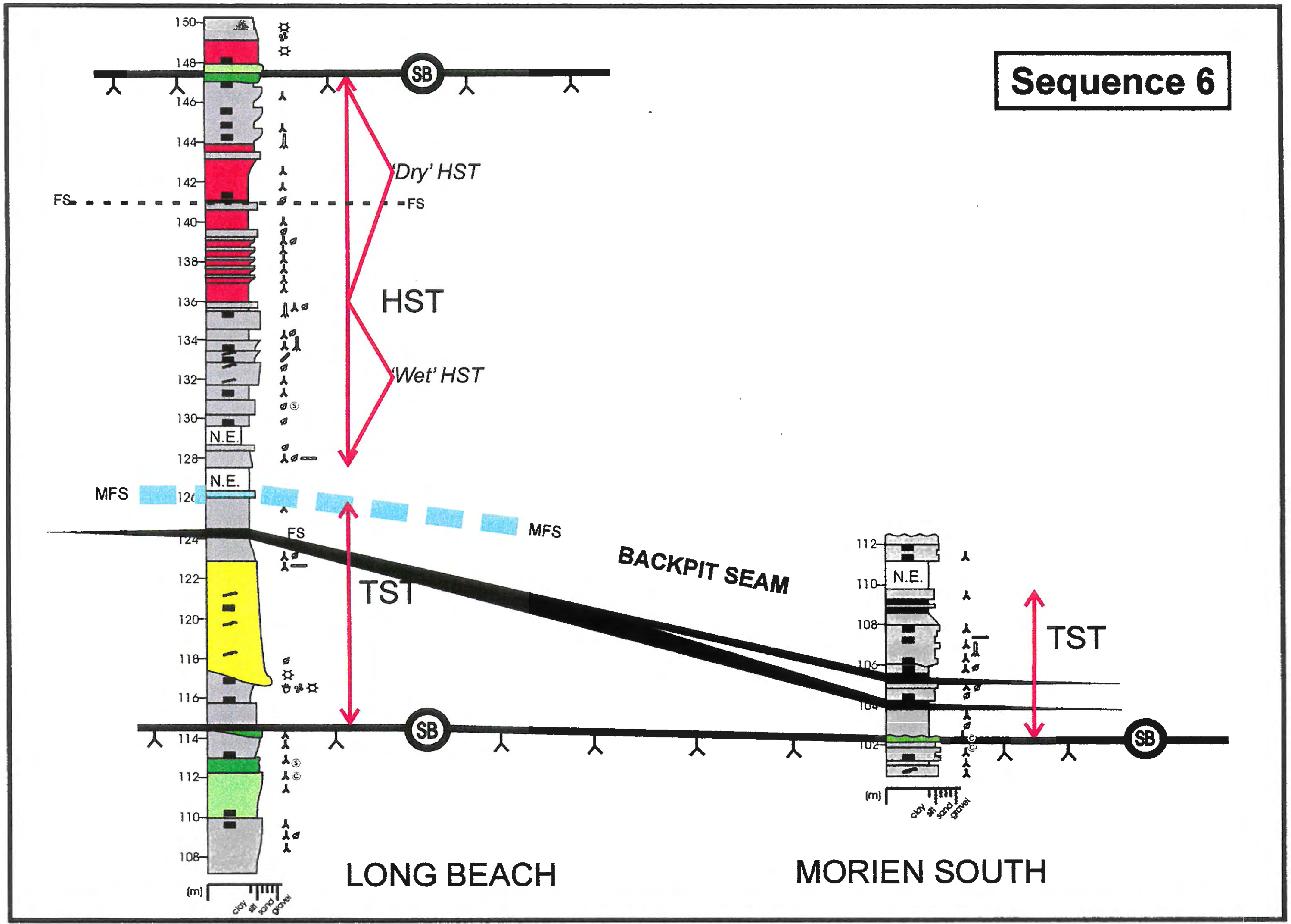


Figure 49. Sequence 6 at Long Beach and Morien South. Long Beach and Morien South are approximately 4.5km apart. For legend, see Fig. 30.

1994; Shimeld and Deptuck, 1998). White et al. (1994) interpreted dulling upward pulses in the upper part of the Backpit seam as inundations that eventually drowned the mires.

Shortly above the Backpit coal is a 0.25m thick limestone-shale unit. This unit is traceable for >45km across the Sydney Basin (Gibling et al., in press) and correlates with White's (1992) Backpit Roof Unit. This limestone-shale unit contains abundant bivalves and ostracods, dark grey to black shale, minor siderite bands, and fine-grained carbonate. It represents the maximum flooding surface. At the Victoria Mines Section, this unit was found to contain bivalves, ostracods, branchiopods, serpulids, fish fragments, agglutinated foraminifera and plant fragments (White, 1992). TOC values for the unit averaged 3.67 % (up to 20%) and consisted of mainly liptinite with vitrinite and inertinite (White, 1992). The unit also contained up to 11.3% by volume of pyrite as crystals and framboids (White, 1992).

Coarsening-upwards packages of fossiliferous grey mudstones overlie the limestone unit. Stigmarian root systems, in situ and prostrate *Calamites* stems, as well as numerous rooted horizons are prominent within this unit. Erect lycopsid trees are also present approximately 10m above the limestone. An abrupt change to red, well-drained sediments occurs above the grey poorly drained facies. These rooted red mudstones repeatedly coarsen up to grey sandstone beds. The red beds thicken until they are capped by a 3m thick package of grey laminated and rooted paleosols. As with Sequence 1, these redbeds may be indicative of a drier phase of the HST above.

As with Sequence 4, the distinct limestone layer is apparently not traceable landwards to the Morien South section. As outcrops at Morien South end approximately 2-6 m above the Backpit seam, the stratal level of the limestone unit is not present.

However, it seems unlikely that this unit would be found at greater distances above the Backpit seam and likely the effects of the transgression were not felt to the same extent in the Morien South area. A thick TST deposit is observed at Morien South along with minor flooding surfaces above the Backpit coals.

### *Sequence 7 (not fully exposed)*

The sequence boundary is taken at the top of a nodular calcrete horizon with a strong vertic fabric and numerous calcareous nodules (Figure 50). Overlying the sequence boundary is a 1m bed of dryland red laminated mudstone containing desiccation cracks and raindrop impressions. Grey dryland strata overlie the red beds, also containing abundant rainprints and desiccation cracks. Numerous thin channel sandstones with ripple cross lamination, possibly channelised splays, cut through the grey dryland strata. The Bouthilier coal seam lies atop a fairly thick dryland interval. A large channel body lies above the Bouthilier, capped by poorly exposed rooted grey mudstones. Characteristic systems tracts are not easily identified in the partial cliff exposure of sequence 7 and the MFS is tentatively placed at the top of the Bouthilier coal. If this is confirmed, much of the TST is represented by grey dryland-type deposits and the grey siltstones and channel body above the MFS would then be associated with the HST.

## 4.4 Correlations of Sections

Correlation between sections at Schooner Pond and Long Beach was surprisingly problematic, given the short distance between them (~ 4 km). Above the Emery Seam, numerous candidates can be suggested at Schooner Pond for both flooding surfaces and sequence boundaries. A preferred correlation for Sequence 1 between the two sections is

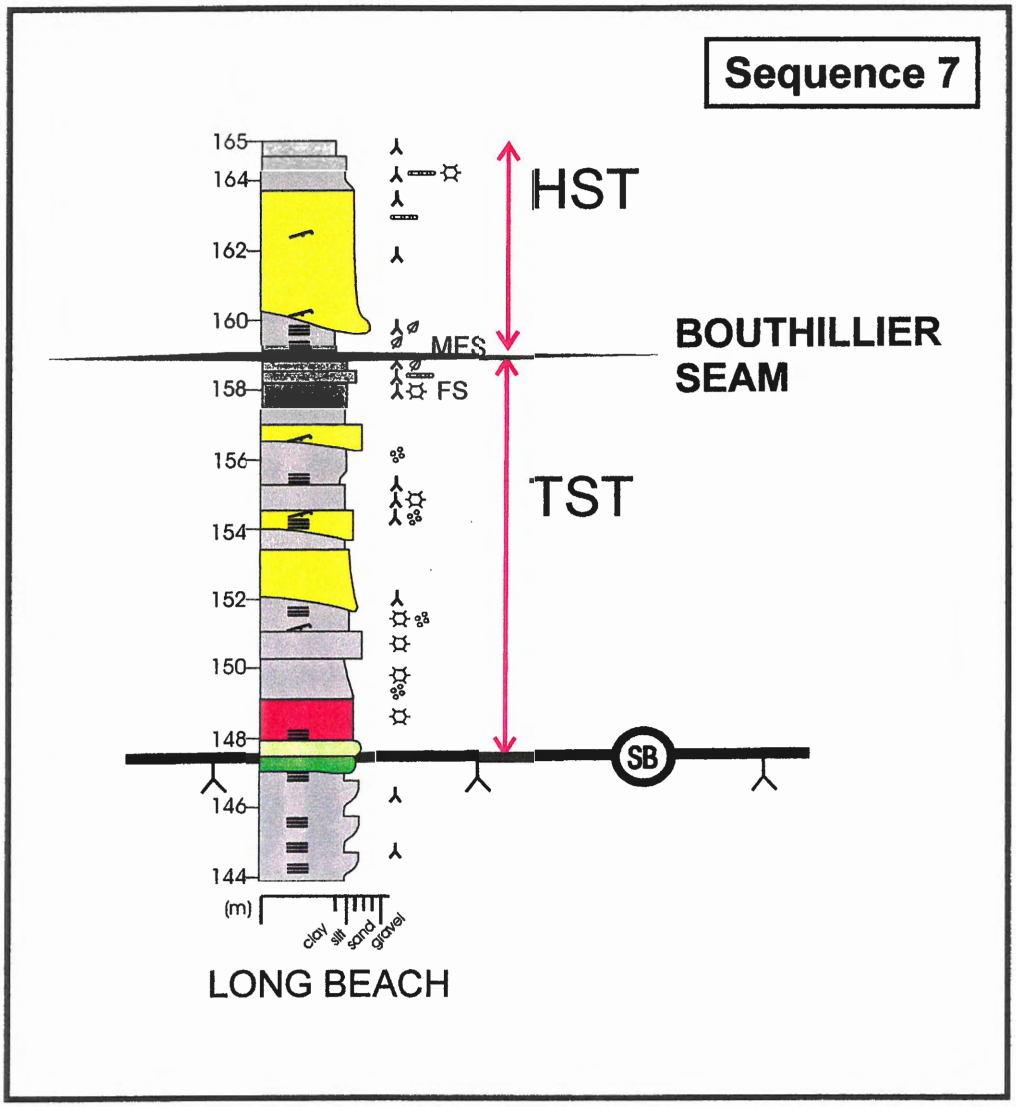


Figure 50. Sequence 7 at Long Beach. For legend, see Fig. 30.

presented (Fig. 44). The section has a limited stratigraphic range and is inaccessible at higher levels; correlations for Sequence 2 and higher sequences were not fully resolved during the present study, and correlation between Schooner Pond and sections farther west is also uncertain.

Stratigraphic sections across the entire onshore Sydney Basin have been measured by numerous workers (Table 1). Cross-sections linking these sections allows for correlation of coal seams, flooding surfaces and lithological features. The coals in the basin are very good stratigraphic markers. The next best surface for correlation across great distances is limestone layers. Calcrete horizons are also key stratigraphic markers. Specific facies, such as channel body development and red floodplain sediments are also added to these cross-sections to see lateral facies changes and/or trends. In order to first easily make generalized comments on the correlations between the study sections and the rest of the Sydney Basin a basin-wide cross-section is needed.

Various cross-sections through the basin can be found in the literature but vary in quality and extensiveness. Batson and Gibling (2002) studied the architecture of channel bodies and paleovalley fills across the Sydney Basin and produced an excellent cross-section linking a series of coastal sections at various levels within the Sydney Mines Formation. It reaches across nearly the entire ~45km onshore extent of the Sydney Mines Formation outcrops, following a NW-SE traverse. They classified the different channel body systems present at each section based on their distinct architectural style that corresponded to formation during different stages in the relative sea-level cycle. Major coal seams, flooding surfaces and sequence boundaries were also identified.

Data from the three sections studied here was added to Batson and Gibling's (2002) cross-sections and now extend the data set and their correlations another ~11km to the south-east (Figure 51). Some of the added sections are not on direct depositional strike and this may slightly affect the thicknesses portrayed in the diagram. This was considered negligible overall when used for a visual comparison and augmentation of the data set. The Backpit coal seam is used as the datum, but whereas this seam is not present at the Schooner Pond section it could not be used and the Emery seam was used as a correlative marker.

From this diagram, changes across the basin in stratal continuity, facies distribution, and sequence thickness are easily and quickly observed. Firstly, stratal packages or sequences thicken in the Morien Bay outcrops. The intervals between the Emery and Phalen, Phalen and Backpit, and Backpit and Bouthilier coal seams all thicken towards the east (Long Beach and Morien South sections). This increased sedimentation could be due to an increased subsidence rate (and resulting increase in accommodation space), an change in fluvial discharge and distance from active channels, a change in base level, or a combination of these and other factors. As tectonic effects on the Sydney Mines Formation are believed to be minimal, a continual increase in accommodation space may have helped allow for greater thicknesses of the fluvial successions to accumulate. The Phalen coal seam noticeably thickens towards the Long Beach section.

Another major change across the basin is an increased abundance in the amount of red mudstone and siltstone floodplain material towards the east. A few intervals of 'redbeds' are recognized above the Backpit coal, at the western margin, in the Bras d'Or, Sydney Mines, and Victoria Mines section. There are also minor intervals beneath the

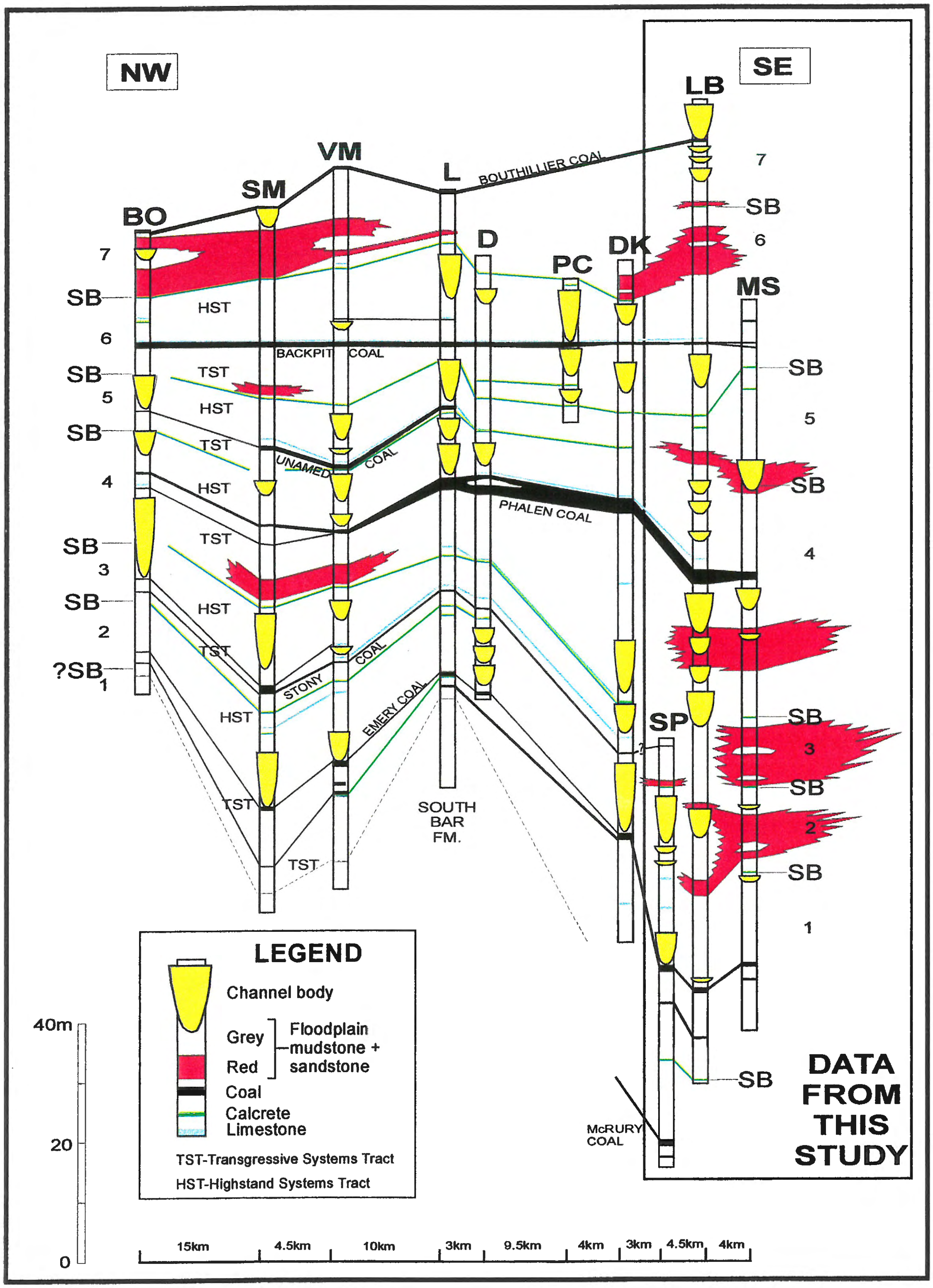


Figure 51. Correlation of stratigraphic sections and sequences in coastal sections of the Sydney Mines Formation. Data from study sections in outlined and added to diagram from Batson and Gibling (2002). Stratigraphic position and thickness of channel bodies shown but widths are schematic. Discussion on basin-wide trends and local comparisons in text section 4.4. BD= Bras d'Or; SM= Sydney Mines; VM= Victoria Mines; L= Lingan; D= Dominion; PC= Port Caledonia; DK= Donkin; SP= Schooner Pond; LB= Long Beach; MS= Morien South.

Phalen coal in the Sydney Mines and Victoria Mines sections. Moving towards the east, the number of redbed packages markedly increases. At Morien South and Long Beach, at least five major redbed intervals are identified. Some of these layers are not entirely red, but may have minor grey muds interlayered, however the overall interpretation for them is well-drained mudstones and siltstones. There is major redbed accumulation between the Emery and Phalen coal seams at Long Beach and Morien South, and also above the Phalen. The last major phase of redbed deposition occurs during the Backpit to Bouthilier coal seam interval. This interval also corresponds well with redbeds identified at the Donkin section in Batson and Gibling (2002). Semi-arid climates with strongly seasonal conditions were major factors contributing to the development of calcareous paleosols (Tandon and Gibling, 1994). These redbed layers also have a climatic factor in their development. Semi-arid climates and well-drained settings can increase the presence of red, oxidized floodplain sediments. However, climate can not be the only factor as the climate at Morien Bay is not likely different from that at Sydney Mines. Increased drainage towards the Morien South region also likely played a major role.

The stratal record of relative sea-level change is not the same across the basin. The Sydney Mines formation is dynamic in that it consists of cyclical strata, changing from well-drained alluvial plain sedimentation to more poorly drained, interdistributary bay and forested wetland environments with peat formation. This repeated cyclic pattern is seen in each section in the cross-section of Figure 51, yet the duration and extent of transgressions and regressions is not the same everywhere. Many limestone layers are not traceable as far as the Morien South section and this could be due to the fact that the maximum transgressive levels of the coastline did not penetrate any further up the coastal plain. The alluvial plain was probably more developed at the eastern margin and possibly slightly higher in topography. Better drainage would also help account for the increased 'red' colour of these oxidized floodplain sediments. Many coal seams also seem to pinch out or separate in the direction of increasing redbeds to the south. This could occur if areas that were conducive to peat formation, with moderate subsidence and accommodation, regularly became invaded by sediment infill events, quite possible in a more proximal alluvial setting. A drop in ponding and lower groundwater levels could also affected peat formation. Calcrete horizons are also not always traceable across the entire basin and this could be because maintaining a completely 'stable' landscape in this dynamic environment was not possible, and positioning on the floodplain and with respect to major drainage channels was ever-changing. Also, if base level is lowered due to channel incision during lowstands, sediment supply would likely be reduced to the floodplain (Leckie et al., 1989). Better developed soil horizons tend to form farther from channel margins as sedimentation is slow and steady here, rather than rapid and episodic (Bown and Kraus, 1987). Additional evidence for the existence of calcretes are calcrete clasts in lag deposits at channel bases, as channels could possibly cut out calcrete horizons at individual sections.

In order to explain the well developed cyclic representation that displays markedly different climatic paleoenvironmental conditions, factors other than base-level change and sedimentation must be involved. Base-level change and increased groundwater level, potentially created during transgressive events, is alone not enough to initiate significant peat formation and accumulation. Climatic factors likely provide the additional mechanism conducive for peat-forming (humid) environments followed by extensive calcrete formation (arid and seasonal climates).

Tandon and Gibling (1994) have suggested a climatic change from humid to strongly seasonal conditions to explain these paleosol cycles. They suggest that the coal-bearing intervals (upper transgressive to highstand systems tracts) formed under relatively humid conditions and that the calcrete-vertisol intervals (lowstand to transgressive systems tracts) formed under relatively arid conditions. Lowstand conditions in the Sydney Basin were arid based on microscopic evaluation of calcretes (Tandon and Gibling, 1997). Channel and floodplain deposits associated with vertisol development also provided good evidence for strongly seasonal flow (Tandon and Gibling, 1997). Climatic cycles were concluded to be linked to sea-level fluctuations in the Sydney Basin (Tandon and Gibling, 1994).

Finally, the type of channel body architecture also appears to change in the study area with respect to the rest of the measured sections in the basin. Numerous smaller channels, distributary systems, and sand-flat systems (as characterized by Batson and Gibling, 2002) appear in the Long Beach and Morien South sections whereas the large, strongly incised paleovalley fills or coarse-bedload systems, found in the western part of the section, were not observed. These channel bodies likely formed under more dryland (possibly braided) fluvial conditions, rather than the meandering, crevasse-splay conditions found during deposition within poorly drained intervals.

The stratigraphic record of the Sydney Mines formation is excellent along depositional strike yet little is known about proximal to distal trends. Very few offshore wells exist in the area and the record they contain is quite limited. Hacquebard (1983) identified individual coals that he correlated with major seams in the P-05 well approximately 50km offshore. Thus, the sequences we observe in the sections could possibly exist in a similar, conformable pattern to at least that distance. Offshore, the coal measures form a prominent seismic reflector package that dips gently and onlaps basement rocks (Pascucci et al., 2000).

In summary, applying sequence stratigraphy to the coastal- and alluvial plain strata of the Sydney Mines Formation at Morien Bay proved challenging. Sequence boundaries and resulting systems tracts designations in this setting are highly variable and a number of candidate surfaces can often be presented. As the strata at Morien Bay lie near the proximal end of the classical ‘slug’ diagram (Fig. 38), the predicted facies simply are not always represented and recognition of correlative conformities may not be possible. This thesis attempted to apply and test concepts of a sequence stratigraphic framework in a non-marine setting, and preferred (and some alternative) interpretations are presented here for these surfaces and systems tracts within the Morien Bay strata.

# Chapter 5: PALEOECOLOGY

## 5.1 Introduction to the vegetation of the Carboniferous wetlands

Tree lycopsids evolved in wetland environments in the Late Devonian (Scheckler, 1986). By the onset of the Westphalian, they were dominants in these wetlands and serve as the best proxies for physical habitats among the lowland plant groups (DiMichele and Phillips, 1994). Lycopsid stems and reproductive organs are common fossils in the roof-shales and sandstones, with their rooting organs (*Stigmaria*) found in the seat-earths (Cleal and Thomas, 1994). These 'trees' can not be considered identical to modern trees in reproductive or physical terms as they were spore bearing and lacked true wood. They were supported by a thick rind of bark (periderm) that was wood-like in appearance (DiMichele and Phillips, 1994). Wood production was limited and the tree supported itself with an extensive secondary cortex, rather than by wood formation (Cleal and Thomas, 1994). Their lifespan was particularly short for such large trees, probably no more than 10-15 years (Phillips and DiMichele, 1992). The only living relatives of the lycopsids are the club-mosses but these are strikingly different and much smaller than the arborescent forms dominant in the Carboniferous.

*Lepidodendron* is a common form-genus of lycopsid stems with characteristic diamond-shaped leaf cushions and prominent leaf scars in spirals around the trunks and twigs (Fig. 52a). *Lepidodendron* and *Lepidophloios* were two closely related genera spanning the Westphalian with similar developmental and reproductive patterns and occupied similar kinds of standing water habitats (DiMichele and Phillips, 1994). *Lepidodendron* is a common component of mid-continent clastic-swamp deposits, particularly in rocks of pre-Westphalian D age whereas *Lepidophloios* is less abundant in

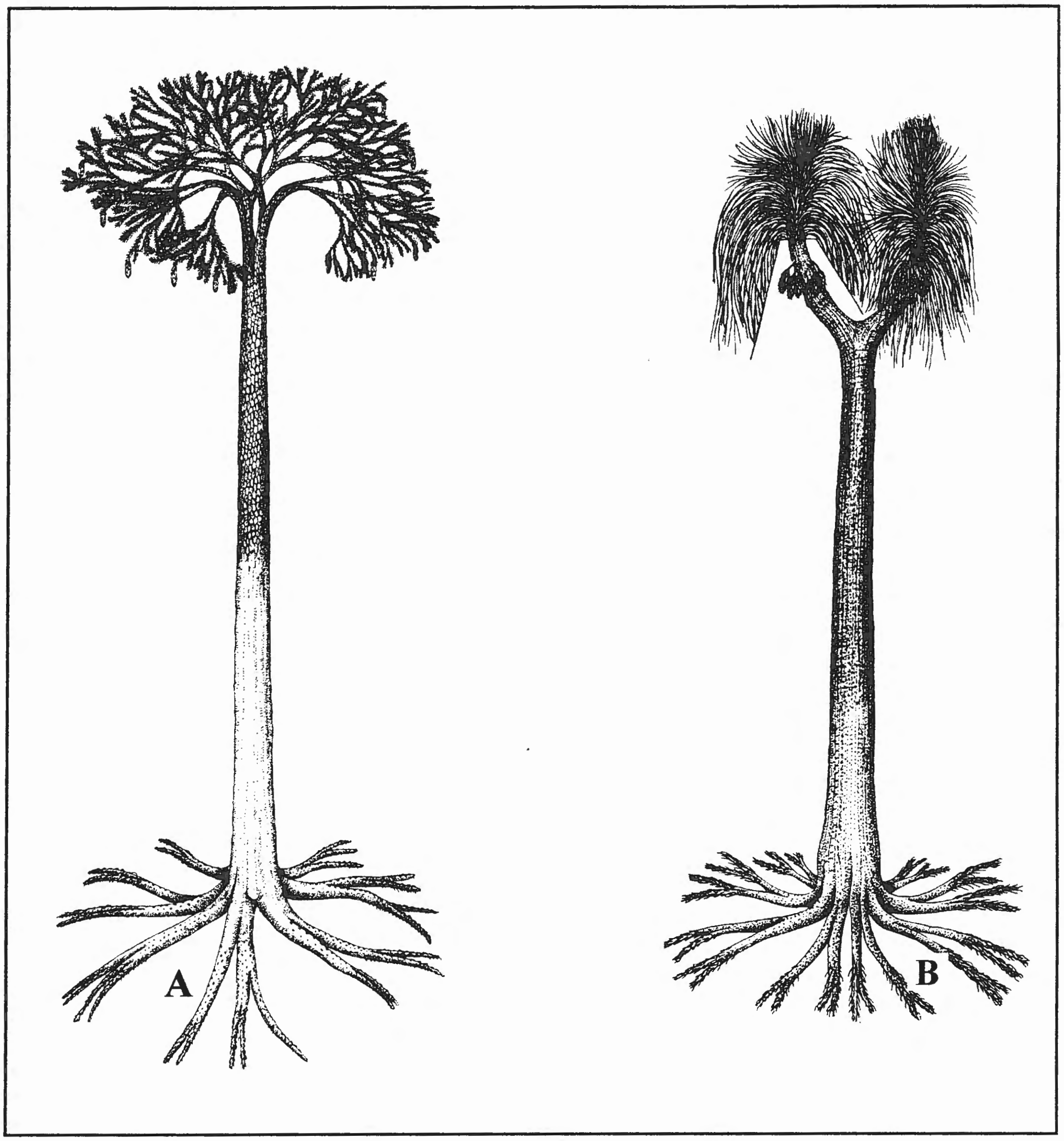


Figure 52. A) Reconstruction of *Lepidodendron* sp. B) Reconstruction of *Sigillaria* sp. Leaves deleted in area of cones on the left side of *Sigillaria* sp. Reconstructed tree height ~20-30 m. From Stewart and Rothwell (1993).

compression floras (DiMichele and Phillips, 1994). At least 200 species of *Lepidodendron* are named. Both genera were anchored by extensive rooting systems called *Stigmaria*. These basal rooting organs were shallow structures, particularly adapted for plants growing in swamp conditions with large air chambers indicative of aquatic submergence and requiring gas exchange (DiMichele and Phillips, 1994). *Stigmaria* are very abundant, classic Carboniferous plant fossils, being subterranean, and are commonly preserved without the original, subaerial tree trunk. In addition to the extensive stigmarian material buried in peat and other substrates, the support bark of these trees was also a major component of forest litter and coals (DiMichele and Phillips, 1994). Isolated leaves are called *Cyperites* (Cleal and Thomas, 1994). Lepidodendrids appear to have been the tallest trees in mire environments (DiMichele and Phillips, 1994), reaching heights of 30 metres or more.

*Sigillaria* is another common, tall arborescent lycopsid with a similar stigmarian rooting system (Fig. 52b). Sigillarian trees are found far more commonly in clastic deposits than in peat, suggesting a centre of distribution in the wetlands surrounding the peat-forming mires, along channel margins, or on wet floodplains fringing channels (DiMichele and Phillips, 1994). The ongoing reproductive strategy of *Sigillaria* accorded it an ecological advantage in these disturbed environments (Calder et al., in press). *Sigillaria* has its leaf scars secondarily arranged in characteristic vertical rows (Cleal and Thomas, 1994) and produced tall, columnar, rarely branched trunks. Plant assemblages found in association with sigillarian litter are often high in diversity yet poorly preserved and found with abundant fusain, suggesting fire-razed, rheotrophic mires and seasonal climates (DiMichele and Phillips, 1994).

Two types of sphenopsids are represented in Late Carboniferous tropical wetlands, the arborescent pioneer *Calamites* and the more shrubby, ground-covering sphenophylls (DiMichele and Phillips, 1994). *Calamites* were very similar to living horsetails (*Equisetum*), but they were larger (up to 10m) and formed dense thickets in areas of aggrading sediment, often forming a succession to buried lycopsid forests (Calder et al., in press) (Fig. 53a). The leaves of the smaller branches are recognized by the form genera *Annularia* and *Asterophyllites*. They displayed vegetative reproduction, and when disturbed or covered by sediment could extend lateral rhizomes or continue growth of their vertical stems upwards through the mud. *Calamites* were framework plants in some parts of the landscape, mainly areas of substrate aggradation or instability, such as stream and lake margins and clastic flood basins (DiMichele and Phillips, 1994; Scott, 1978; Gastaldo, 1987). *Calamites* were more abundant in these environments than in mires (DiMichele and Phillips, 1994). The sphenophylls were much smaller plants, forming a low-lying scrambling type of vegetation. The name given to the leaves of sphenophylls common in the Sydney Basin is *Sphenophyllum* (Fig. 53b).

Ferns comprised a diverse group of plants in the Late Carboniferous and fell into two main morphological groups, columnar trees and small ground-cover-to-vine habits (DiMichele and Phillips, 1994). The tree ferns belonged to the order Marattiales. The genus of stems is called *Psaronius* and the stem name is applied to the whole plant (Fig. 54). *Psaronius* was the most important biomass producer among the ferns with minimal thick-walled tissues in all organs (DiMichele and Phillips, 1994) and most of the root biomass composed of air-chambered tissues (Ehret and Phillips, 1977). The tree trunks do not display as prominent distinguishing characteristics as the lycopsids, and roots

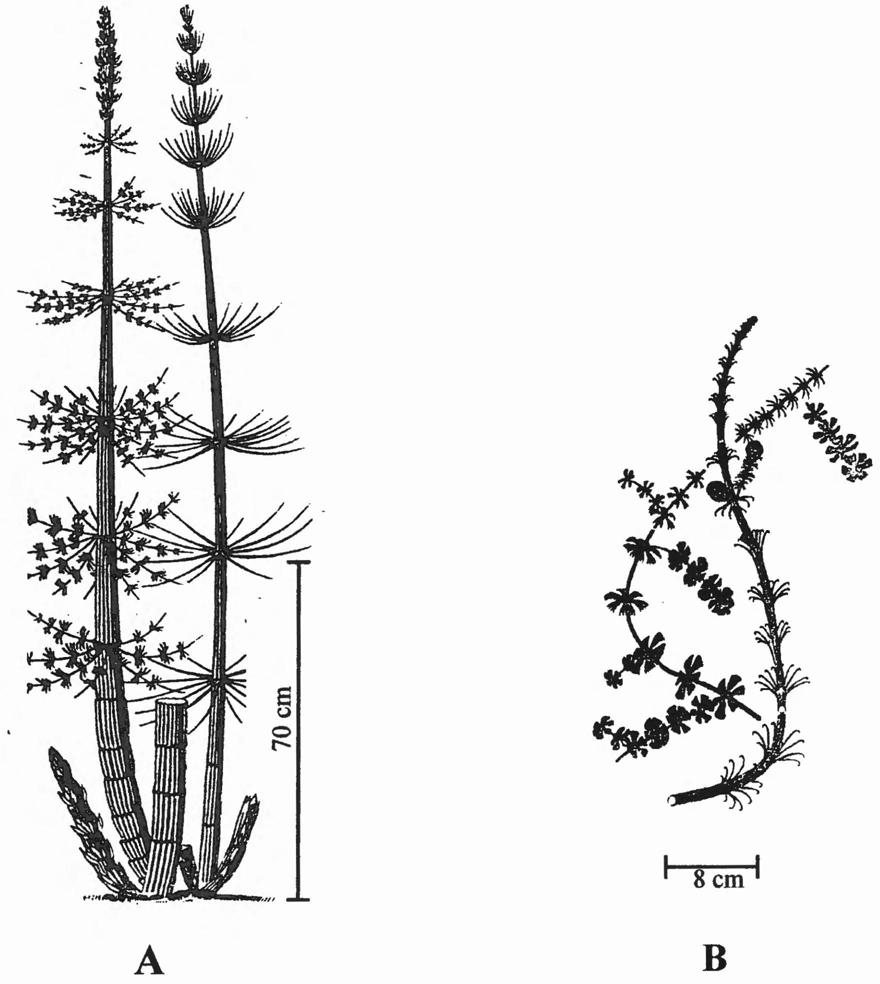


Figure 53. Sphenopsids. A) Sketch of *Calamites suckowii* and *Calamites cisti*. From Dawson (1891). B) Partial reconstruction of scrambling vegetative type *Sphenophyllum emarginatum*. From Cleal and Thomas (1994) and Batenburg (1977).

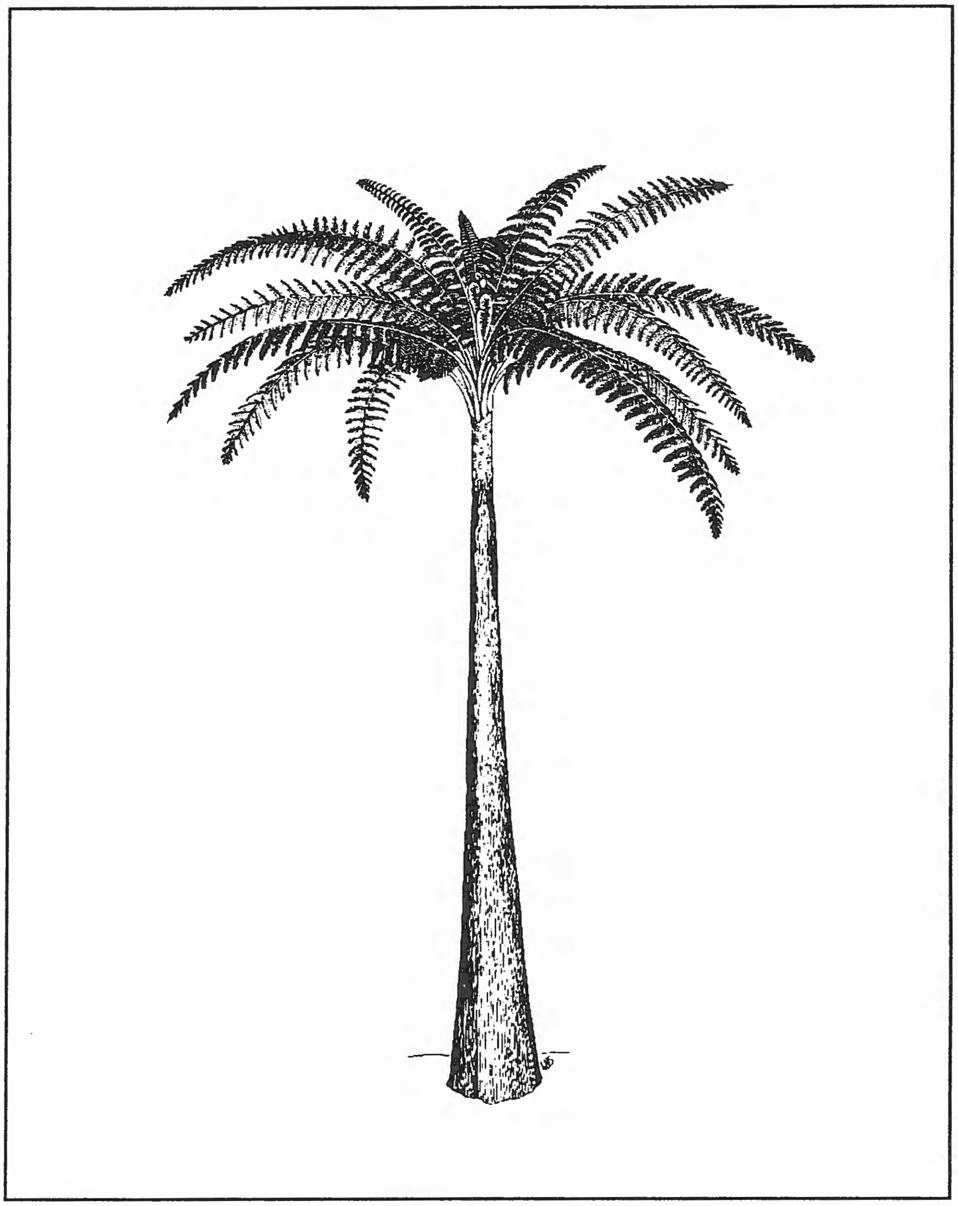


Figure 54. Reconstruction of the marattialean tree-fern *Psaronius*, about 8m tall. From Cleal and Thomas (1994) and Morgan (1959). Abundant foliage derived from these tree-ferns is found in the Sydney Mines Formation, such as the genus *Pecopteris*.

generally constituted most of the biomass in a *Psaronius*-dominated peat (DiMichele and Phillips, 1994). *Psaronius* had massive reproductive output from sporangia on the undersides of pinnules, yet a limited ability to colonize flooded substrates because of a free-sporing life history and lack of vegetative propagation (DiMichele and Phillips, 1994). There are many organ genera applied to foliage derived from these ferns, with *Pecopteris* representing a very common genus, later in the Westphalian and in the Sydney Basin.

Pteridosperms or "seed ferns" comprised a broadly dominant group of lowland gymnosperms during the Late Carboniferous (DiMichele and Phillips, 1994). These plants varied from shrub-like, scrambling vines to small trees and they lived mainly on the raised levees of the rivers (Cleal and Thomas, 1994). The main pteridosperms occupying the lowlands were the medullosan seed ferns. The medullosan fronds are the most commonly preserved organs of the plant. Based on foliage, DiMichele and Phillips (1994) describe the three most encountered groups of medullosans in mires as *Neuropteris*, *Alethopteris* and *Linopteris*. Certain medullosan species have been identified as representing different ecological preferences. Wnuk and Pfefferkorn (1984) identified different species in drier, topographic highs (*Neuropteris scheuchzeri*) and wet, topographic lows (*N. rarinervis* and *N. ovata*). Isolated seeds (e.g. *Trigonocarpus*) are also relatively common.

Cordaites were gymnosperms, primitive relatives of modern conifers in the Carboniferous landscape with dense wood, axillary branching and strap-shaped leaves (DiMichele and Phillips, 1994) (Fig. 55). They occupied a wide range of habitats from flood basins to levees, sea coasts and the so-called uplands (i.e. extrabasinal habitats)

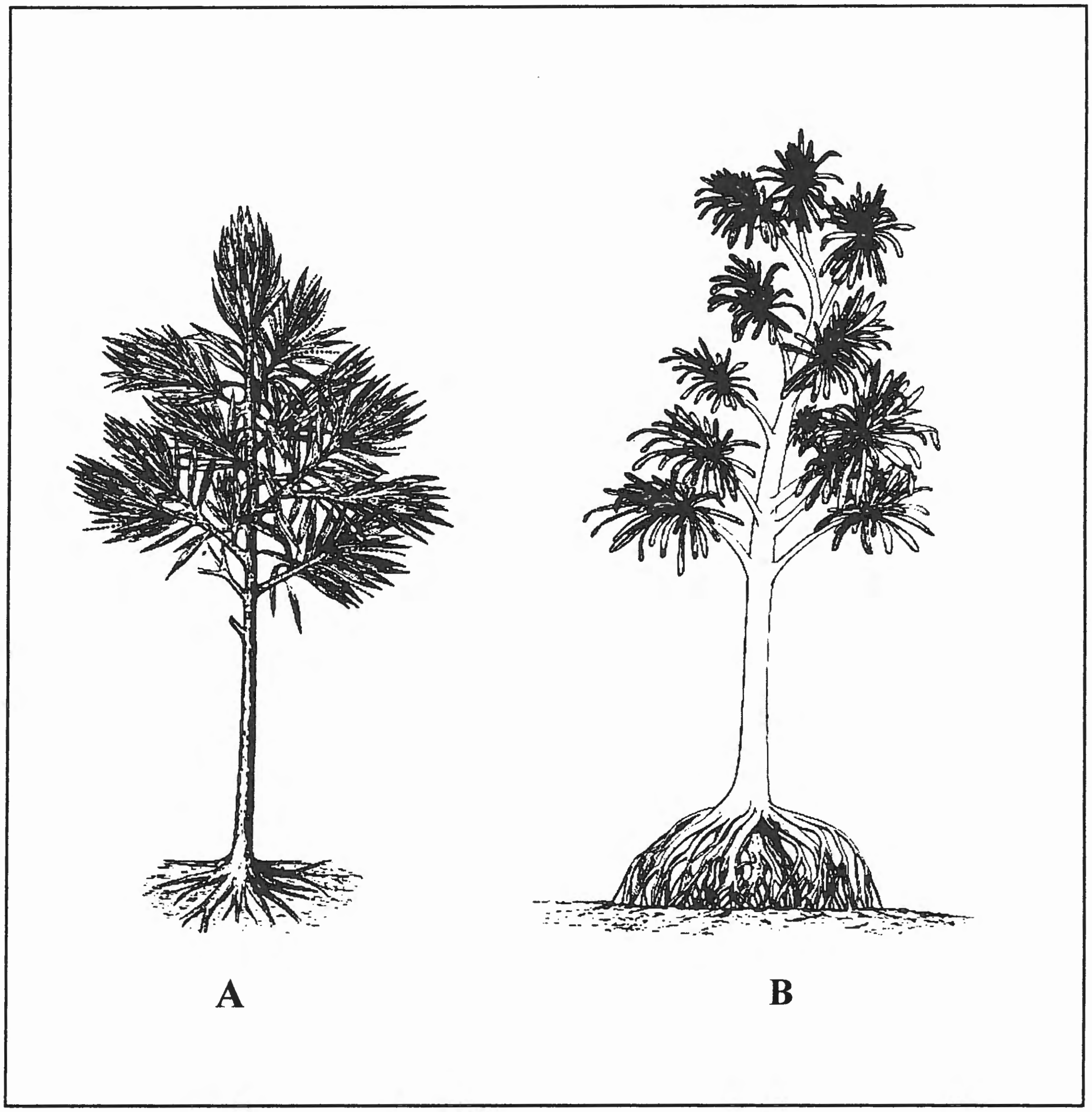


Figure 55. Reconstructions of cordaitean trees. Trees probably grew up to 30m high in arborescent (A), scrambling, or more mangrove-type (B) forms. From Cleal and Thomas (1994) and Thomas and Spicer (1987).

(Cleal and Thomas, 1994). Their habit ranged from straight trees to smaller, scrambling ground plants. Cordaites, with their heavy investment in woody trunks, were likely the slowest growing of the major Carboniferous trees, which would put them at a disadvantage in mires which were a highly disturbed environment, thus selecting against slow-growing and potentially long-lived plants (DiMichele and Phillips, 1994). Some *Cordaites* species may have had a mangrove-like root system allowing them to survive in shallow bodies of water. Many other plants also contributed to the Carboniferous wetland landscape but are not described here as they are not found commonly within the Sydney Mines Formation.

## 5.2 Paleobotany of the Morien Bay Sections

The Carboniferous fossil record of Nova Scotia was most recently compiled by Calder (1998). The macroflora taxonomy was compiled for the first time in recognition of its fundamental importance to the chronostratigraphy of the Carboniferous of Nova Scotia (Calder, 1998). Earlier work by Bell first identified and described the fossil flora of the Sydney Coalfield (1938) and Nova Scotia in general (1944). Zodrow and McCandlish (1980) identify Upper Carboniferous fossil flora in Nova Scotia with special reference to the Sydney Coalfield. Most collections of floral specimens are from coal-bearing, dominantly grey strata. Few assemblages are known from redbed intervals. The lower degree of preservation within this 'dryland' strata preferentially lowers the number and diversity of specimens collected from these intervals in the study sections. In addition, the lack of primary field data concerning Late Carboniferous dryland floras may reflect their relatively low species richness and poor preservation (Falcon-Lang, 2003).

Exceptionally well preserved plant fossils can be found in all three study sections. Large abundances are found in some units, especially those near and in the major coal seams and overlying roof shales. Plant fossils were collected from each unit that was found to contain material. In certain units, additional time was spent collecting many different types and higher quality samples. Different parts of individual plants can be found, including trunks, leaf foliage, twigs, and rooting systems. Many incomplete or broken specimens were found, allowing for identification to the genus level only in the majority of samples. Collecting from the redbed units proved to be difficult as the degree of preservation was much lower than in the grey mudstones and claystones. Attempts were made to collect from the redbed intervals, but accurate species identification was usually not possible.

Table 3 is a summary chart of the flora identified at the Morien Bay sections. Four classes of plant are represented: Lycopsida, Sphenopsida, Filicopsida, and Gymnospermopsida. Table 3 includes the order, genus and species (if possible) of plant samples identified as well as the type of genus, either stem, foliar or root. Table 3 also includes the interpreted systems tract in which the flora is found (abundant, common, rare etc.). This very valuable information may form the basis for subsequent work. Plant identifications along with the unit in which they were found are documented in Appendix 4.

### *5.2.1 Erect lycopsids*

Fossil trees are continually revealed and destroyed at coastal sections of the Sydney Mines Formation due to tides, wave action, and cliff erosion. Thus, depending on when the sections are visited, previously discovered fossil specimens may not exist or new flora

**Table 3. Plant species identified at Schooner Pond, Long Beach and Morien South**

| Class | Order | Genus and Species | Genus Type | Systems Tracts |
|---|---|---|---|---|
| Lycopsida | Lepidodendrales | *Lepidodendron* sp. | Stem Genera | 80% HST, 15% TST, 5% LST? |
| | | *Diaphorodendron (Lepidodendron) scleroticum?* | Stem Genera | |
| | | *Sigillaria* sp. | Stem Genera | HST |
| | | *Cyperites* sp. | Foliar Genera | 67% TST, 33% HST |
| | | *Stigmaria ficoides* | Root Genera | 60% TST, 40% HST |
| Sphenopsida | Sphenophyllales | *Sphenophyllum cuneifolium* | Foliar Genera | 67% TST, 33% HST |
| | | *Sphenophyllum emarginatum?* | Foliar Genera | |
| | | *Sphenophyllum* sp. | Foliar Genera | |
| | Equisetales | *Calamites cisti* | Stem Genera | 68% HST, 26% TST, 6% LST? |
| | | *Calamites* sp. | Stem Genera | |
| | | *Annularia* sp. | Foliar Genera | |
| | | *Asterophyllites* sp.? | Foliar Genera | |
| | | *Pinnularia* sp. ? | Root Genera | |
| Filicopsida | Filicales | *Sphenopteris* ? | Foliar Genera | 53% HST, 47% TST |
| | Marattiales | *Pecopteris hemitelioides?* | Foliar Genera | |
| | | *Pecopteris* sp. | Foliar Genera | |
| Gymnospermopsida | Pteridospermales | *Medullosa* sp.? | Stem Genera | 60% TST, 40% HST |
| | | *Alethopteris serli?* | Foliar Genera | 50% TST, 50% HST |
| | | *Alethopteris* sp. | Foliar Genera | |
| | | *Mariopteris* sp. | Foliar Genera | 75% TST, 25% HST |
| | | *Neuropteris scheuchzeri* | Foliar Genera | 62% TST, 38% HST |
| | | *Neuropteris ovata* | Foliar Genera | |
| | | *Neuropteris* sp. | Foliar Genera | |
| | Cordaitales | *Cordaites principales?* | Foliar Genera | 67% TST, 33% HST |

may present itself. During the field season of 2000 and 2001, 30 erect lycopsid trees were recorded in their growth position at a minimum of twenty separate stratigraphic horizons. Four trees were identified at Schooner Pond, 17 at Long Beach, and 9 at Morien South. Trees were measured between the McRury to Bouthilier coal seam interval at all three sections. Additional trees were identified in the Bouthilier to Harbour coal seams at Long Beach but paleobotanical and stratigraphic data for this section was not quantified and thus these specimens are not used in this discussion. Erect *Stigmaria* bearing lycopsid trunks are particularly common in strata interpreted as highstand systems tracts.

Most trees were single, isolated trunks (Fig. 56a), however fossil forest horizons consisting of multiple tree trunks at the same stratigraphic level also are preserved (Fig. 57). The trunks themselves have often been eroded leaving casts or bark impressions documenting where the tree once stood (Fig. 56b). Trees are rooted in substrates ranging from clastics (sands and muds) to coaly shale or thin carbonaceous layers. Trees did not always appear to be rooted directly within coal horizons, and were generally within two to nine metres above the coal seams. Lycopsid stigmarian roots are abundant at all sections (Fig. 58) and often infilled with sediment and replaced by siderite.

Trunk diameter at breast height (DBH ~1.3m), the recommended height in present day forestry measurements to avoid exaggerated measurements of trunks that flare downward, could not always be determined due to the poor preservation of many trunks. Diameter measurements were attempted on most trees even if a DBH measurement was not possible. Most of the standing trees in the study were columnar, with only a few displaying flared bases, thus, can be considered to represent DBH measurements. The range of diameter sizes of trees in the study sections was 0.25 - 0.6 m. No estimates on

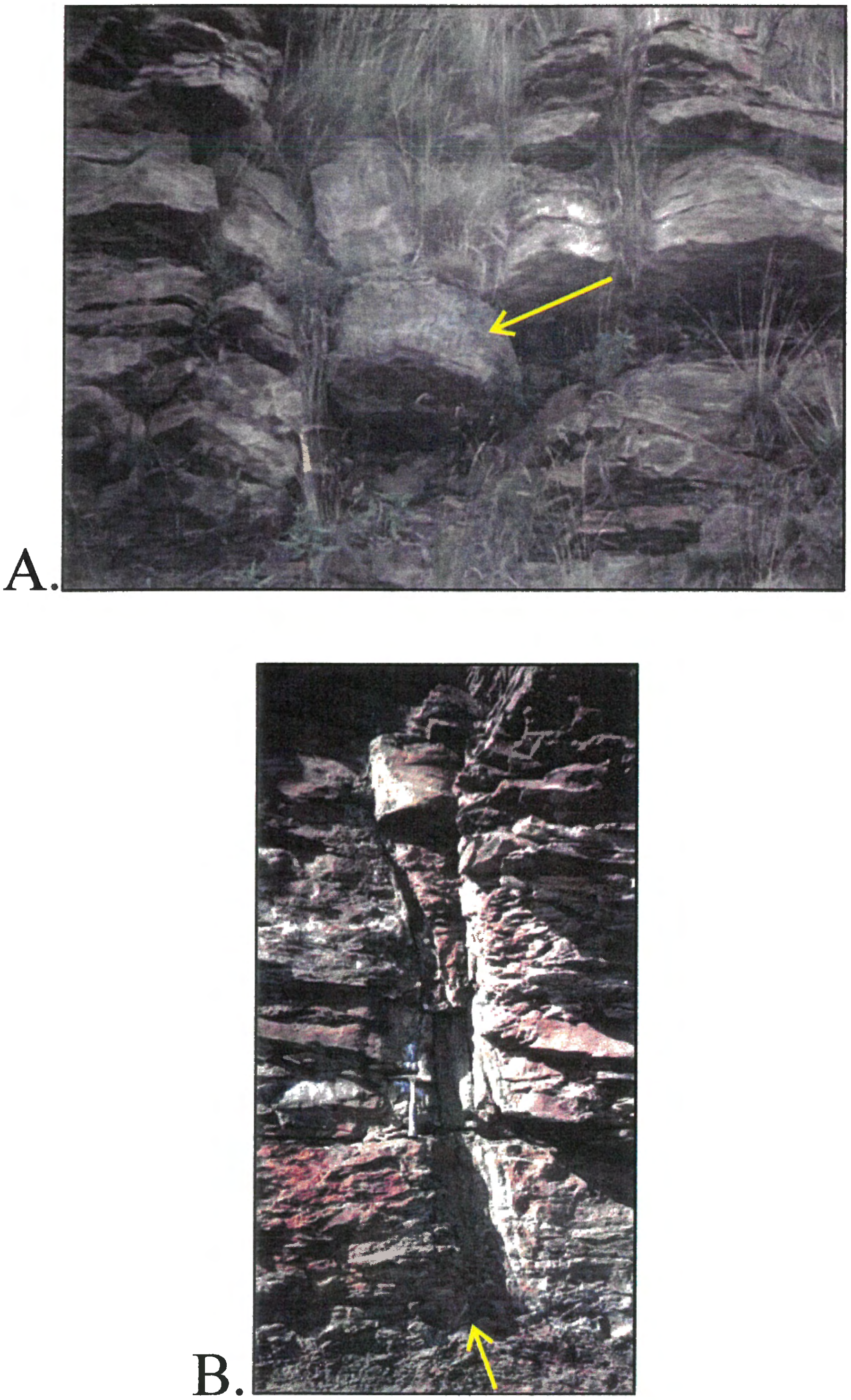


Figure 56 a & b. A) Weathered lycopsid trunk (arrow) in growth position at Morien South. Diameter of trunk is 55cm. B) Partially weathered out lycopsid tree trunk at Morien South section. Note the thin coaly layers at the root base (arrow). Hammer is ~30cm for scale.

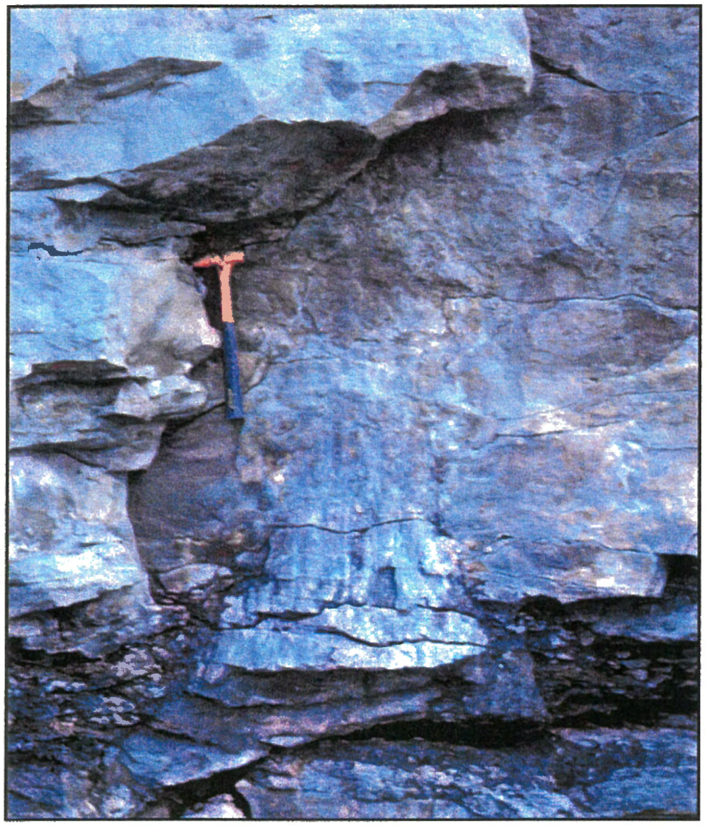


Figure 57. *Lepidodendron* sp. from fossil forest horizon at Schooner Pond. Tree diameter is 60 cm at base and height is 1.85 m. Four large trees are preserved in the fossil forest layer. Trough cross-bedded channel sandstones infilled depressions and scours around the large trees.

Figure 58. Large stigmarian roots above the Phalen coal seam at Morien South. Hammer is ~30cm for scale. View is of the bottom of a bedding surface.

biomass or stand population dynamics are made here as representation is poor with such a low sample population. The maximum height of standing trees measured was 2.2 m.

The majority of trees at the study sections were identified as *Lepidodendron* sp. Further identification to the species level was generally not possible as bark layers were eroded or not preserved. A smaller number of trees were identified as *Sigillaria* sp. A characteristic of this genus is the presence of strongly defined parallel ribs on its bark (Calder et al., 1996). Figure 59 is a photo of *Sigillaria* sp. bark identified at the Morien South section. In this specimen, fine, scattered charcoal remains line the outer layer of bark preserving evidence of a past forest fire prior to burial. The presence of strongly ribbed bark is not limited to *Sigillaria* sp. so caution must be taken if using this as a single, defining characteristic (Calder et al., 1996). Fissured bark impressions were found to be consistent with the basal trunk of *Lepidodendron* (Thomas and Watson, 1976).

Most tree trunks did not have their bark preserved, thus making identification based on leaf scars difficult. Trees often lose distinguishing leaf scars towards the tree base. The absence of leaf scars could be attributed to decorticated preservational conditions, or may be a result of secondary growth at the base, obliterating the leaf cushions (Calder et al., 1996). Minor longitudinally ribbed trees appear to flare gradationally downward, an adaption of certain modern wetland trees to fluctuating water levels (Calder et al., 1996). Flared tree and root bases (or buttress root systems) are found in modern day trees that occupy swamp or standing water body niches, such as the bald cypress (*Taxodium distichum*), common in the Mississippi River delta (Fig. 60).

Figure 61a shows a hole where one of the largest (~50 cm diameter) trees once stood at Long Beach. This photo was taken in 2000. A photo from underneath the overhanging

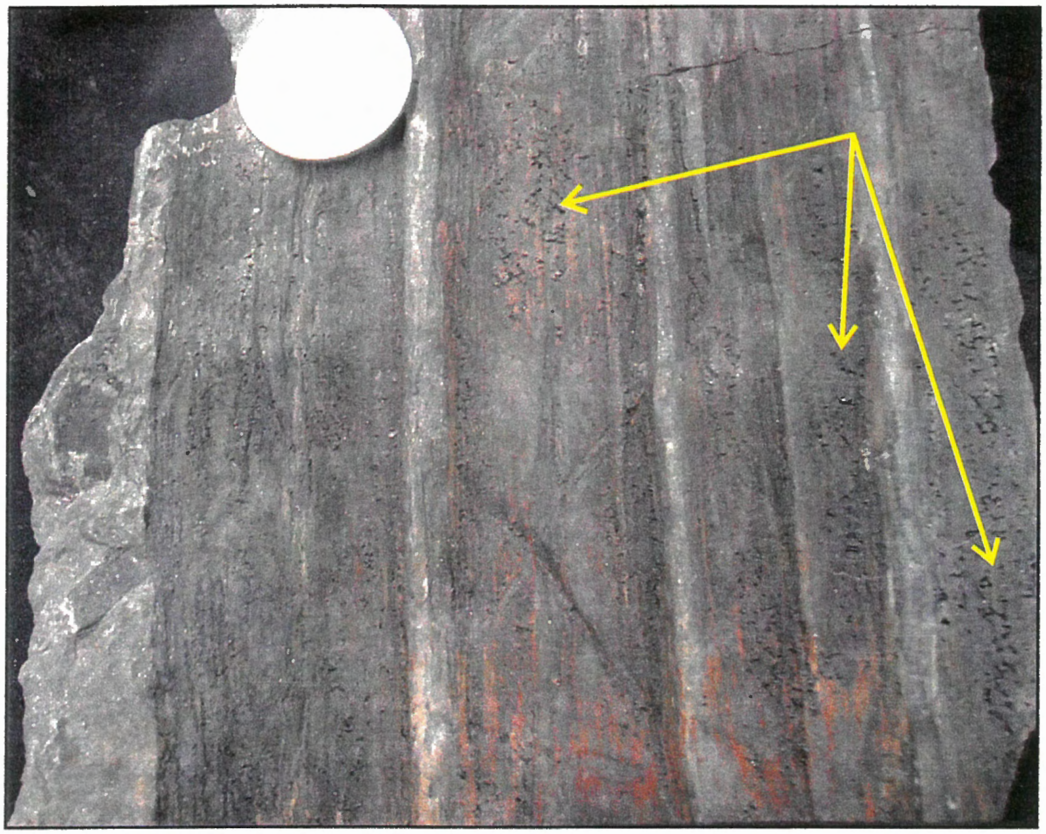


Figure 59. Photograph of strongly ribbed sigillarian bark from the Morien South section. Fine charcoal remains (arrows) are preserved on the outer layer of bark. Quarter for scale is 2.3 cm in diameter.

Figure 60. Bald cypress *(Taxodium distichum)* trees in standing deltaic water bodies in the present day Mississippi River delta complex. Photo taken on the Atchafalaya River, Louisiana, USA.

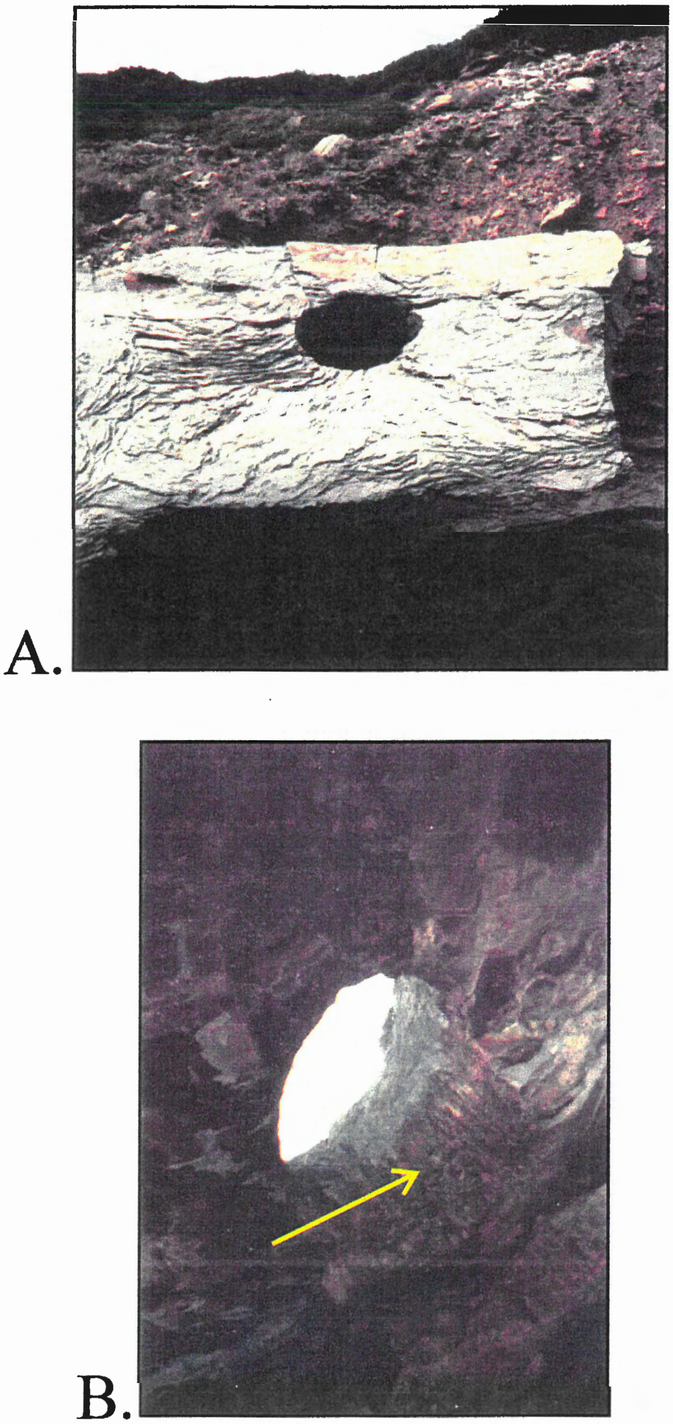


Figure 61. A) Photograph of hollowed out tree stump exposed in cliff at Long Beach. Diameter of trunk is approximately 50 cm. B) View underneath overhang, showing bark impressions (arrow) not visible in A.

rock (Fig. 61b) shows that bark impressions were preserved, but the site was inaccessible and identification was impossible. A number of other hollowed out lycopsid trunks were found in this unit (Fig. 21b). Upon revisiting the site in late 2001, the bed had broken off the cliff and half the preserved trunk imprints had been lost.

### *5.2.2 Compression Flora*

Compression flora was abundant at Schooner Pond, Long Beach and Morien South. The flora consists of vegetation mainly rooted in clastic substrates rather than directly within coal seams. Rare stem genera of *Diaphorodendron* and *Lepidodendron* were identified. Minor zonation of compression flora can be recognized within some of the study sections. At Schooner Pond, near the McRury seam, pteridosperm foliage is dominant, especially *Alethopteris* sp. Further up the section (the Emery to Phalen coal seam interval) the dominant foliage is pecopterid, with *Neuropteris* sp. (Fig. 62c) and *Calamites*. *Odontopteris* sp., *Sphenophyllum* and *Alethopteris* sp. (*serli*?) (Fig. 62a) were also identified. Rooted siltstones 3.5 m above the McRury coal at Schooner Pond display radial rooting systems (Fig. 63). These are not believed to be lycopsid stigmarian roots, but are more likely of medullosan affinity (cf. Calder et al., 1996).

At Long Beach and Morien South, the flora at and above the Emery coal seam is dominated by pteridosperms (*Neuropteris* sp., *Alethopteris* sp., *Mariopteris* sp. (Fig. 62b)), marattiales (*Pecopteris* sp. (Fig. 64a)) and *Calamites*. *Sphenophyllum cuneifolium* (Fig. 64b), *S. emarginatum*? (Fig. 64c) and rare *Cordaites* leaves were also identified. Near the Phalen seam, *Calamites*, pteridosperms and marattialean tree ferns (*Pecopteris* sp.) again dominate the flora. Further up the section near the Backpit seam, the flora appears to be dominated by lepidodendrids and pteridosperms. Marrattialean tree ferns

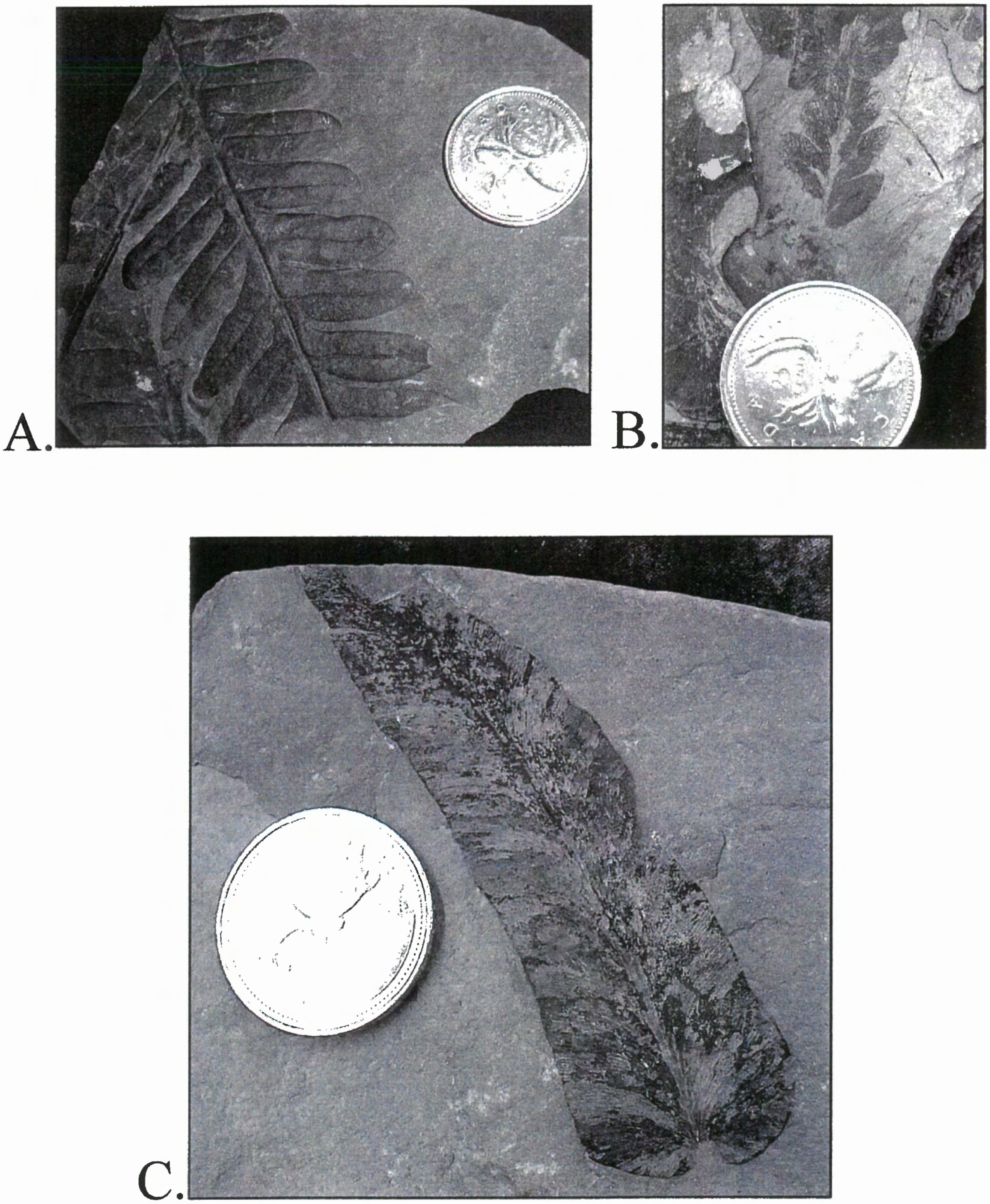


Figure 62. Pteridosperms. A) *Alethopteris* sp.*(serli?)*. B) *Mariopteris* sp. C) *Neuropteris scheuchzeri*. Quarter for scale is 2.3cm in diameter.

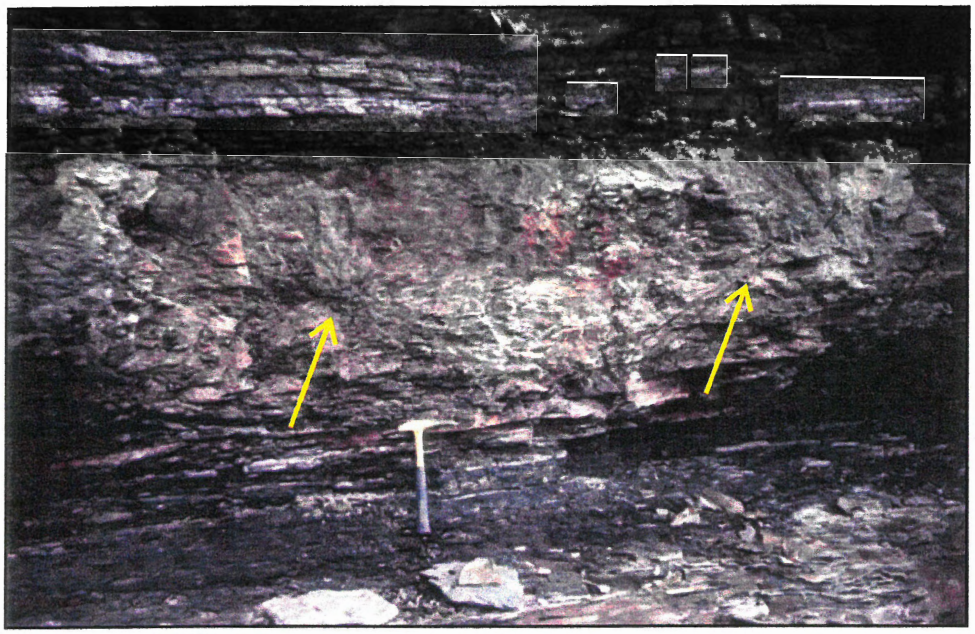


Figure 63. Radial roots (arrow) in siltstones 3.5m above the McRury coal seam at Schooner Pond. Roots are up to 35 cm in length and likely have a medullosan tree-fern affinity rather than lycopsid. Hammer is ~30cm for scale.

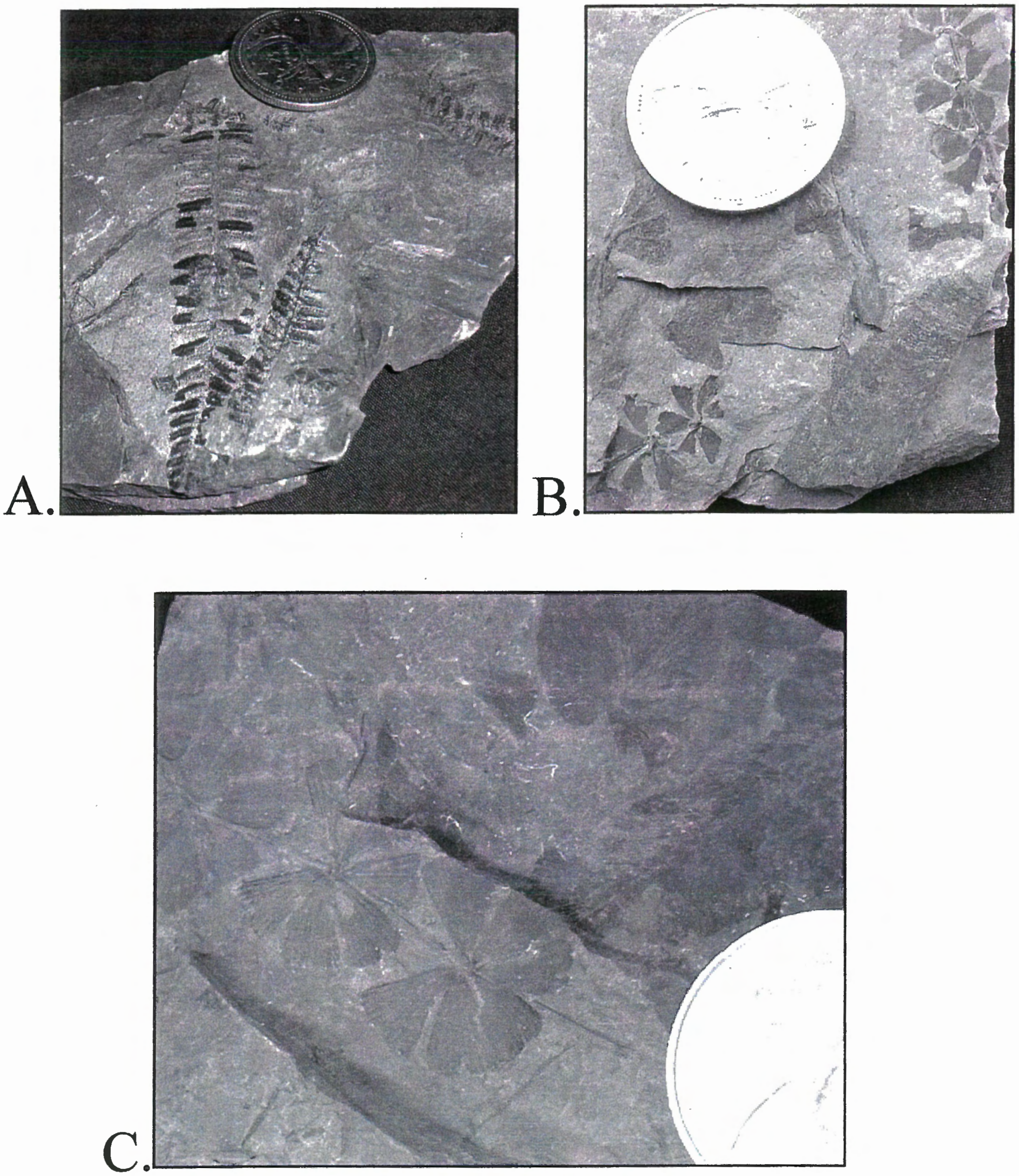


Figure 64. Marattiales and Sphenophyllales at Long Beach. A) *Pecopteris hemitelioides.* Quarter for scale is 2.3 cm. B) *Sphenophyllum cuneifolium.* C) *Sphenophyllum emarginatum?*

and *Calamites* were also identified. Numerous calamitacean groves (stands) were found at all three stratigraphic sections.

### *5.2.3 Prostrate Logs*

Prostrate logs were recognized in some units and attempts at identification were made where possible. A large (2.5 m long and 60 cm wide) prostrate lycopsid log was found at Long Beach in strata between the Bouthilier and Harbour coal seams. The tree was coalified along some edges and extremely weathered, making species identification difficult. All that remained was the flattened bark impressions of the trunk, but no leaf scars were preserved. Smaller lycopsid prostrate logs were also found within the study sections and are identified on the stratigraphic sections (Fig. 30).

### *5.2.4 Palynology*

No units were sampled for miospores or megaspores during this study due to constraints of fieldwork and time. Palynological work on Sydney Mines Formation strata elsewhere in the basin is documented by Barss and Hacquebard (1967), Marchioni et al. (1994), and Dolby (1989).

## 5.3 Floral Assemblages and Environments

Very few of the preserved lycopsids in the study sections were rooted directly in coal seams. Most were rooted in thin coaly/carbonaceous layers or sandy substrates and can be assumed to represent clastic wetland trees rather than peat-land vegetation. Calder et al. (1996) proposed that, where trees on clastic substrates were actually rooted on thin carbonaceous horizons, the trees could be considered colonizers of failed mires, rather than true clastic wetland trees. A vegetational transition between peatland (lycopsids) and clastic wetland (*Calamites*) floras is observed. Lycopsid tree genera were capable of tolerating periods of standing water and were further differentiated by their preferences in substrate and nutrient levels (DiMichele and Phillips, 1985). Lycopsid flora was predominantly found in facies 3b (laminated grey clay), 4a (stratified grey siltstone and sandstone), 4b (non-stratified grey siltstone and sandstone), and sandstone channel bodies. Only occasionally was a lycopsid found rooted in a coal layer (facies 1). These facies are associated with deposition in poorly drained settings, standing bodies of water, and wetlands with clastic influx. The lycopsids were found preserved in sandstones more frequently than with mudstones. The presence of such 'peat-swamp' vegetation is consistent with this paleoenvironment. Although preservation is a problem, no lycopsids were found rooted in redbed layers, emphasizing their preference for more poorly drained, water-logged settings rather than the well-drained alluvial plain.

Marrattialen tree ferns and lycopsids are common in or at the margins of mires (where coal seams thin) at Morien Bay. It is hard to determine which trees dominated the mire vegetation when the rooting substrate is not observed. The trees could represent vegetation distinct from the dominant mire vegetation, but it is less likely for this to apply to erect lycopsids rooted within coal beds (Calder et al., 1996). The trees likely represent peat-forming vegetation if they are rooted in coal layers. Compression flora above coal seams is generally considered to have been ecologically distinct from the mire flora (Scott, 1978; DiMichele et al., 1991; Gastaldo et al., 1995). Tree-ferns, pteridosperms and sphenophytes were found in facies 1 (coal), 3a (non-stratified grey claystone), 3c (underclay), 3e (laminated red claystone), 4c (red siltstone), 4d (stratified red siltstones), 4e (sandstone sheets), as well as in facies 3b, 4a, and 4b. Leaves and stems of these plants were abundant in and above coal layers. Plants found within coal layers are likely indicative of the mire-forming vegetation. Foliage found in other layers likely represents the wetland vegetation. Marrittalean species are mostly found in stratified grey siltstones and claystones, probably suggesting a preference for poorly drained settings and calm bodies of standing water. Water depth was likely shallow as many beds are intensively rooted with abundant plant flora preserved. Pteridosperms are found in stratified grey siltstones as well as non-stratified siltstones and sandstones, and comprised much of the forest understory. Many pteridosperms were likely robust and tolerant to disturbance from distributary channel splays or floods events.

*Calamites* was also an important vegetational component in the ecosystem. Forests or groves of *Calamites* (multiple in situ trunks at the same rooting level) were located at all three study sections. They preferred levees or the margins of major channels and may have been strong initial colonizers. Repeated successions of *Calamites* fossil forests indicate their tolerance of disturbance and strong re-colonizing potential (cf. Calder et al., in press). Figure 21A displays a *Calamites* stand at Morien South. Numerous in-situ and prostrate *Calamites* stems were observed. The stems at Morien South averaged 50 cm in length and 14 cm in width. At Long Beach, a grove of hollowed-out *Calamites* stems was observed (Fig. 65) with nodular soil development around the stems. This stand of 30+ plants occurs at the top of a channel splay. There are also observable shallows or hollows around the stems. These represent structures created when living vegetation affects how sediment is deposited in the immediate vicinity by altering current flow patterns (Vegetation-induced sedimentary structures of Rygel et al., in press). *Calamites* were most commonly preserved in facies 4a, 4b, and 3b as well.

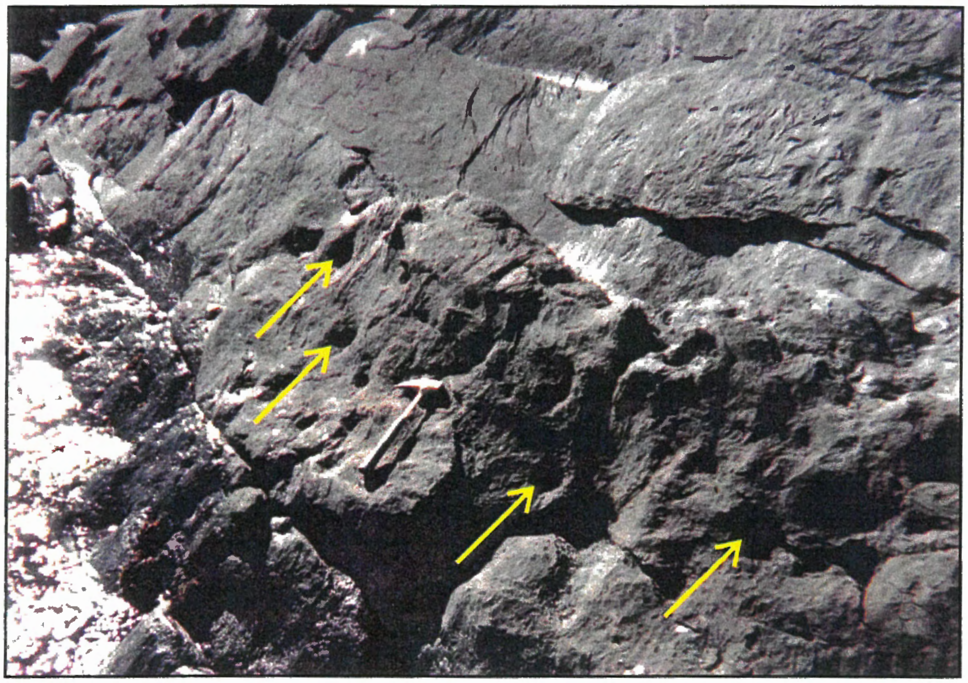


Figure 65. *Calamites* fossil forest with no stems preserved, only holes (arrows), at Long Beach. 30+ trees were found at this level. Hammer is ~30cm for scale.

*Calamites* were also found near channel margins, perhaps occupying the edge (transition) between standing water bodies and levees. Flood events may have triggered recolonization as evidenced by the presence of repeated fossil forest horizons of *Calamites*. They were able to persist in the face of such disturbance, more so then any other plant. Pieces of prostrate lycopsid trunks and *Calamites* were also found at the base of channel bodies, likely indicating short transport distances from their original growth position.

Table 3 includes a summary of the systems tracts with which the plant fossil specimens were most commonly associated. Unfortunately, only modest correlations can be made based on the lack of systems tract designation to certain levels of the stratigraphic sections, especially at Morien South and Schooner Pond. Thus, Table 3 is presented as a broad overview. The estimated percentages shown in Table 3 were calculated from the number of occurrences identified within a specific systems tract. Where identified plant fossils are not found within an assigned systems tract, they can not be used in this analysis. This dramatically reduced the utility of this potential data set.

Some connections can be drawn between paleobotanical samples and the systems tracts with which they are associated. Standing lycopsids (*Lepidodendron* sp. and *Sigillaria* sp.) and fossil forest horizons are predominantly found within HST deposits. However, their stigmarian root stalks are often more common in TST deposits. Pteridosperm foliage was found to be slightly more predominant in TST deposits than HST. The limited *Cordaites* sp. that were identified were found within both TST and HST deposits. Prolific *Calamites* sp., as well as most other equisetales representatives, are found predominantly in TST deposits. *Calamites* sp. are also found within HST deposits and very minor calamitacean foliage was recovered from LST deposits.

Figure 66 represents a representative cross-section of a late Carboniferous mire depicting habitat showing relative ecological partitioning of the major genera of mire plants (after DiMichele and Phillips, 1994). This figure is broadly representative of the paleoenvironments of the Morien Bay sections and the plant distribution within them. The following paleocological interpretations are generalized from DiMichele and Phillips (1994). Lycopsids could be found in standing water bodies or within peats that were occasionally inundated. *Sigillaria* sp. lived on clastic substrates, especially levees close to streams and in clastic swamps. Medullosan tree ferns were most abundant in areas of peat accumulation, particularly where nutrient levels were high and near areas of clastic influx. Sphenopsids ranged from rare to most abundant in areas of clastic influx at the margins of peat bodies. Tree ferns, pteridosperms and sphenopsids were common on levees and in the clastic swamps and largely dominated the understory of the forest environment.

As very little data was recorded on plant material in redbed intervals, no definite conclusions are made on the plant communities and preferences in these environments. Minor plants (loosely identified as marattialean foliage) at Morien South were found in truly red strata. Some plants, however, are found within grey/coal beds within the dominantly redbed intervals.

It is important to note that there is a preservation bias in the fossil record, as some parts of a plant are more likely to be preserved. This differential preservation potential of plants and plant parts affects what we observe in the fossil record. The paleoenvironment

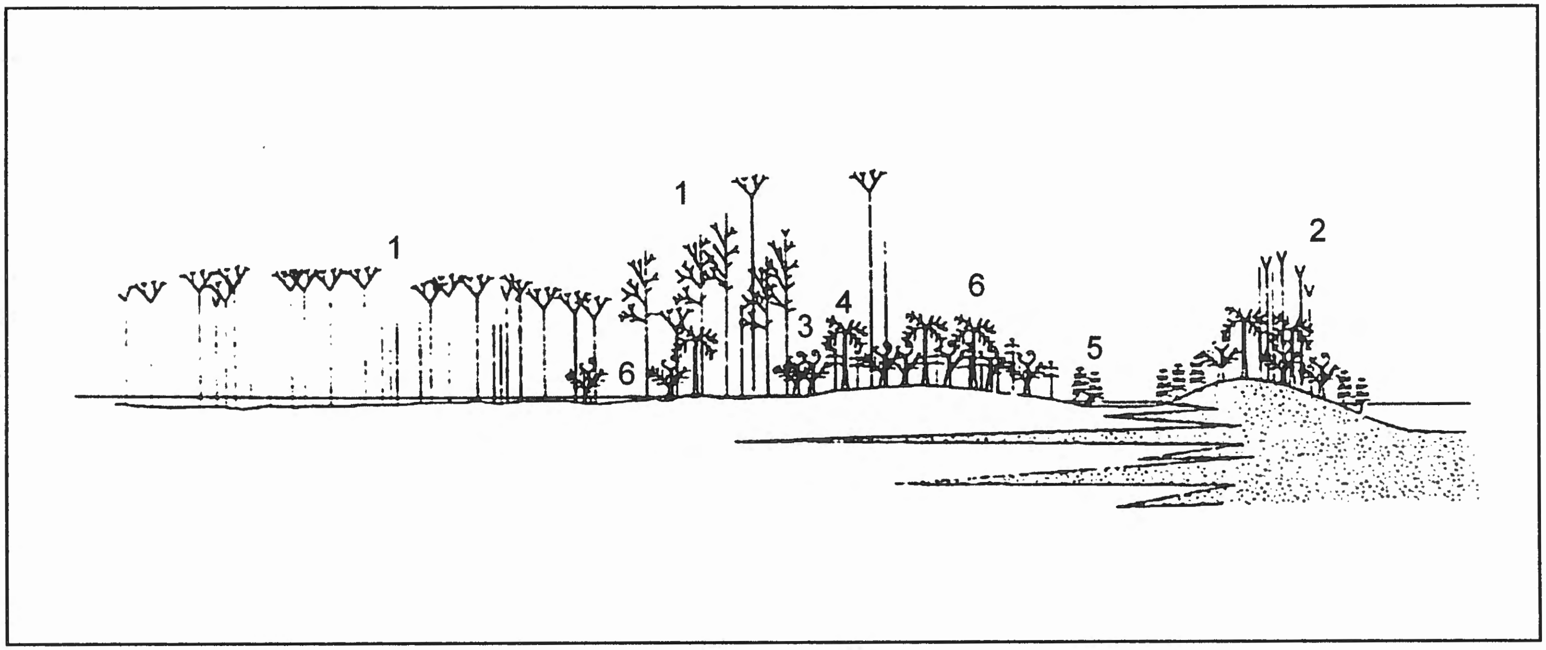


Figure 66. Cross-section through a late Carboniferous mire showing habitat partitioning among the major genera of mire plants. Modified from DiMichele and Phillips (1994).1- Lycopsids; 2- *Sigillaria*; 3- Pteridosperms; 4- Tree ferns; 5- Sphenopsids; 6- *Calamites*.

has a major effect on the preservation, and plant fossils are more often observed in wetland versus dryland strata, although this does not necessarily mean that plants were more abundant in the wetland ecosystem. Plant material is easily transported and inferences on paleoenvironments could be skewed based on representation from allochthonous or drifted plant material rather than *in situ* or parautochthonous plant material (Calder, 2001). There is also a bias in sampling as collections are easier to obtain in some levels than others. Also, certain species are more distinctive than others, preferentially increasing their apparent abundance. All of these factors need to be considered when interpreting paleobotanical data and inferring paleoenvironments. However, the plant fossil record at Morien Bay is exemplary and warrants further observation and documentation, even given all the limitations noted above.

### 5.4 Tetrapod Fossil Record

The fossil record of tetrapod footprints extends from the Upper Devonian to the Neogene (Lucas, 2003). 'Tetrapod' refers to four-legged vertebrates. Late Carboniferous tetrapod faunas contain early representatives of the amphibian and amniote lineages (Ahlberg and Milner, 1994). The study of tetrapod tracks has grown steadily and these footprints are useful for demonstrating vertebrate presence and activity where skeletal remains are absent (Lockley, 1998). The main hindrance to investigations of tetrapod ichnofacies is the confusing state of ichnotaxonomy of Mississippian and Pennsylvanian tetrapod footprints (Lucas, 2003), many of which were first named by independent authors in different countries a century ago.

Carboniferous tetrapod footprints have a strictly Euramerican, paleotropical distribution (Lucas, 2003). The most extensive Carboniferous footprint record comes from Nova Scotia. This includes Mississippian tracks in the Horton and Mabou groups (Sargeant and Mossman, 1978), Pennsylvanian tracks from the Cumberland and Pictou groups (Matthew, 1903, 1905; Sternberg, 1933; Sargeant and Mossman, 1978; Mossman and Grantham, 1996, 2000), and early Permian tracks in Pictou Group red beds in northern Nova Scotia (Calder et al., 1995) and on PEI (Mossman and Place, 1989). Lucas (2003) evaluated the utility of tetrapod footprints in Carboniferous biostratigraphy and biochronology and concluded that in this respect, tetrapod footprints are generally poorly constrained primarily due to taxonomic (naming) issues. However, much information can be gained from the discovery of a set of footprints or tracks, namely the paleoenvironmental indicators provided by the lithology, sedimentary structures and the fossils themselves (Haubold and Katzung, 1978). Careful description of the three-dimensional morphology and sedimentological context of tracks should be encouraged as they offer insight into trackmaker-habitat relationships (Lockley, 1998).

In eastern Canada a remarkable Carboniferous stratigraphic succession is present and could be proposed as a global standard (though not a complete one) (Lucas, 2003). Three intervals of Carboniferous time can be discriminated using tetrapod footprints (Lucas, 2003): Mississippian, early-mid Pennsylvanian (Westphalian) and late Pennsylvanian (Stephanian).

### *5.4.1 Tetrapod Trackway at Long Beach*

A well-preserved tetrapod trackway was found at the Long Beach section. Another set of much smaller, less informative tracks was also located at Long Beach. All information gained from the trackway is from observations at the tracksite and photographs, as the original trackway is impossible to recover due to the steep dip and its precariously perched position on the side of the cliffs (Fig. 67). No latex mould has been made of the trackway as yet.

The tetrapod that created the larger tracks at Long Beach was likely a temnospondyl amphibian (J. Calder, pers.comm). Temnospondyls are an extinct group of labyrinthodont amphibians (early Carboniferous to late Mesozoic) that were adapted to walk on land as adults but returned to the water to lay eggs. They had a wide variability of body length (<15 cm to 5-10 m). Their front feet (manus) had four toes while rear feet (pes) had five toes. Most temnospondyls were large carnivorous predators in the Carboniferous landscape. They had long snouts, short sprawling limbs and flattened heads.

The Long Beach trackway is among a small number of such tracks discovered recently in the Sydney Mines Formation. A set was discovered in North Sydney by Richard Brown in the late 1800's and was identified by Dawson as *Sauropus sydnensis* (Dawson, 1891). This was later reassigned to the genus *Baropezia* by Haubold (1971) and is now referred to as *Baropezia sydnensis*. Based on comparisons of Brown's set of tracks with the Long Beach trackway, it may be possible to assign the Long Beach tracks to *Baropezia sydnensis* (J. Calder, pers. comm). This species is assigned to the Class Amphibia and Order Temnospondylii. *Baropezia* has also been assigned to early Carboniferous trackways at Horton Bluff, Nova Scotia (Sargeant and Mossman, 1978), however, these tracks are significantly different from the type genus. *Baropezia* is a common Mississippian-Pennsylvanian tetrapod footprint ichnogenus. Measurements of the larger Long Beach footprints were taken by the author and J.H. Calder and are described in Table 4.

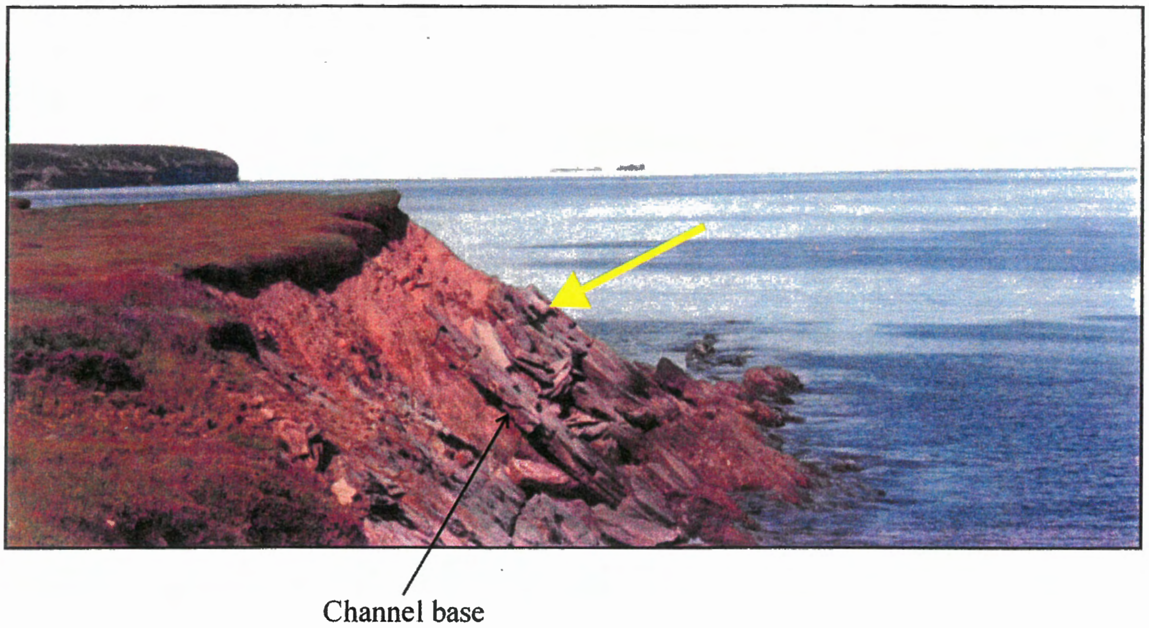


Figure 67. Photograph of precarious position of the larger Long Beach trackways (at 78 m) on the cliffs of Morien Bay. Direction of view is north-eastward. Arrow indicates surface of slab with trackways. Cliffs are approximately 8m high from water level to the edge of vegetation. Strike of channel axis is 330.

**Table 4**: Detailed Measurement of Footprints of *Baropezia sydnensis* (Dawson) Haubold

| | |
|---|---|
| Width of trackway (centre to centre) | 26-30 cm |
| Width of trackway (outside of footprints) | 36-41 cm |
| Number of footprints | 17 (possibly up to 20) |
| Manus length | 6 cm |
| Manus width | 5.5 cm |
| Pes length | No measurement |
| Pes width | No measurement |
| Glenoacetabular distance ('trunk') | 20.5-26 cm |
| Stride (estimated) | 18-22.5 cm |
| Pace of pes and manus (estimated) | 19.8 cm, 17 cm |
| Step angle of pes and manus (estimated) | 70°, 68° |

The tracks are preserved as indentations without clear digits, suggesting a soft, wet substrate at the time of impression. The glenoacetabular distance is the distance between the shoulder and hip sockets and is an indirect measurement of torso length derived from a trackway. Animal length can be estimated by twice the glenoacetabular distance. The estimated length of the trackmaker at Long Beach is between 41 and 52 cm.

The set of tracks occurs within the topmost fill of a large channel body (Facies 5b) of 6.5 m thickness (Unit 46) at the Long Beach Section (at the 78m level of Fig. 37; Fig. 68). The trackway site is approximately 0.75 m above the base of the unit which is exposed resting on a grey siltstone. There is a conglomerate base to the channel, with 30 cm sets of trough-cross strata developed as well as northward trending crossbeds near the

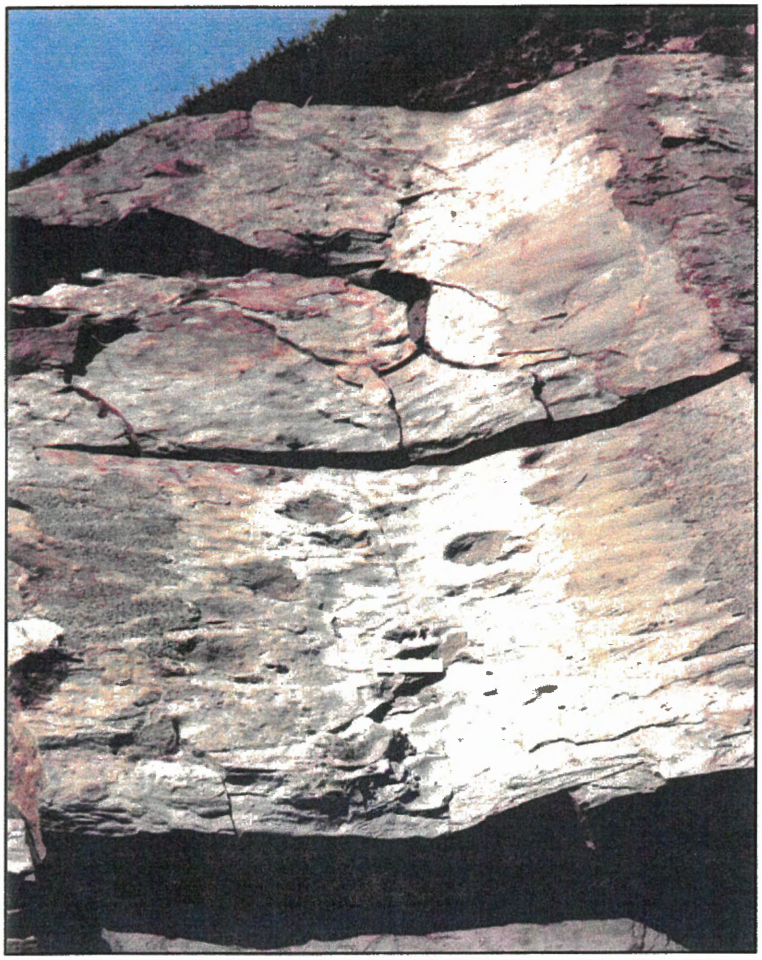


Figure 68. Tetrapod trackway at Long Beach (Unit 46). Details on footprint measurements and paleoecology in text. Individual footprints and sedimentary structures within tracksite are sketched in Fig. 69. Trackmaker was moving up the exposed surface and is possibly identified as *Baropezia sydnensis,* a temnospondyl amphibian. Scale card is 9cm.

channel margins. The tracksite itself appears to be within an exhumed linear shallow channel, 15 cm deep and 1.2 m wide. The trend of the channel axis was measured as 330°. The thin stratal package that forms the marginal part of the channel body is composed of planar lamination grading from gravel to sand. Root traces are present in the beds below the channel body, as well as a large (40 cm diameter) tree stump, hollowed-out at present, that penetrates up through the channel fill.

Due to the numerous features preserved at the tracksite (Fig. 69), detailed observations of the environment can be proposed as well as a chronological order of events that took place. The larger channel body was cut and the initial gravel margins grade upwards into more sandy deposits as the flow velocity likely dropped slightly. Deposition and partial fill of the main channel continued, possibly as a bank-attached bar deposit with northwards paleoflow. The smaller channel containing the tracks was likely cut at this time. The channel may have been in the process of abandonment and/or the water level may have been dropping. Sand and silt with ripple marks then developed, also indicating a northward paleoflow. A thin mud drape lastly was deposited over the sand/silt. In the wet mud, the tetrapod walked through this minor channel, traveling downflow and churning up the soft sediment. The direction of paleoflow is inferred from the numerous ripple marks along the same surface as the tracks and the well developed ridge-and-furrow structures. Sub-vertical burrows are also present at this level, some of which are paired and filled with coarse sand (cf. Arenicolites sp.). The water was likely very shallow (a few centimetres) while the tetrapod left the tracks and beginning to dry up. A network of thin desiccation cracks appears alongside the footprints. It rained soon afterwards as there are numerous rain prints at the margins. There is also indication of

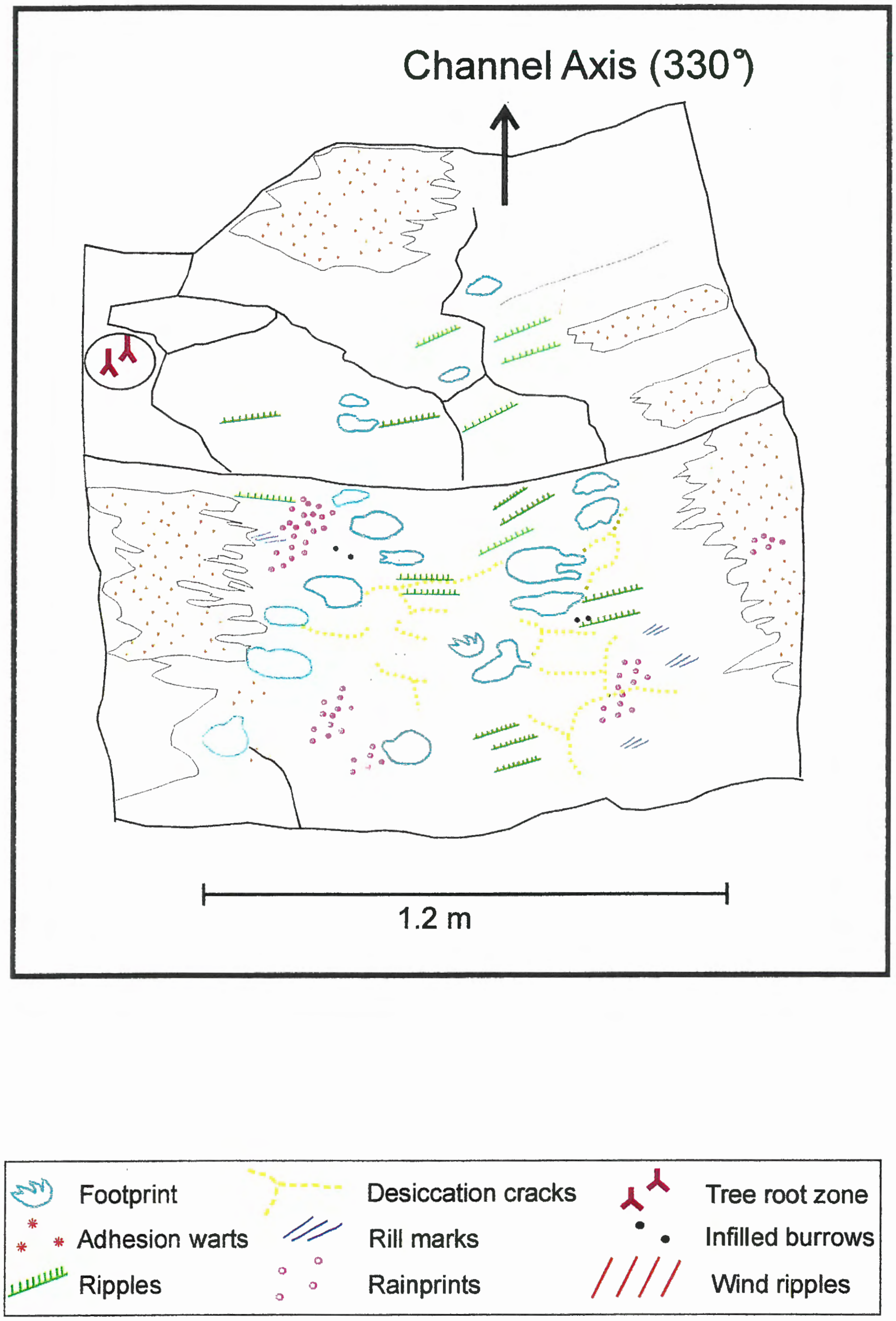


Figure 69. Sketch of trackway at Long Beach showing footprints, sedimentary structures and channel axis. Dark cracks are modern fractures. Ripples cover much of surface; only some are shown.

windblown sand that covered rain prints, generated adhesion warts along the channel margins and infilled parts of the trackway. The adhesion warts are in the capping few millimeters of sediment and have broken off at the tracksite to reveal the beds below. Beds closely above the tracks are sandy with ripple marks, probably aeolian, indicating a southward paleoflow. These beds are more apparent in upper storeys of the channel, where overlying beds are visible. Finally, the trackway was covered by silt and fine sand. The main channel body, exposed further along the cliff, has a capping paleosol with abundant root traces.

## Chapter 6: CONCLUSIONS

The following conclusions are drawn relating to the sedimentology, sequence stratigraphy and paleoecology of the Late Carboniferous Sydney Mines Formation at Morien Bay:

1. Three outcrop sections at Schooner Pond, Long Beach and Morien South measured 73, 159, and 104 m in thickness, respectively. This included the McRury to Bouthilier coal seam interval.
2. The dominant facies assemblage at Long Beach and Schooner Pond represents a poorly drained coastal plain and comprises grey sandstone and shale, hydromorphic paleosols, thick coals and distributary channel bodies. The second facies assemblage represents a well drained alluvial plain and comprises red mudstone, nodular calcrete, vertic red and grey paleosols, massive limestone and dryland channel bodies. Repetition of these facies generally reflects transgressive and regressive cycles of relative sea level. At Morien South, the dominant facies assemblage is the well-drained alluvial plain.
3. The major facies identified at all three sections are stratified and non-stratified grey silt- and sandstone, thick channel body sandstones and laminated grey claystone. Minor facies identified at Schooner Pond include coal, carbonaceous limestone and thin channel bodies. Minor facies at Long Beach include coal, calcrete and calcareous sandstone, red claystone and thin channel bodies. Minor facies at Morien South include red claystone, stratified red siltstone, calcrete and coal. The amount of well-drained alluvial plain facies appears to increase southward towards the basin margin.

There is a higher sand content in the well-drained facies assemblage compared with the poorly drained assemblage.

4. Unidirectional paleocurrent data from channel bodies in all three sections yield a paleoflow direction of 347° (NNW). The paleocurrent direction at each study section based on measurements from channel systems is summarized as: 029° (ENE) at Schooner Pond, 001° (N) at Morien South and 334° (NNW) at Long Beach. This suggests a major source to the south of Morien Bay, possibly Proterozoic rocks of the Avalon Terrane (Scatarie Ridge) uplifted during the Acadian Orogeny. These paleoflow estimates suggest a southern source in this part of the Sydney Basin, indicating a local variation from the regional southwestern source within the northern Appalachian Mountains proposed from measurements in western parts of the Sydney Basin. Paleoflow estimates are based on 114 measurements from the three study sections. Measurements of ripple cross-lamination, primary current lineation, cross-bedding, and groove casts were collected, the majority of measurements coming from cross-bedding (including planar- and trough cross-strata) and ripple cross-lamination.
5. Applying sequence stratigraphic concepts in this setting is very challenging. To the extent they were recognizable, the signature of sequence boundaries varies across the coastal plain. The three main types of sequence boundary observed are (a) single well defined calcretes with minimal sedimentation for a long period, (b) sequence boundary zones of vertisol-type paleosols, several metres thick, where sediment was still being supplied during lowstand periods, and (c) sequence boundary zones of small paleovalley fills or large channel bodies in association with paleosols.

6. Flooding surfaces in the Sydney Basin are recognized by thick, extensive coal seams or thin coal or coaly shale. Maximum flooding surfaces can be represented by distinct faunal-concentrate limestone layers rich in bivalve and ostracod fossils, and form excellent regional stratigraphic markers, traceable across much of the basin. Some coals may mark the maximum flooding surface in updip locations. In the most proximal setting, identifying the MFS becomes difficult or impossible.
7. Seven stacked high-frequency sequences 11-38 m thick were measured. Long Beach provided the most complete section with six complete sequences and part of a seventh exposed. As strata in the McRury to Emery interval are poorly exposed, sequence numbering commences just below the Emery seam at all three sections.
8. The grey, wetland facies and economic coals are well represented within the transgressive and highstand systems tracts (TST, HST). The TST is prominent in the Morien Bay sections and deposits are thick, probably due to higher accommodation space. Thick coals are most abundant in the TST. The HST is also well represented in the Morien Bay sections and less sediment was deposited as the rate of sea-level rise decreased and channel and distributary systems re-established. Two sub-sections within the HST were identified: a 'dry' and 'wet' component. In many cases indicators of change to drier conditions are found in the top portion of HST deposits, possibly representing the early stages of relative sea-level fall. These strata contrast with the typically bay-fill or water-logged facies of the lower 'wet' HST. Systems tract terminology was not applied to the alluvial plain data as no open-marine influence is normally demonstrated and facies trends become more cryptic.

9. Red and grey dryland facies are represented in the topmost highstand to possible lowstand systems tract. Few lowstand systems tract deposits were identified in the study sections due to either erosion during lowstand incision or a preservational bias. In addition, LST deposits are not expected to be present at significant thickness in the most proximal settings according to sequence stratigraphic models. The small thickness of LST deposits with respect to sequence boundaries creates difficulty in their outcrop identification. No formal falling stage systems tract was identified because a lower bounding surface could not be recognized. However, the presence of sediments deposited during the falling stages of sea level at Morien Bay can be argued for, especially in the Morien South section, where within a strongly incised paleo-gully, a lowstand surface rich in carbonate material suggests landscape degradation (not bayfill accumulation) during falling stage.
10. Record of sea level (or lake level) rise and fall is not uniform across the basin. A repeated cyclic pattern of poorly drained interdistributary bay and swamp-like environments with peat formation changing to more well-drained alluvial plain sedimentation is seen in each exposed coastal section, suggesting that glacioeustasy and sea-level effects dominate the stratal architecture. The duration and extent of transgressions and regressions was not the same everywhere as major limestone (MFS) layers are not traceable as far as Morien South. Some coaly layers at Morien South may be updip MFS equivalents to these limestones at Long Beach. The thickness of the major coal seams also decreases from Long Beach to Morien South and the relative amount of seam splitting increases. The stratal packages appear to thicken in the Morien Bay sections when compared to sections of similar intervals

towards the west side of the Sydney Basin. This suggests increased subsidence in the Morien Syncline, allowing for preservation of thicker stratigraphic packages. The Morien Syncline was likely a paleotopographic low during deposition. The Phalen coal seam noticeably thickens eastward towards the Long Beach section.

11. Cycles of climate change are linked to sea-level fluctuations in the Sydney Basin and involve changes from humid to strongly seasonal conditions and arid conditions.
12. Morien South, in particular, records an increased amount of red mudstone and siltstone floodplain material. This is a result of a more proximal and well-drained region towards the southern limb of the Morien Syncline, where the effects of maximum flooding are not always recorded in the strata. At least five major redbed intervals are identified at Long Beach and Morien South, with major redbed accumulation between the Emery and Phalen coal seams. Semi-arid climates and well-drained settings likely account for the presence of these red, oxidized floodplain sediments
13. Erect lycopsids, abundant compression flora and prostrate logs comprise the paleobotanical record at Schooner Pond, Long Beach and Morien South. Thirty erect lycopsid trees were recorded in their growth position. Trunk diameters ranged from 0.25–0.6 m. *Lepidodendron* sp. and *Sigillaria* sp. are the two main lycopsids identified. Trees are rooted in substrates ranging from clastics to coaly shale or thin carbonaceous layers.
14. Compression flora consists dominantly of pteridosperms (*Alethopteris* sp., and *Neuropteris* sp.), marattialean tree-fern foliage (*Pecopteris* sp.), sphenophytes (*Sphenophyllum* sp.), and rarer species of *Cordaites* sp. Most specimens were

collected from the dominantly grey, coal-bearing strata. Abundant casts of *Calamites* stems are found in all sections. Forested horizons of standing calamitacean and lepidodendrid trees are observed at many levels, especially within the highstand systems tract and less commonly within transgressive systems tract, along with abundant compression flora, suggesting that base level rise led to paludification and onset of peat accumulation. Few plant specimens were recovered from redbeds of the highstand through lowstand systems tracts. A vegetational transition between peatland (lycopsids) and clastic wetland (calamites) floras can be observed.

15. Modest links are made between paleobotanical samples and the systems tracts with which they are associated. Standing lycopsids (*Lepidodendron* sp. and *Sigillaria* sp.) are predominantly found within HST deposits. Their stigmarian root stalks are often more common in TST deposits. Pteridosperms are slightly more predominant in TST deposits than HST while limited occurrences of *Cordaites* sp. found in TST and HST deposits. *Calamites* (and most equisetales specimens identified) are found predominantly in TST deposits. Minor calamitacean foliage was recovered from LST deposits.
16. A well-preserved tetrapod trackway in the Long Beach section contains a series of 18 tracks preserved as indentations without clear digits. The tracksite appears to be within an exhumed linear shallow channel (15cm deep) within the topmost fill of a large 6.5 m thick channel body. The trackmaker is potentially identified as *Baropezia sydnensis*, a temnospondyl amphibian adapted to walk on land. Extensive paleoenvironmental information is obtained from the tracksite including

sedimentological (ripple marks, rill marks, wind blown ripples) and climatic indicators (rain prints, desiccation cracks).

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## APPENDIX 1: Facies Percentage Values of Well Drained Alluvial Plain and Poorly Drained Coastal Plain Strata used in Figures 8, 27, 28, and 29

### LONG BEACH

| Unit # | Thickness | Facies | units | 1 | 2a | 2b | 2c | 3a | 3b | 3c | 3d | 3e | 4a | 4b | 4c | 4d | 4e | 5a | 5b | total m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| total | 158.63 | | m | 4.58 | 0.60 | 3.17 | 1.95 | 5.63 | 12.16 | 2.87 | 7.73 | 1.16 | 19.36 | 53.85 | 4.80 | 0.00 | 0.00 | 6.22 | 34.55 | 158.63 |
| total | 62.61 | WDAP | % | 0.03 | 0.00 | 0.02 | 0.01 | 0.04 | 0.08 | 0.02 | 0.05 | 0.01 | 0.12 | 0.34 | 0.03 | 0.00 | 0.00 | 0.04 | 0.22 | |
| total | 96.02 | PDCP | % | 2.89 | 0.38 | 2.00 | 1.23 | 3.55 | 7.67 | 1.81 | 4.87 | 0.73 | 12.20 | 33.95 | 3.03 | 0.00 | 0.00 | 3.92 | 21.78 | |

### MORIEN SOUTH

| Unit # | Thickness | Facies | units | 1 | 2a | 2b | 2c | 3a | 3b | 3c | 3d | 3e | 4a | 4b | 4c | 4d | 4e | 5a | 5b | total m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| total | 104.1 | | m | 2.38 | 0.00 | 0.36 | 1.07 | 5.22 | 5.36 | 1.08 | 4.25 | 3.31 | 9.21 | 48.42 | 2.57 | 5.06 | 4.44 | 8.65 | 2.72 | 104.10 |
| total | 55.09 | WDAP | % | 0.02 | 0.00 | 0.00 | 0.01 | 0.05 | 0.05 | 0.01 | 0.04 | 0.03 | 0.09 | 0.47 | 0.02 | 0.05 | 0.04 | 0.08 | 0.03 | |
| total | 49.01 | PDCP | % | 2.29 | 0.00 | 0.35 | 1.03 | 5.01 | 5.15 | 1.04 | 4.08 | 3.18 | 8.85 | 46.51 | 2.47 | 4.86 | 4.27 | 8.31 | 2.61 | |

### SCHOONER POND

| Unit # | Thickness | Facies | units | 1 | 2a | 2b | 2c | 3a | 3b | 3c | 3d | 3e | 4a | 4b | 4c | 4d | 4e | 5a | 5b | total m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| total | 72.98 | | m | 4.05 | 0.49 | 1.10 | 0.25 | 2.50 | 16.64 | 0.70 | 0.00 | 0.00 | 13.83 | 14.96 | 0.55 | 0.00 | 0.00 | 3.25 | 14.66 | 72.98 |
| total | 20.98 | WDAP | % | 0.06 | 0.01 | 0.02 | 0.00 | 0.03 | 0.23 | 0.01 | 0.00 | 0.00 | 0.19 | 0.20 | 0.01 | 0.00 | 0.00 | 0.04 | 0.20 | |
| total | 52 | PDCP | % | 5.55 | 0.67 | 1.51 | 0.34 | 3.43 | 22.80 | 0.96 | 0.00 | 0.00 | 18.95 | 20.50 | 0.75 | 0.00 | 0.00 | 4.45 | 20.09 | |

Notes:

WDAP: Well drained alluvial plain facies assemblage

PDCP: Poorly drained coastal plain facies assemblage

See Table 2 for facies numbers and descriptions

# APPENDIX 2: Paleocurrent Measurements from all sections

## Long Beach Section

| Unit # | Facies | Lithology | Structure/Type | Measurements |
|---|---|---|---|---|
| 5 | 4b | sandstone | trough x-sets | 030 |
| 5 | 4b | siltstone | climbing ripples | 062 |
| 6 | 4a | sandstone | ripples (~1cm) | 076 |
| 13 | 5a | sandstone | climbing ripples (<2cm) | 078 |
| 15 | 4a | sandstone | climbing ripples (<2cm) | 101 |
| 17 | 4a | sandstone | ripples | 086 |
| 17 | 4a | sandstone | ripples | 217 |
| 17 | 4a | sandstone | trough x-sets (~40cm) | 090 |
| 20 | 4a | siltstone | current lineations | 073 |
| 20 | 4a | siltstone | current lineations | 076 |
| 20 | 4a | siltstone | ripples | 062 |
| 21 | 4b | sandstone | ripples (<2cm) | 005 |
| 21 | 4b | sandstone | groove casts | 078 |
| 29 | 4b | sandstone | ripples | 265 |
| 29 | 4b | sandstone | ripples | 248 |
| 29 | 4b | sandstone | x-strat (<1/2cm) | 232 |
| 29 | 4b | sandstone | troughs (~10cm) | 251 |
| 31 | 5b | channel ss | current lineations | 056 |
| 31 | 5b | channel ss | current lineations | 052 |
| 31 | 5b | channel ss | current lineations | 065 |
| 31 | 5b | channel ss | troughs | 069 |
| 31 | 5b | channel ss | troughs | 072 |
| 31 | 5b | channel ss | lineation w/l minor ch | 030 |
| 32 | 4a | siltstone | ripples | 234 |
| 34 | 4b/a | sandstone | x-strat | 274 |
| 34 | 4b/a | sandstone | x-beds | 261 |
| 34 | 4b/a | sandstone | ripples | 272 |
| 34 | 4b/a | sandstone | ripples | 297 |
| 35 | 4a | sandstone | ripples | 212 |
| 37 | 4b | sandstone | ripples (<3cm) | 042 |
| 38 | 5b | channel ss | climbing ripples | 037 |
| 38 | 5b | channel ss | troughs | 045 |
| 40 | 5a | channel ss | troughs | 243 |
| 40 | 5a | channel ss | groove casts | 080 |
| 44 | 5a | channel ss | ripples | 334 |
| 44 | 5a | channel ss | current lineations | 336 |
| 46 | 5b | channel ss | ripples | 352 |
| 46 | 5b | channel ss | troughs (up to1m) | 340 |
| 46 | 5b | channel ss | current lineations | 340 |
| 46 | 5b | channel ss | current lineations | 325 |
| 46 | 5b | channel ss | current lineations | 325 |
| 46 | 5b | channel ss | current lineations | 005 |
| 46 | 5b | channel ss | current lineations | 350 |
| 46 | 5b | channel ss | current lineations | 350 |
| 46 | 5b | channel ss | ripples | 340 |
| 46 | 5b | channel ss | ripples | 325 |
| 46 | 5b | channel ss | ripples | 340 |
| 46 | 5b | channel ss | ripples | 360 |
| 46 | 5b | channel ss | troughs | 342 |
| 46 | 5b | channel ss | current lineations | 360 |
| 46 | 5b | channel ss | ripples | 330 |
| 46 | 5b | channel ss | ripples | 350 |
| 70b | 4b | siltstone | troughs | 228 |

| | | | | |
|---|---|---|---|---|
| 70d | 4b | sandstone | current lineations | 045 |
| 70d | 4b | sandstone | ripples | 027 |
| 70e | 4b | sandstone | ripples | 009 |
| 80 | 2b | carbonate sand | lineations | 337 |
| 82 | 4a | sandstone | ripples | 244 |
| 85 | 5a | channel ss | lineations | 218 |
| 85 | 5a | channel ss | lineations | 218 |
| 85 | 5a | channel ss | lineations | 220 |
| 85 | 5a | channel ss | ch PT? | 280/100? |
| 85 | 5a | channel ss | ripples | 216 |
| 87 | 4b | siltstone | x-strat | 344 |
| 87 | 4b | siltstone | x-strat | 313 |
| 88 | 5a | channel ss | lineations | 287 |
| 88 | 5a | channel ss | x-strat | 248 |
| 94 | 5b | channel ss | x-lams | 042 |
| 94 | 5b | channel ss | lineations | 065 |
| 111 | 5a | channel ss | lineations | 278 |
| 111 | 5a | channel ss | scours | 268 |
| 111 | 5a | channel ss | x-strat | 290 |
| 111 | 5a | channel ss | x-strat | 292 |
| 111 | 5a | channel ss | x-strat | 292 |
| | | | | |

## Schooner Pond Section

| Unit # | Facies | Lithology | Structure/Type | Measurements |
|---|---|---|---|---|
| 18 | 4b | f. sandstone | x-strat | 97 |
| 18 | 4b | f. sandstone | x-strat | 88 |
| 18 | 4b | f. sandstone | x-strat | 93 |
| 18 | 4b | f. sandstone | x-strat | 92 |
| 18 | 4b | f. sandstone | x-strat | 77 |
| 18 | 4b | f. sandstone | x-strat | 89 |
| 20 | 4a | f. sandstone | troughs | 191 |
| 20 | 4a | f. sandstone | troughs | 193 |
| 20 | 4a | f. sandstone | troughs | 197 |
| 21 | 3b | claystone | ripples | 272 |
| 21 | 3b | claystone | ripples | 291 |
| 21 | 3b | claystone | ripples | 272 |
| 21 | 3b | claystone | ripples | 276 |
| 21 | 3b | claystone | ripples | 276 |
| 23.2 | 4a | f. sandstone | ripples | 245 |
| 29 | 5b | channel ss | troughs | 327 |
| 29 | 5b | channel ss | troughs | 159 |
| 29 | 5b | channel ss | troughs | 196 |
| 40 | 5a | channel ss | troughs | 309 |
| 40 | 5a | channel ss | troughs | 345 |
| 40 | 5a | channel ss | troughs | 338 |
| 40 | 5a | channel ss | current lineations | 328 |
| 40 | 5a | channel ss | current lineations | 327 |
| 44 | 5a | channel ss | ripples | 46 |
| 44 | 5a | channel ss | ripples | 77 |
| 46 | 5b | channel ss | troughs | 64 |
| 46 | 5b | channel ss | troughs | 75 |

## Morien South Section

| Unit # | Facies | Lithology | Structure/Type | Measurements |
|---|---|---|---|---|
| 11 | 5a | channel ss | x-strat | 324 |
| 22 | 5a | channel ss | current lineation | 12 |
| 22 | 5a | channel ss | current lineation | 350 |
| 22 | 5a | channel ss | grooves | 10 |
| 26 | 2b | calcareous ss | x-strat | 331 |
| 26 | 4b | sandstone | grooves | 334 |
| 26 | 4b | sandstone | ripples | 22 |
| 26 | 4b | sandstone | ripples | 19 |
| 26 | 4b | sandstone | ripples | 12 |
| 54A | 5b | channel ss | current lineation | 259 |
| 54A | 5b | channel ss | ripples | 252 |
| 59 | 4b | sandstone | troughs | 326 |
| 74 | 5a | channel ss | x-strat | 96 |
| 74 | 5a | channel ss | ripples | 128 |

## APPENDIX 3

Large print-out of stratigraphic columns measured at Schooner Pond, Long Beach and Morien South (Identical to Figure 37). This Appendix is included in a fold-out version at the back of the thesis.

## APPENDIX 4A: Schooner Pond Plant Fossils

| | Plant Foliage Fragments | *Lepidodendron* sp. | *Sigillaria* sp. | *Cyperites* sp. | *Stigmaria ficoides* | *Sphenophyllum cuneifolium* | *Sphenophyllum* sp. | *Calamites cisti* | *Calamites* sp. | *Annularia* sp. | *Sphenopteris* sp.? *(incertae sedis)* | *Pecopteris hemitelioides?* | *Pecopteris* sp. | *Medullosa* sp.? | *Alethopteris* sp. | *Mariopteris* sp. | *Neuropteris scheuchzeri* | *Neuropteris ovata* | *Neuropteris* sp. | *Cordaites principales?* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNIT # | (no ID) | Lepidodendrales | | | | Sphenophyllales | | Equisetales | | | Filicales | Marattiales | | Pteridospermales | | | | | | Cordaitales | FACIES | SYSTEMS TRACT |
| 1 | X | | | | | | | | | | | | | | | | | | | | 4a | TST |
| 2 | X | | | | | | | | | | | | | | | | | | | | 3c | TST |
| 3 | X | | | | | | | | | | | | | | | | | | | | 1 | TST |
| 4 | X | | | | | | | | | X | | | | | | | | | | | 4b/3b | TST |
| 5 | X | | | | | | | | | | | | X | | X | | | | | | 1 | TST |
| 6 | X | | | | | | X | | X | | | | X | X? | X | | | | | | 4a | TST |
| 8 | | | | | | | | | X | | | | | | | | | | | | 4b | HST |
| 10 | X | | | | | | | | | | | | | | | | | | | | 3a | HST |
| 11 | X | | | | | | | | | | | | | | | | | | | | 3b | TST |
| 15 | X | | | | | | | | | | | | | | | | | | | | 4b/3b | TST |
| 18 | X | | | | | | | | | | | | | | | | | | | | 4b | TST |
| 24 | X | | | | | | | | | | | | | | | | | | | | 4a | TST |
| 25 | X | | | | | | | | | | | | | | | | | | | | 3c | TST |
| 26 | | | | | | | | | | | | | | X? | | | | | | | 3b | TST |
| 27 | X | | | | | | | | | | | | | | | | | | | | 4a | TST |
| 28 | X | | | | | | | | | | | | | | | | | | | | 1 | TST |
| 29 | X | | | | X | | X | | X | | | | X | | X | | | X | X | | 5b | TST |
| 30 | X | | | | | | | | | | | | | | | | | | | | 3b | TST |
| 33 | X | | | | | | | | | | | | | | | | | | | | 4b | HST |
| 34 | X | | | | | | | | | | | | | | | | | | | | 3a | HST |
| 38 | X | | | | | | | | | | | | | | | | | | | | 1 | HST |
| 39 | X | | | | | | | | | | | | X | | | | | | | | 4b | HST |
| 40 | X | | | | | | | | | | | | | | | | | | | | 5a | HST |
| 42 | X | | | | | | | | | | | | | | | | | | | | 3b | HST |
| 43 | X | X | | | | | | | | | | | | | | | | | | | 4b | HST |
| 44 | | X | | | | | | | | | | | | | | | | | | | 5a | HST |
| 45 | X | | | | | | | | | | | | | | | | | | | | 4a | HST |
| 57 | | | | | X | | | | | | | | | | | | | | | | 4a | TST? |
| 58 | X | | | | | | | | | | | | | | | | | | | | 1 | TST? |
| 59 | X | | | | | | | | | | | | | | | | | | | | ? | TST? |

## APPENDIX 4B: Long Beach Plant Fossils

| | Plant Foliage Fragments | *Lepidodendron* sp. | *Sigillaria* sp. | *Cyperites* sp. | *Stigmaria ficoides* | *Sphenophyllum cuneifolium* | *Sphenophyllum* sp. | *Calamites cisti* | *Calamites* sp. | *Annularia* sp. | *Sphenopteris* sp.? *(incertae sedis)* | *Pecopteris hemitelioides?* | *Pecopteris* sp. | *Medullosa* sp.? | *Alethopteris* sp. | *Mariopteris* sp. | *Neuropteris scheuchzeri* | *Neuropteris ovata* | *Neuropteris* sp. | *Cordaites principales?* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNIT # | (no ID) | Lepidodendrales | | | | Sphenophyllales | | Equisetales | | | Filicales | Marattiales | | Pteridospermales | | | | | | Cordaitales | FACIES | SYSTEMS TRACT |
| 3 | X | | | | | | | | | | | | | | | | | | | | 4a | TST |
| 4 | X | | | | | | | | | | | | | | | | | | | | 3b | TST |
| 7 | X | | | | | | | | | | | | | | | | | | | | 4b | TST |
| 9 | X | | | | | | | | | | | | | | | | | | | | 1 | TST |
| 10 | | | | | X | | | | | | | | | | | | | | | | 4b | TST |
| 11 | X | | | | | | | | | | | | | | | | | | | | 1 | TST |
| 12 | X | | | | | | | | | | | | X | | | | | | X | | 4b | HST |
| 13 | X | X? | | | | | | | X | | | | X | | | | | | | | 5a | HST |
| 14 | X | | | | | | | | X | X | | | X | | | | | | X | X | 4b | HST |
| 15 | | X | | X? | | | | | | | | | | | | | | | | | 4a | HST |
| 16 | X | X | | | | | | | X | | | | | | | | | | | | 4b | HST |
| 17 | X | X? | X? | | X | | | | X | | | | X | X | | | | | | | 4a | HST |
| 18 | X | | | | X | | | | | | | | | | | | | | | | 4b | HST |
| 20 | X | | | | | | | | | | | | | | | | | | | | 4a | HST |
| 21 | X | X | | | | | | | | | | | | | | | | | | | 4b | HST |
| 23 | X | | | | | | | | | | | | | | | | | | | | 3b | HST |
| 24 | X | X | | | | | | | | | | | | | | | | | | | 4b | HST |
| 26 | X | | | | | | | | | | | | | | | | | | | | 3a/3b | TST |
| 28 | X | | | | | | | | | | | | X | | | | | | | | 4a | HST |
| 29 | | X | | | | | | | X | | | | | | | | | | | | 4b | HST |
| 35 | X | | | | X | | | | X | | | | | | | | | | | | 4a | TST |
| 36 | X | | | | | | | | | | | | | | | | | | | | 3a/3b | TST |
| 40 | X | | | | | | | | | | | | | | | | | | | | 5a | LST? |
| 41 | X | | | | | | | | | | | | | | | | | | | | 4b/3e | LST? |
| 44 | | X | | | | | | | X | | | | | | | | | | | | 5a | LST? |

|  | Plant Foliage Fragments | *Lepidodendron* sp. | *Sigillaria* sp. | *Cyperites* sp. | *Stigmaria ficoides* | *Sphenophyllum cuneifolium* | *Sphenophyllum* sp. | *Calamites cisti* | *Calamites* sp. | *Annularia* sp. | *Sphenopteris* sp.? (*incertae sedis*) | *Pecopteris hemitelioides?* | *Pecopteris* sp. | *Medullosa* sp.? | *Alethopteris* sp. | *Mariopteris* sp. | *Neuropteris scheuchzeri* | *Neuropteris ovata* | *Neuropteris* sp. | *Cordaites principales?* |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNIT # | (no ID) | Lepidodendrales |  |  |  | Sphenophyllales |  | Equisetales |  |  | Filicales | Marattiales |  | Pteridospermales |  |  |  |  |  | Cordaitales | FACIES | SYSTEMS TRACT |
| 50 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3b | TST |
| 51 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | TST |
| 53 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | TST |
| 55 | X | X? |  |  |  |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  | 4b | HST |
| 58 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | TST? |
| 61 |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2c/4b | HST? |
| 64 | X | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5b | TST |
| 65 | X |  |  |  |  | X? |  |  |  |  | X | X | X |  |  | X | X | X | X | X | 4a | TST |
| 67 | X |  |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |  |  |  | 3a | HST |
| 68 |  | X? | X? |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3c | HST |
| 70 | X | X | X |  |  |  |  |  | X |  |  |  |  |  | X |  |  |  | X |  | 3b/4b | HST |
| 71 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3b | HST |
| 74 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3d/3a | HST |
| 75 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4a | HST |
| 77 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4a | HST |
| 78 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3c | HST |
| 90 |  |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4a | TST |
| 92 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | TST |
| 93 | X |  | X |  |  |  |  |  | X |  |  |  | X |  | X |  |  |  |  |  | 3b | HST |
| 94 |  |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 5b | HST |
| 95 | X |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4a | HST |

# APPENDIX 4C: Morien South Plant Fossils

| | Plant Foliage Fragments | *Lepidodendron sp.* | *Sigillaria sp.* | *Cyperites sp.* | *Stigmaria ficoides* | *Sphenophyllum cuneifolium* | *Sphenophyllum sp.* | *Calamites cisti* | *Calamites sp.* | *Annularia sp.* | *Sphenopteris sp.? (incertae sedis)* | *Pecopteris hemitelioides?* | *Pecopteris sp.* | *Medullosa sp.?* | *Alethopteris sp.* | *Mariopteris sp.* | *Neuropteris scheuchzeri* | *Neuropteris ovata* | *Neuropteris sp.* | *Cordaites principales?* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNIT # | (no ID) | Lepidodendrales | | | | Sphenophyllales | | Equisetales | | | Filicales | Marattiales | | Pteridospermales | | | | | | Cordaitales | FACIES | SYSTEMS TRACT |
| 1 | X | | | | | | | | | | | | X | | | | | | | | 4a | TST |
| 2 | X | | | | | | | | | | | | | | | | | | | | 3c | TST |
| 3 | X | | | | | | | | | | | | | X | | | | | | | 3a | TST |
| 4 | X | | | X | | | | | | | | | | | | X | X | | | | 1 | TST |
| 5 | X | | | | | | X | | | | | | X | | X | X | X | | X | | 4b | HST |
| 6 | X | X | X | | | | X | X | X | | | | X | | X | | | | | | 4b | HST |
| 7 | | X | | | X | | | | X | | | | | | | | | | | | 4b | HST |
| 9 | X | | | | | | | | | | | | | | | | | | | | 3c/3a | HST |
| 10 | X | X | | | X | | | | X | | | | X | | | | | | | | 2b/4b | HST |
| 18 | X | | | | | | | | | | | | | | | | | | | | 4c/4a | - |
| 19 | X | | | | | | | | | | | | | | | | | | | | 4b | - |
| 20 | X | | | | | | | | | | | | | | | | | | | | 4d | - |
| 21 | X | | | | | | | | | | | | | X | | | | | | | 4b | - |
| 31 | X | | | | | | | | | | | | | | | | | | | | 4d/4a | - |
| 32 | X | X | | | | | | | X | | | | | | | | | | | | 4e | - |
| 33 | X | | | | | | | | | | | | | | | | | | | | 4c/4a | - |
| 34 | X | | | | | | | | | | | | X | | | | | | | | 4b/4d | - |
| 35 | | X | | | | | | | | | | | | | | | | | | | 4b/4d | - |
| 36 | X | | | | | | | | | | | | X | | | | | | | | 3c/4b | - |
| 37 | X | | | | | | | | | | | | | | | | | | | | 4b/4d | - |
| 38 | | X | | | | | | | | | | | | | | | | | | | 5a | - |
| 46 | | | | | X | | | | | | | | | | | | | | | | 4e | - |
| 47 | X | | | | | | | | | | | | | | | | | | | | 3e | - |
| 48 | X | | | | | | | | | | | | | | | | | | | | 4e | - |

|  | Plant Foliage Fragments | *Lepidodendron* sp. | *Sigillaria* sp. | *Cyperites* sp. | *Stigmaria ficoides* | *Sphenophyllum cuneifolium* | *Sphenophyllum* sp. | *Calamites cisti* | *Calamites* sp. | *Annularia* sp. | *Sphenopteris sp.? (incertae sedis)* | *Pecopteris hemitelioides?* | *Pecopteris* sp. | *Medullosa* sp.? | *Alethopteris* sp. | *Mariopteris* sp. | *Neuropteris scheuchzeri* | *Neuropteris ovata* | *Neuropteris* sp. | *Cordaites principales?* |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UNIT # | (no ID) | Lepidodendrales |  |  |  | Sphenophyllales |  | Equisetales |  |  | Filicales | Marattiales |  | Pteridospermales |  |  |  |  |  | Cordaitales | FACIES | SYSTEMS TRACT |
| 58 | X |  |  | X | X |  | X |  |  |  |  |  | X |  | X | X | X |  | X | X | 4b/3b | TST |
| 59 | X |  |  |  | X |  |  |  | X |  |  |  | X |  |  |  |  |  |  |  | 4b | TST |
| 60 |  | X |  |  | X |  |  |  | X |  |  |  |  |  |  |  |  |  |  |  | 4b | TST |
| 61 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b/4a | TST |
| 63 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | - |
| 65 | X |  |  |  |  |  |  |  |  |  |  |  | X |  |  |  |  |  |  |  | 3a/4b | - |
| 66 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | - |
| 68 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4c/4a | - |
| 69 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | TST |
| 71 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | TST |
| 73 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3a | HST |
| 74 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3a/5a/4b | HST |
| 77 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3a | TST |
| 78 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1/4b | TST |
| 79 | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 4b | TST |
| 80 |  | X |  |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3b/4b | TST |