SEDIMENTOLOGY, FACIES SUCCESSIONS AND CYCLICITY OF A SECTION OF THE JOGGINS FORMATION, JOGGINS, NOVA SCOTIA

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for the Degree of Bachelor of Science, Honours
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Abstract

The Joggins cliffs near Amherst, Nova Scotia, form one of the world's premiere Carboniferous coal-bearing exposures. A 145 m section was measured in the vicinity of Bell's Brook. The section is classified into three lithofacies groups (*sandstone, mudstone*, and *organic-rich sediments*) deposited in a fluvial to coastal (delta plain) environment. Multistoried channel sandstones up to 6 m thick represent delta distributary and anastomosing channel bodies, and sheet sandstones represent crevasse splay deposits. Heterolithic sandstones are either overbank levee deposits (in part stacked crevasse splays), or formed in subaqueous settings, possibly interdistributary bays, as a result of repeated crevassing. Grey clay-rich mudstones classify as "seat earths" or *Gleysol* paleosols and grey platy mudstones are hydromorphic soils that experienced less vegetative activity. Red mudstones are *Vertisols* formed under seasonal, oxidizing conditions. Carbonaceous shales are clastic swamp deposits and are associated with coals (*Histosol*) formed in peat mires. A single carbonaceous, shell-rich limestone formed after a major transgressive event which flooded a peat mire.

The rock types are grouped into two facies successions: *wetland facies succession* (coastal plain deposit) and *dryland facies succession* (alluvial plain deposit). The two successions alternate up section in regular intervals between 10-47 m thick. The wetland succession represents an interdistributary bay fill or progradation of delta lobes in areas close to major river mouths. A distinct feature is composite units, up to 15 m thick, that commence with a flooding surface (coal, grey shale, carbonaceous shale) and coarsen upwards through grey shale to stacked sandstones with in situ lycopsid trunks and *Calamites*; they are capped with grey paleosols. The dryland succession represents a relative drop in groundwater levels, generating a well drained flood plain with intermittent influx of sediment in sheet flows (crevasse splays). Boundaries between the red and grey successions are gradational, and the strata comprise progradational (grey to red upwards) and retrogradational (red to grey) parasequence sets. Sequence boundaries could not be identified. The cause of cyclicity cannot be determined with certainty, but tectonic and glacio-eustatic (allocyclic) effects are implicated, coupled with climatic and autocyclic factors (delta switching or channel migration).

Key Words: lithofacies, delta plain, facies succession, cyclicity, allocyclic and autocyclic effects

.... I dedicate this thesis to Jennifer and my family for their patience and understanding during this thesis and the last five years of academia at Dalhousie University

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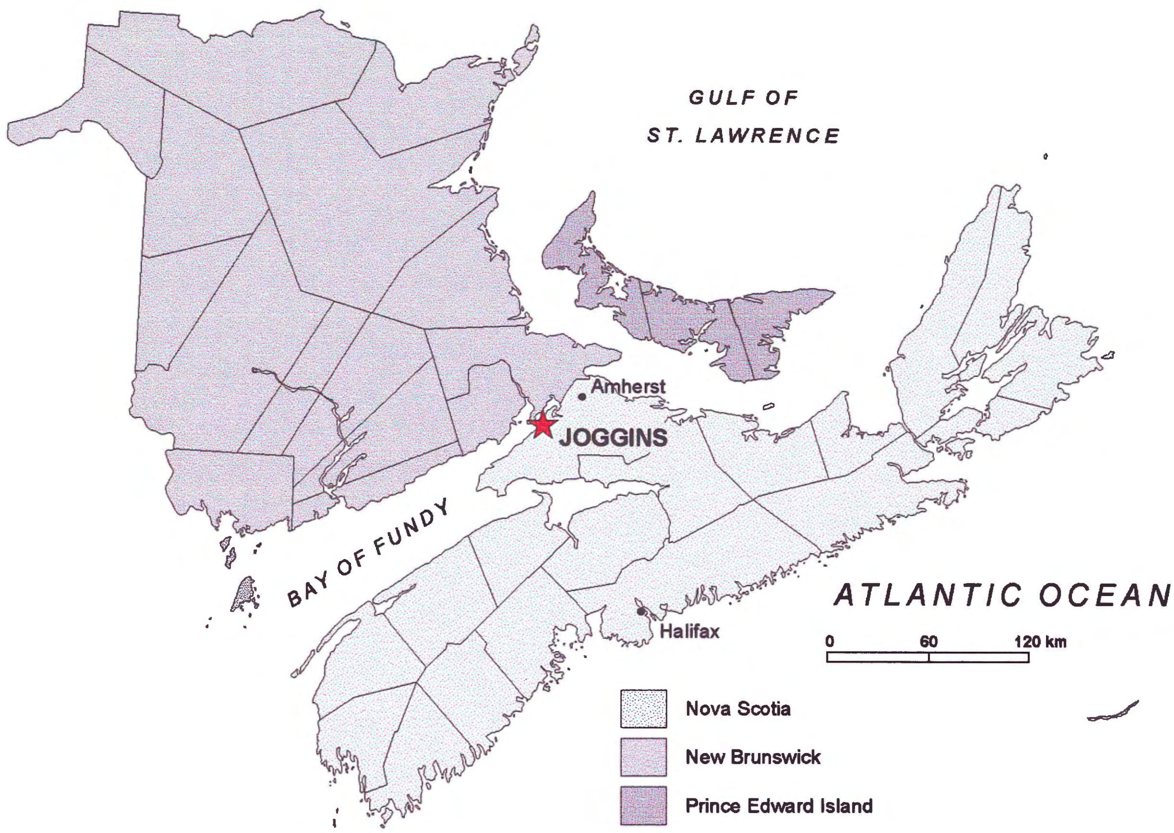
CHAPTER 1: INTRODUCTION

1.1 Geological Background

1.1.1 Joggins section

The Joggins section is located near the village of Joggins in Cumberland County, Nova Scotia. The section is exposed on the Chignecto Bay (Bay of Fundy) Coast between Lower Cove and Ragged Reef Point (Fig 1.1). The almost continuous section exposes approximately 1400 m of Carboniferous strata along 6 km of coastline (Gibling, 1987). The Joggins section forms part of the Cumberland Group which is up to 3900 m thick in the incomplete type section and locally may be in excess of 5000 m thick (Ryan et al., 1994).

There have been many previous attempts at dividing the Joggins section into stratigraphic subdivisions. Logan (1845) subdivided the section into divisions 3 and 4 (descending order) based on his work in the Joggins Section. Division 4 of the section extends from Hardscrabble Point (Coal Mine Point) to MacCarrons River and is approximately 774 m in stratigraphic thickness. Division 3 extends from MacCarrons River to Ragged Reef Point and is approximately 650 m thick (Fig 1.2). Bell (1944) combined Logan's division 3 and 4 into a formal stratigraphic division called the Joggins Formation. This name was not used frequently until Ryan et al. (1991) updated the lithostratigraphic divisions of the Cumberland Group. The Joggins section currently divides into the Joggins Formation and Springhill Mines Formation. These stratigraphic terms are officially used in this thesis to describe the Joggins section.



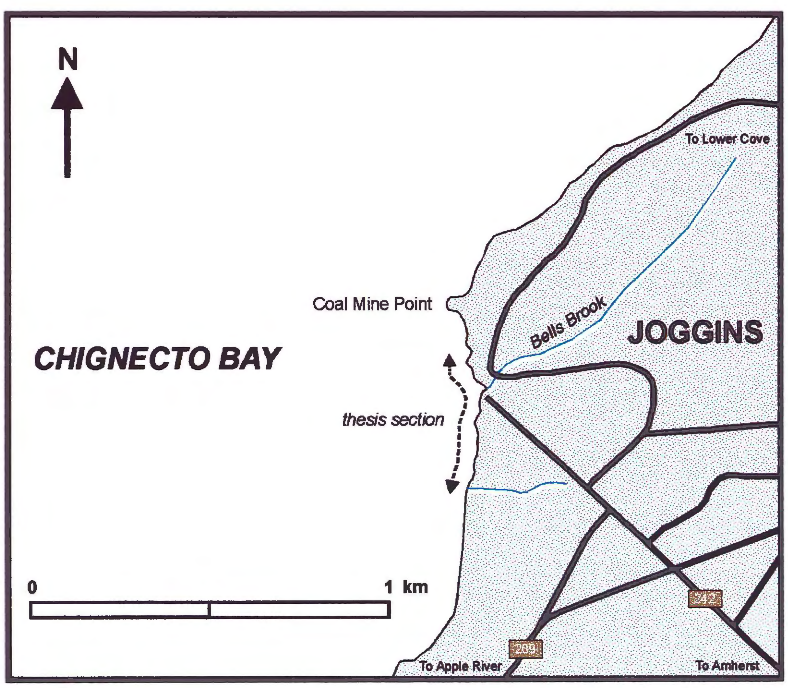


Fig 1.1 Location map for the Joggins area and the thesis study area

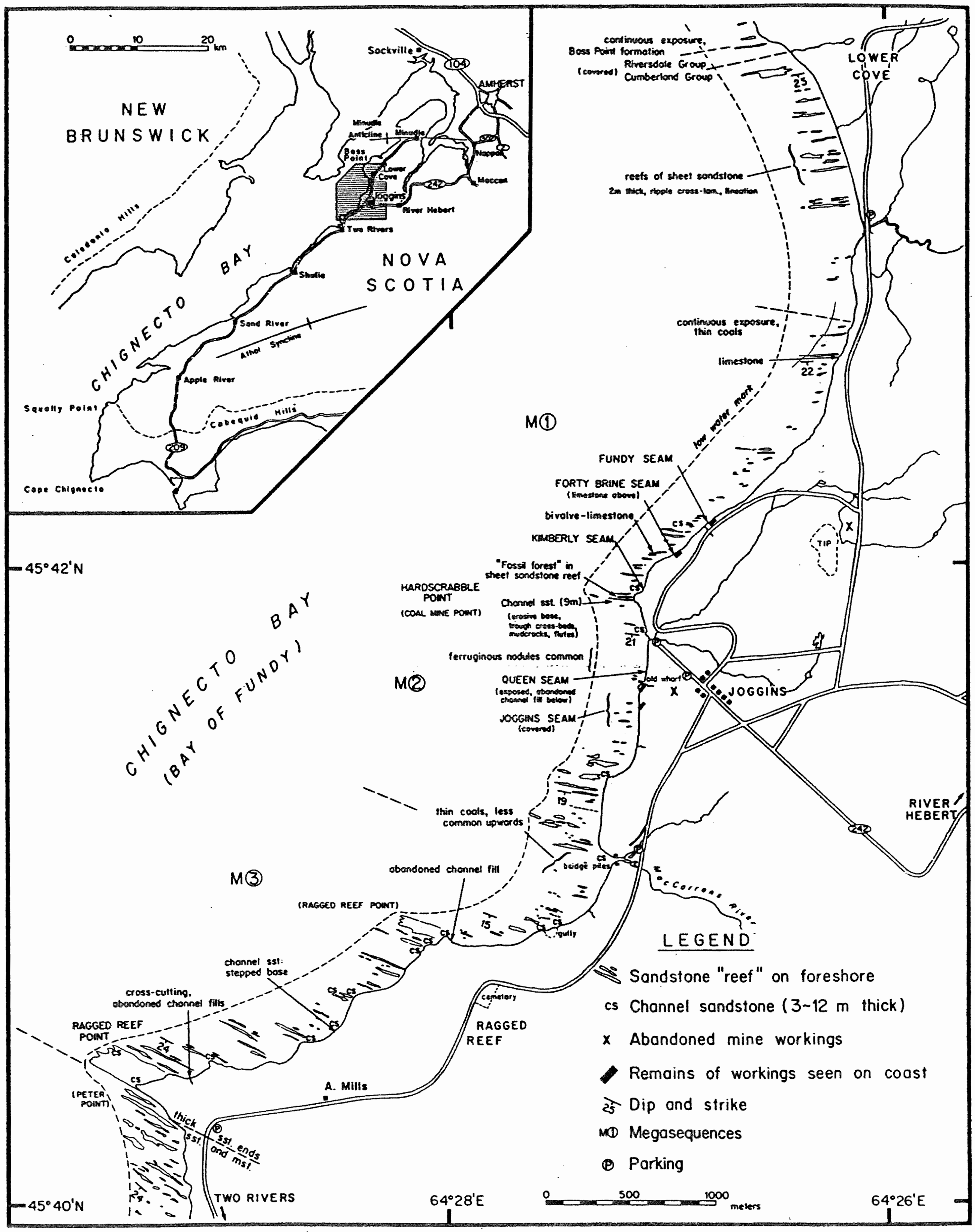


Fig 1.2 Geological features of the Joggins section (Gibling, 1987)

1.1.2 Geology of the Cumberland Group

The Joggins and Springhill Mines Formations belong to the Cumberland Group of Late Carboniferous, late Westphalian A to Middle Westphalian B (Pennsylvanian) age (Ryan et. al., 1991). These rocks lie on the gently dipping (~25°) northern limb of the Athol Syncline and are relatively undeformed. The Cumberland Group formed in the Cumberland Basin between the Cobequid Hills of Nova Scotia to the south, and the Caledonia Hills of New Brunswick to the northwest. The Cumberland Basin is the largest onshore coal basin in eastern Canada (Archer et. al., 1995), formed during extremely rapid basin filling resulting from tectonically induced subsidence. The Cumberland Basin formed part of the extensive Maritimes Basin during the Late Carboniferous, and was subjected to active subsidence associated with major strike-slip faulting between the Late Devonian and Early Permian, following the Acadian Orogeny (Gibling, 1987). The Cumberland Group contains seven formations (in ascending order): (1) Claremont, (2) Boss Point, (3) Polly Brook, (4) Joggins, (5) Springhill Mines *(MacCarron's River Member)*, (6) Ragged Reef, and (7) Malagash (Ryan et al., 1991).

The following is a general summary of the geology of the Cumberland Group based on other authors work in the area. The strata of this group are mainly continental in origin and formed in a predominantly alluvial environment. The Claremont Formation is characterized by poorly sorted boulder to pebble polymictic conglomerate indicating a proximal, high relief, alluvial fan deposit. The sandstone-dominated Boss Point Formation has multistoried and multilateral sandstone, and conglomerate channel deposits. This deposit is regarded as a braided stream facies assemblage (see Plint and Browne, 1994; Ryan et al., 1994). The Polly Brook Formation consists of coarsening upward cycles of polymictic cobble to pebble conglomerate and downflow coarse-grained sandstone (see Calder, 1994). The sequence decreases in overall bed thickness and clast size, and shows crude horizontal stratification northward away from the Cobequid Hills. This formation is interpreted as a transition between a proximal and a distal alluvial fan environment. The Joggins Formation consists of red and grey mudstone and grey sandstone, with thick coals, and dark grey carbonaceous limestones. The cyclic sequences contains thick channel sandstone units, and alternate beds of up to ~1 m thick sandstone, thick mudstones, and thin bands of coal and limestone. Thin sheet sandstones contain many fossils such as large lycopsid tree trunks, *Stigmaria* roots, *Calamites*, *Cordaites*, and trackways of the terrestrial arthropod *Arthropleura*. The Joggins Formation is interpreted as an anastomosing/meandering river transition within an alluvial flood plain or delta plain setting. The Springhill Mines Formation comprises multilateral and multistoried channel sandstones interpreted as an anastomosing channel system of moderate sinuosity. The Ragged Reef Formation consists of a cobble to pebble conglomerate and coarse grained sandstone member, and a distal, finer grained sandstone and redbed Athol member with few thin conglomerate beds. The Ragged Reef Formation represents a transition from marginal braided streams to meandering streams within the stable area of the basin. The sandstone-dominated Malagash Formation contains multilateral and multistoried sandstone and conglomerate channel deposits. The channel deposits have a crude fining upward trend and paleocurrent directions are unimodal. Freshwater limestone is interbedded with overbank deposits. This formation is interpreted as a sandy braided stream facies assemblage associated with a shallow lacustrine facies assemblage (Ryan et al., 1994).

1.1.3 Previous work

The Joggins section is regarded as one of the finest Carboniferous exposures in the world. Much work has been done on this section by such notable geologists as Sir Charles Lyell, Sir William Logan, and Sir J. William Dawson. One of the first to describe the Joggins section was Logan for the first Geological Survey of Canada project in 1842. Logan (1845) was the first to describe the coal-bearing sequences in detail and he divided the Carboniferous strata into 8 divisions. He further subdivided the beds into coal groups which had different characteristics. Logan also identified many plant fossils (*Stigmaria*, *Calamites*, *Sigillaria*, *Cyperites*, etc.) in his detailed bed by bed descriptions. Dawson and Lyell further described the coal horizons within the Joggins section, and noted the cyclic nature of the sediments. Dawson (1878) described cycles that showed alternation between marine (sediments with no coal) and non-marine (coal-bearing sediments) conditions. During the 1840's and 1850's, using Logan's descriptions, Dawson identified in detail the plant and animal fossils and discovered small terrestrial vertebrates entombed in formerly hollow tree stumps. He later published his work in Acadian Geology (1855) which brought further attention to the Joggins section. Bell (1944) introduced new stratigraphic names for the Cumberland basin strata, and recognized the complex depositional conditions and laterally variable sedimentary sequences. Stratigraphic correlations within the basin have been aided by detailed palynostratigraphy and seismic studies. Biostratigraphic markers (spores and other fossils) are currently under investigation to provide a more precise age assignment.

Despite detailed work, the depositional setting of the Joggins section received infrequent attention until Duff and Walton (1973) interpreted part of the coal bearing section (Logan's Division 4, Joggins Formation) as a delta-plain deposit based on the presence of bivalves (*Naiadites* and *Curvirimula*) that were inferred to have lived in brackish conditions. Way (1968) and Kaplan (1980) described the section between MacCarrons River and Ragged Reef Point (Logan's Division 3, Springhill Mines Formation) as a fluvial, meandering river setting. More recent work by Rust et al. (1984) has described Logan's Division 3 as an anastomosing-fluvial system based on the vertically accreted channel sandstones, abundant crevasse-splay sandstones, and other overbank deposits present. Archer et al. (1995) have recently concluded that parts of the Joggins section were deposited in brackish water. This inference is based on paleobiological evidence from a trace-fossil assemblage (which includes *Cochlichnus*, *Kouphichnium*, and *Trepichnus*) that reflects paleodeposition within fluvial systems exposed to marine influences. Other evidence includes the presence in two samples of agglutinated foraminifera characteristic of brackish water conditions. Recently, Calder (1998) has proposed a re-interpretation of the paleoecology suggesting that many marine fauna may have nearshore marine affinities.

1.2 Objectives

The purpose of this thesis is to examine in detail the sedimentological and paleontological features of a section of the Joggins Formation. Based on these observations an accurate facies model can be derived describing the facies successions, cyclicity, and depositional environment of the section. The sedimentological evidence is used to interpret a delta plain depositional environment. The facies model is based on the data collected during this project, previous work on the Joggins section, and other evidence from various authors studying a similar depositional environment. Allocyclic and autocyclic effects on cyclicity are discussed, and a general model for relative base level fluctuations in the thesis section is described.

1.3 Scope

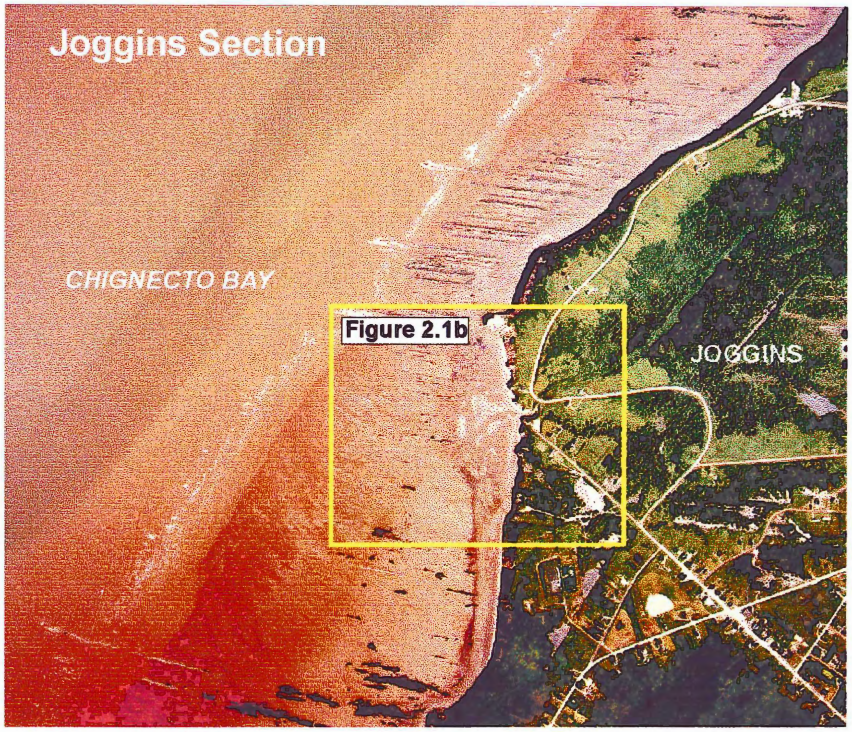
This thesis will closely examine the strata of the Coal Mine Point Member and Bells Brook Member of the Joggins Formation. The thesis study area stretches between the upper part of the Coal Mine Point Member (*Logan's Division 4, Coal-group 13*) and above the Joggins Seam (*Logan's Division 4, Coal-group 6*). This part of the Joggins section was selected in part to add to the detailed bed-by-bed description of the entire section being undertaken by Gibling and others; the first revised section description since that of Logan (1845). This thesis presents descriptive accounts of the sedimentology and paleontology and will not present any geochemical study on fossil species or sediments. Paleocurrent evidence is used to support flow directions and sedimentological models for channel morphology. Paleontological study is restricted to observations of organic/sediment relations, and incorporates previous identifications of taxa where available.

CHAPTER 2: SEDIMENTOLOGY AND FACIES INTERPRETATION

2.1 Introduction

The section measured for the present study has a 145 m stratigraphic thickness along a 400 m length of cliff section within the Joggins Formation (*Division 4 of Logan, 1845*) (Fig 2.1). The section consists of grey sandstone, red and grey mudstone, dark grey to black carbonaceous shale, minor coal, ferruginous and calcareous carbonate nodules, and one dark grey carbonaceous limestone at the top of the section. The mudstones generally show alternate red and grey intervals 30 to 40 m thick. The grey intervals contain thin coal, shell limestone, carbonaceous shale and variably-sized sandstone units, with bioturbated mudstones and carbonate nodules. The red intervals contain thick, less bioturbated mudstones with carbonate nodules, coarsening-upward sheet sands, few organic beds (coal), and thin grey sandstones (Fig 2.2).

The stratigraphic section can be classified into three lithofacies groups: (1) *sandstone*, (2) *mudstone* and (3) *organic-rich facies*. The sandstone lithofacies group contains: multi-storied sandstone, sheet sandstone and heterolithic sandstone facies types. The mudstone lithofacies group contains: grey clayey mudstone, grey platy mudstone, grey friable mudstone, red platy mudstone, and red friable mudstone facies types. The organic-rich lithofacies group contains: carbonaceous shale, coal, and limestone facies types. This chapter describes the sedimentology and paleontology of each lithofacies types, and provides a facies interpretation.



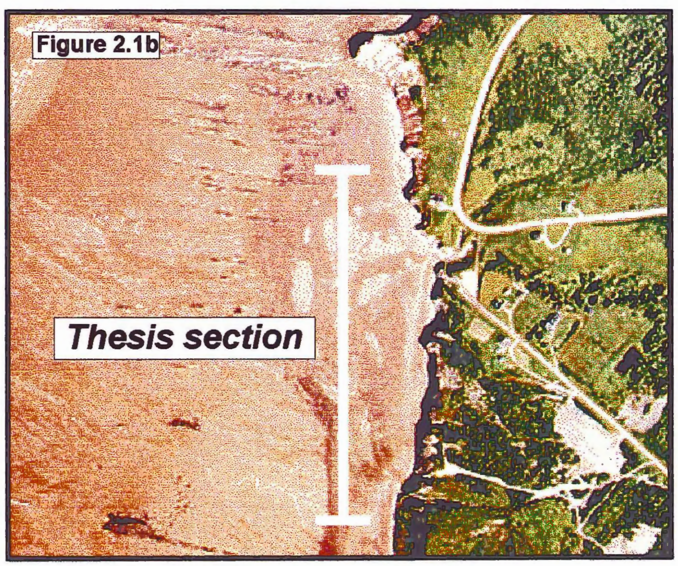


Fig 2.1 Air photo for the Joggins thesis section (Joggins Formation). Airphoto No: 85-07-23 1:10000 21H/09 Nova Scotia Department of Natural Resources.

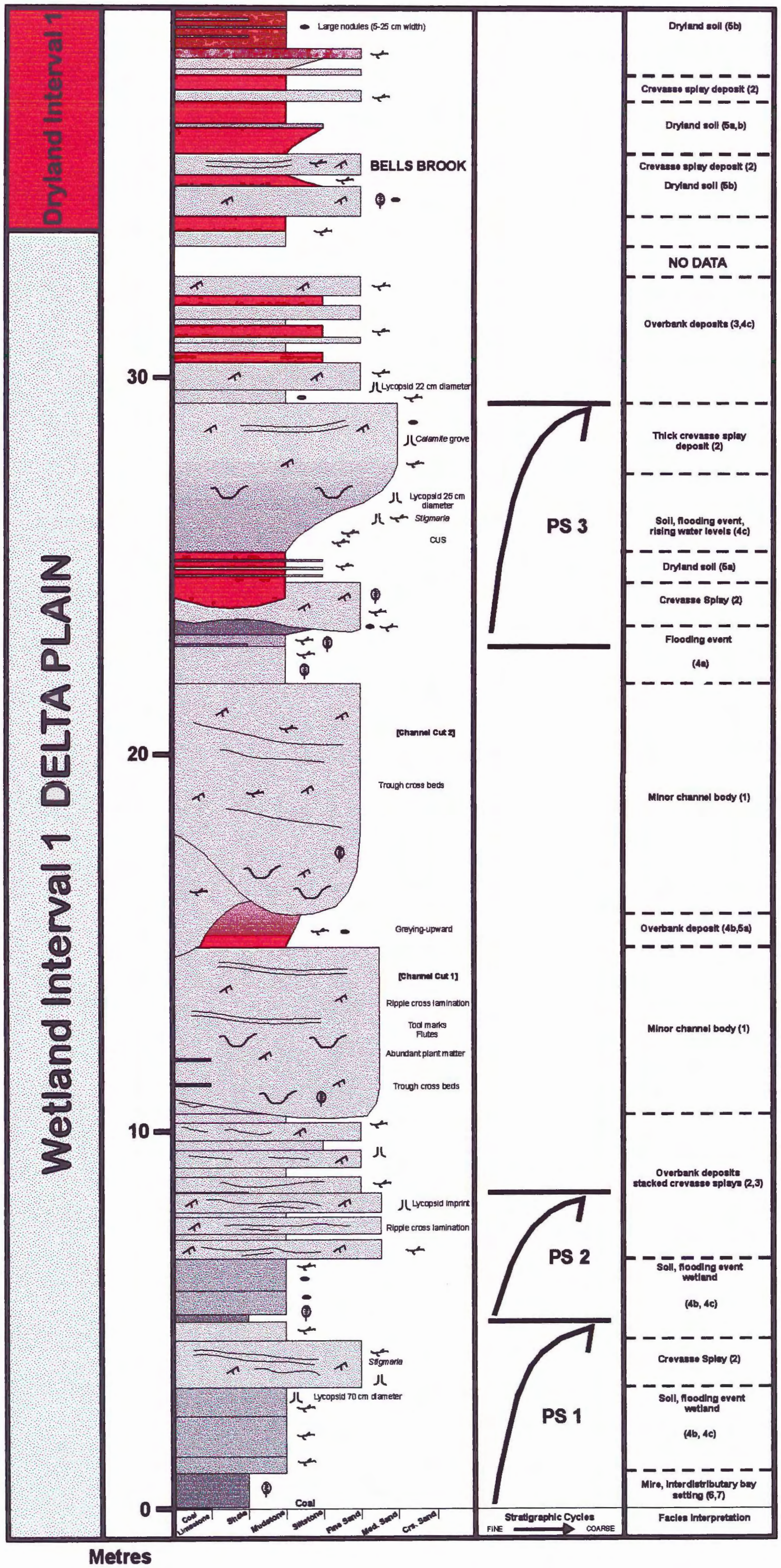
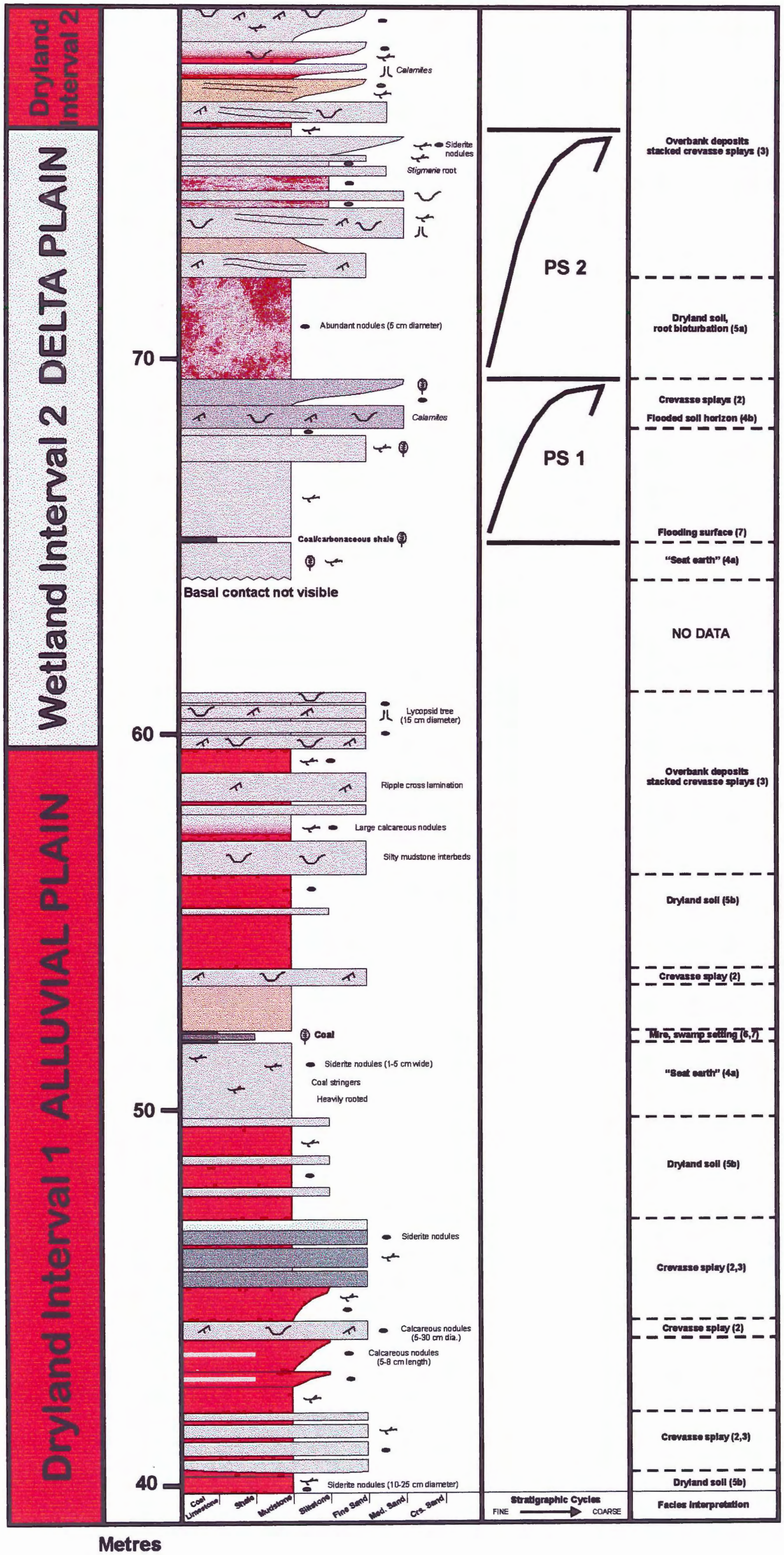
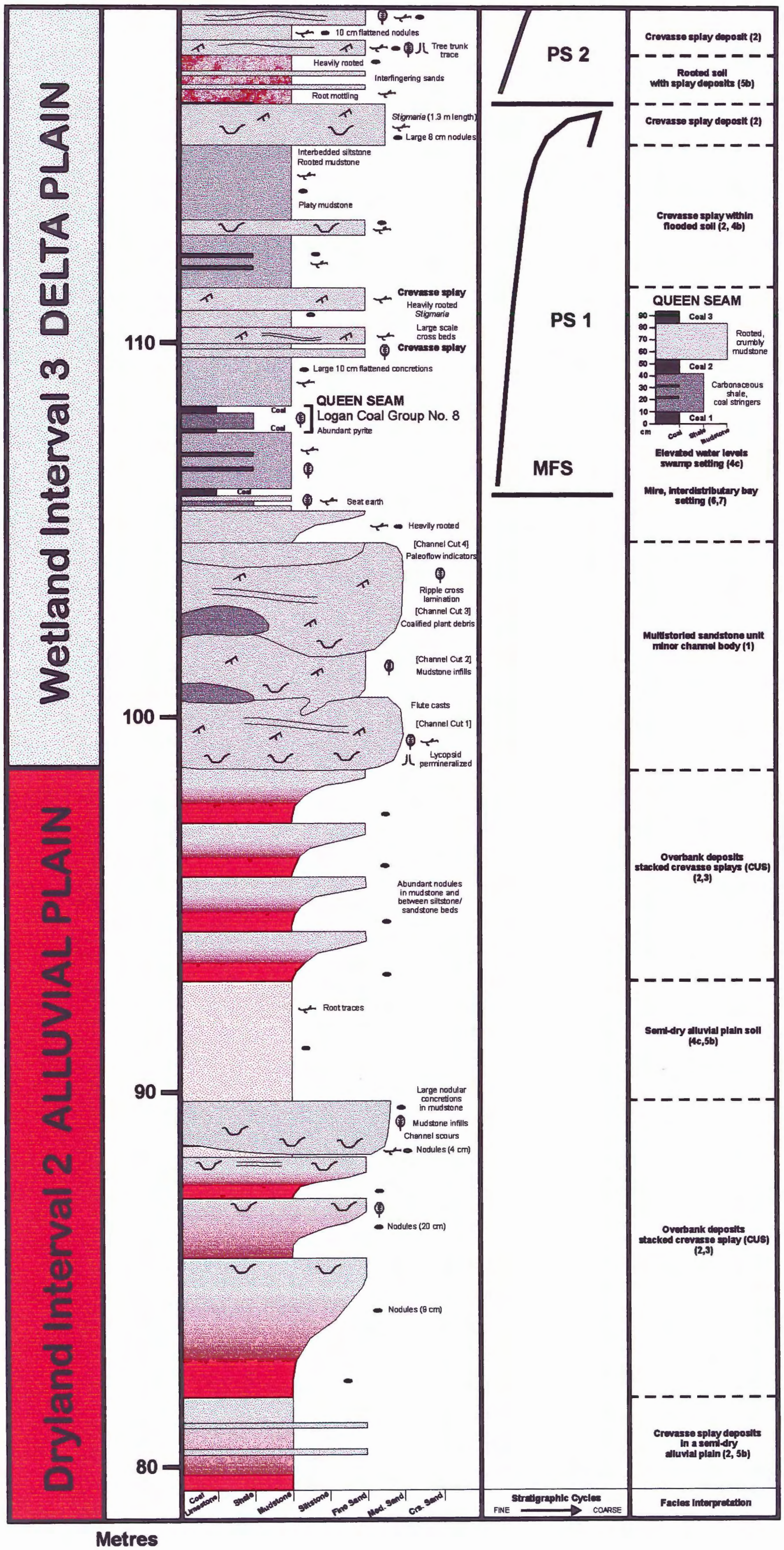
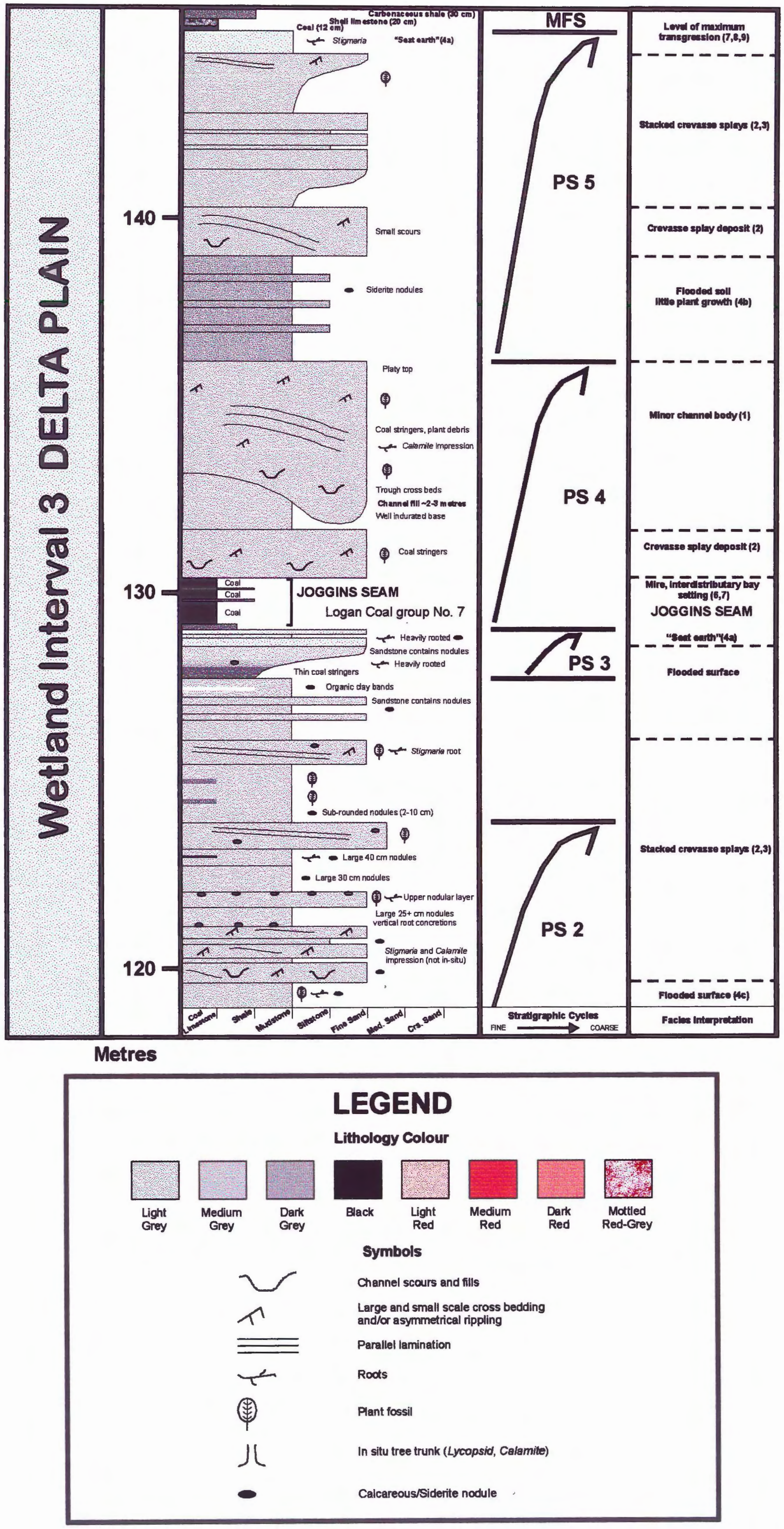


Fig 2.2 Stratigraphic and facies successions column for the Joggins thesis section (145 m). Column divided into next four sections. Legend is on page 14.. *Note*: PS = Parasequence, MFS = Major flooding surface.


Dryland Interval 2
Wetland Interval 2 DELTA PLAIN
Dryland Interval 1 ALLUVIAL PLAIN
70
60
50
40
Metres
Calamites
Siderite nodules
Stigmaria root
Abundant nodules (5 cm diameter)
Calamites
Coal/carbonaceous shale
Basal contact not visible
Lycopsid tree (15 cm diameter)
Ripple cross lamination
Large calcareous nodules
Silty mudstone interbeds
Coal
Siderite nodules (1-5 cm wide)
Coal stringers
Heavily rooted
Siderite nodules
Calcareous nodules (5-30 cm dia.)
Calcareous nodules (5-8 cm length)
Siderite nodules (10-25 cm diameter)
Coal Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
PS 2
PS 1
Stratigraphic Cycles
FINE
COARSE
Overbank deposits stacked crevasse splays (3)
Dryland soil, root bioturbation (5a)
Crevasse splays (2)
Flooded soil horizon (4b)
Flooding surface (7)
"Seat earth" (4a)
NO DATA
Overbank deposits stacked crevasse splays (3)
Dryland soil (5b)
Crevasse splay (2)
Mire, swamp setting (6,7)
"Seat earth" (4a)
Dryland soil (5b)
Crevasse splay (2,3)
Crevasse splay (2)
Crevasse splay (2,3)
Dryland soil (5b)
Facies Interpretation



Wetland Interval 3 DELTA PLAIN
Dryland Interval 2 ALLUVIAL PLAIN
110
100
90
80
Metres
10 cm flattened nodules
Tree trunk trace
Heavily rooted
Interfingering sands
Root mottling
Stigmaria (1.3 m length)
Large 8 cm nodules
Interbedded siltstone
Rooted mudstone
Platy mudstone
Crevasse splay
Heavily rooted
Stigmaria
Large scale cross beds
Crevasse splay
Large 10 cm flattened concretions
QUEEN SEAM
Logan Coal Group No. 8
Abundant pyrite
Coal
Seat earth
Heavily rooted
[Channel Cut 4]
Paleoflow indicators
Ripple cross lamination
[Channel Cut 3]
Coalified plant debris
[Channel Cut 2]
Mudstone infills
Flute casts
[Channel Cut 1]
Lycopsid permineralized
Abundant nodules in mudstone and between siltstone/ sandstone beds
Root traces
Large nodular concretions in mudstone
Mudstone infills
Channel scours
Nodules (4 cm)
Nodules (20 cm)
Nodules (9 cm)
Coal
Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
PS 2
PS 1
MFS
Stratigraphic Cycles
FINE
COARSE
Crevasse splay deposit (2)
Rooted soil with splay deposits (5b)
Crevasse splay deposit (2)
Crevasse splay within flooded soil (2, 4b)
QUEEN SEAM
Coal 3
Rooted, crumbly mudstone
Coal 2
Carbonaceous shale, coal stringers
Coal 1
cm
Elevated water levels swamp setting (4c)
Mire, interdistributary bay setting (6,7)
Multistoried sandstone unit minor channel body (1)
Overbank deposits stacked crevasse splays (CUS) (2,3)
Semi-dry alluvial plain soil (4c,5b)
Overbank deposits stacked crevasse splay (CUS) (2,3)
Crevasse splay deposits in a semi-dry alluvial plain (2, 5b)
Facies Interpretation



Wetland Interval 3 DELTA PLAIN
Metres
120
130
140
Carbonaceous shale (30 cm)
Shell limestone (20 cm)
Coal (12 cm)
Stigmaria
"Seat earth"(4a)
Small scours
Siderite nodules
Platy top
Coal stringers, plant debris
Calamite impression
Trough cross beds
Channel fill ~2-3 metres
Well indurated base
Coal stringers
Coal
Coal
Coal
JOGGINS SEAM
Logan Coal group No. 7
Heavily rooted
Sandstone contains nodules
Heavily rooted
Thin coal stringers
Organic clay bands
Sandstone contains nodules
Stigmaria root
Sub-rounded nodules (2-10 cm)
Large 40 cm nodules
Large 30 cm nodules
Upper nodular layer
Large 25+ cm nodules
vertical root concretions
Stigmaria and Calamite
impression (not in-situ)
Coal Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
MFS
PS 5
PS 4
PS 3
PS 2
Stratigraphic Cycles
FINE
COARSE
Level of maximum transgression (7,8,9)
Stacked crevasse splays (2,3)
Crevasse splay deposit (2)
Flooded soil
little plant growth (4b)
Minor channel body (1)
Crevasse splay deposit (2)
Mire, interdistributary bay setting (6,7)
JOGGINS SEAM
"Seat earth"(4a)
Flooded surface
Stacked crevasse splays (2,3)
Flooded surface (4c)
Facies Interpretation
LEGEND
Lithology Colour
Light Grey
Medium Grey
Dark Grey
Black
Light Red
Medium Red
Dark Red
Mottled Red-Grey
Symbols
Channel scours and fills
Large and small scale cross bedding and/or asymmetrical rippling
Parallel lamination
Roots
Plant fossil
In situ tree trunk (Lycopsid, Calamite)
Calcareous/Siderite nodule

2.2 Sandstone Lithofacies (Table 2.1)

2.2.1 Multistoried sandstone (*Facies 1*)

The section contains two light grey, fine to medium-grained multi-storied sandstone units, ranging from 4 to 6 m in thickness (Fig 2.2). These units consist of numerous stacked (vertically accreted) sandstone bodies with erosional bases, and minor interbedded siltstones and mudstones (Fig 2.3). The basal beds (~1-2 m thick) are heterolithic (alternate sandstone and mudstone beds), and can contain pebble lag deposits and abundant plant fossil material such as leaf fossils and permineralized logs (Fig 2.4). In situ lycopsid tree trunks (~10 cm diameter) are rare in these sandstones. Thick sandstone beds above have interbedded grey mudstones and carbonaceous shales (coal stringers common), vary from 1-2 m in thickness, are well indurated, and have small channel scours ($\leq$ 1 m width) evident in the cut face. The channel scours contain macerated plant remains (*Cordaites*) at their base and can also contain logs (Fig 2.5). The abundance of macerated plant debris at the base of the channel sets and small erosional scours indicate the channel incised through a heavily vegetated surface (or swamp) where plant material was abundant.

The thick sandstone beds have wavy to planar surfaces, contain large-scale trough cross beds, and faint parallel laminae (Fig 2.6). Ridge and furrow structures on many bed surfaces are indicative of internal cross-beds, where these are indistinct in cross section. Other sedimentological features include tool marks, flute casts and small erosional grooves.

Paleocurrent data, interpreted from ridge and furrow, and parting lineations on bed surfaces, suggest multi-directional flow resulting from variable flow directions (Fig 2.7). Paleoflow measurements from the entire section (sheet and channel sandstones) indicate a general flow direction toward the northeast, but multi-directional flow in individual channel sandstones (Fig 2.8). The sheet sandstones tend to show more unidirectional flow conditions. The presence of

Table 2.1: **Sandstone Lithofacies**

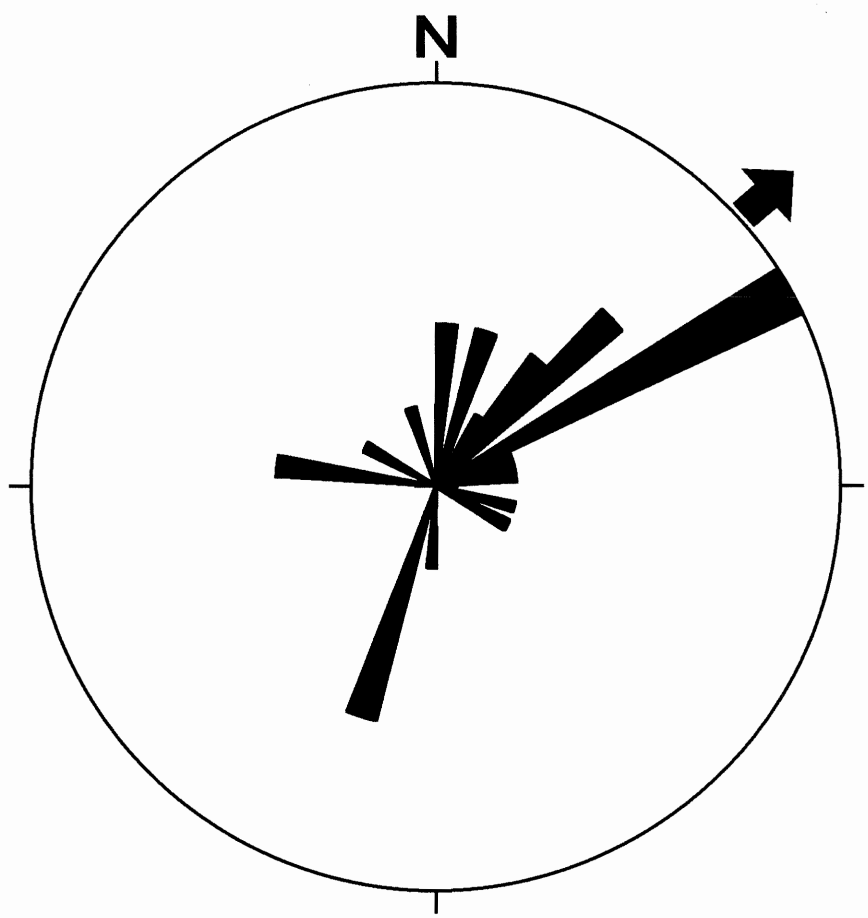
#	Facies Type	Average Thickness	Grain Size	Colour	Bed Style	Sedimentary Structures	Fossils	Other	Lithofacies Interpretation
1	***Multistoried sandstones***	4 to 6 m	fine to medium sand	light grey	numerous sandstone subunits with siltstone and mudstone interbeds (basal beds), pebble lag deposits, small channel fills, thick upper sandstones with trough cross beds	large scale cross beds, faint parallel lamination, ripple cross lamination, tool and flute casts, erosional grooves, ridge and furrow structures	permineralized logs found at the base of the channel fill, abundant plant fossil fragments (*Cordaites*), no root traces	paleocurrent flow multi-directional, thin carbonaceous shale and coal	small-scale fluvial channel bodies, highly sinuous channel (related to anastomosing river type)
2	***Sheet sandstones***	variable: thin sheet sandstones 10 cm to 1.0 m, thick sheet sandstones 1 to 3.5 m	fine to medium sand	light to medium grey, red-grey	undulating and planar bedding surfaces, interbedded mudstone and siltstone, small channel fills (1-2 m thick)	strong cross and parallel lamination, current lineation, ripple cross lamination, groove casts	*Calamites* insitu, small to large root fossils (*Stigmaria*), vertical in situ lycopsid tree trunks and trunk impressions (10-25 cm diameter)	siderite nodules rare to common, paleocurrent flow indicators rare to common (unidirectional flow), mottling	crevasse splay deposit
3	***Heterolithic sandstone units***	variable from 2 to 7 m units	fine to medium sand	light grey, green-grey sandstone/ siltstone, red and grey mudstone	numerous interbedded units of mudstone and siltstone (10-70 cm thick), undulating to planar sandstone bed surfaces, bioturbated, friable and platy mudstone, thin grey clay and carbon-aceous shale layers common	erosional grooves, strong to faint small scale cross lamination and parallel lamination, minor channel fills (~0.50 m)	root fossils and traces rare to abundant in mudstones, plant fossil remains, *Calamites*, *Stigmaria*, in situ lycopsid tree trunks rare to common	siderite nodules common, root mottling (mudstones and siltstones),	stacked crevasse splay deposits in dry to wet floodplain zone, root influence low to high

Fig 2.3 Multistoried channel body (~6 m thick). Carbonaceous shale and mudstone interbeds and scour fills, abundant macerated plant debris at the base of each sandstone unit. Note Queen Seam overlying the channel body.

Fig 2.4 Permineralized log at the base of the second major channel body unit in the section. Tree species unknown, but is a lycopsid (Scale 7 cm).

Fig 2.5 Channel sandstone slab containing *Cordaites* leaf mats.

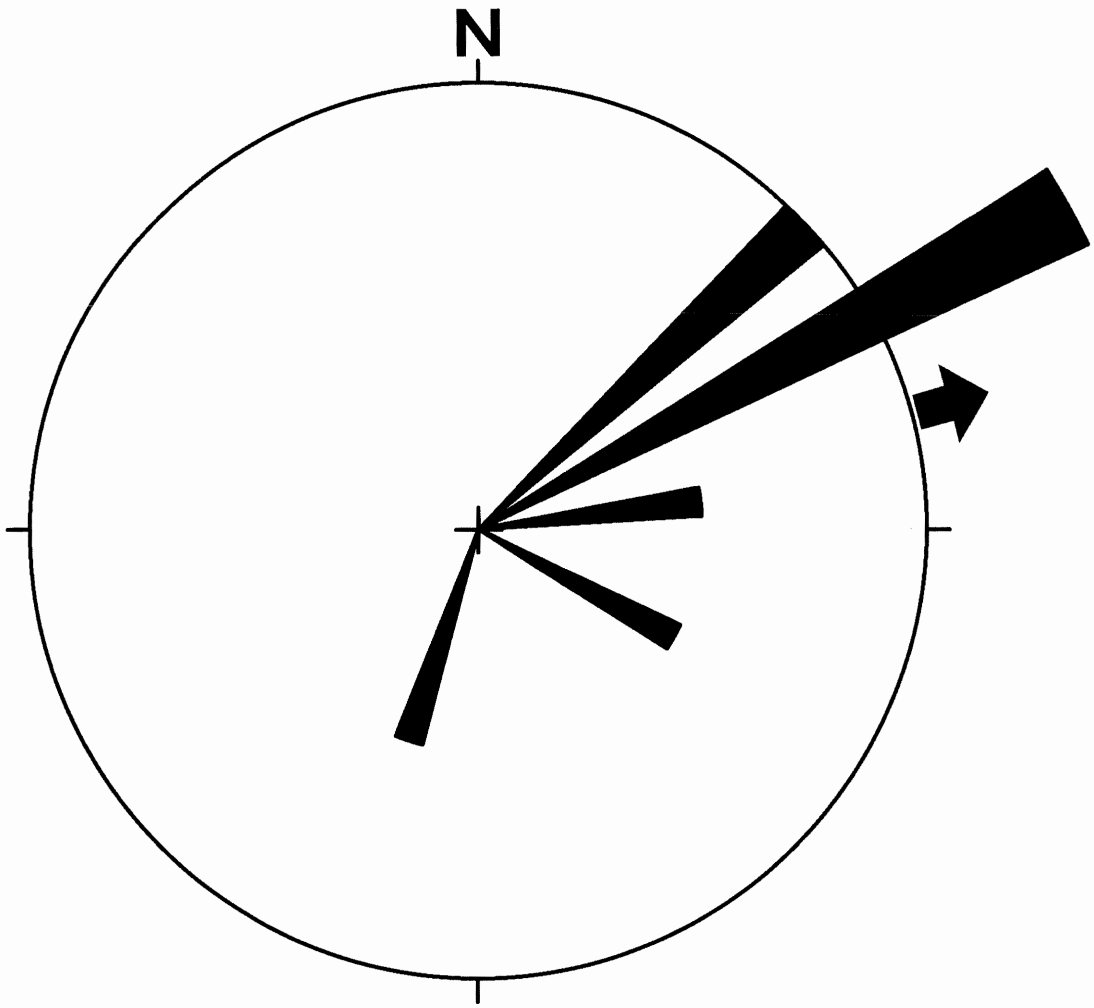
Fig 2.6 Rippling and cross laminae evident in cross section of a fine-medium grained sandstone with undulating bed surfaces. Note small *Calamite* stem at bottom of photo.



Rose Diagram			
N=28	Mean=48.46	R=0.463	

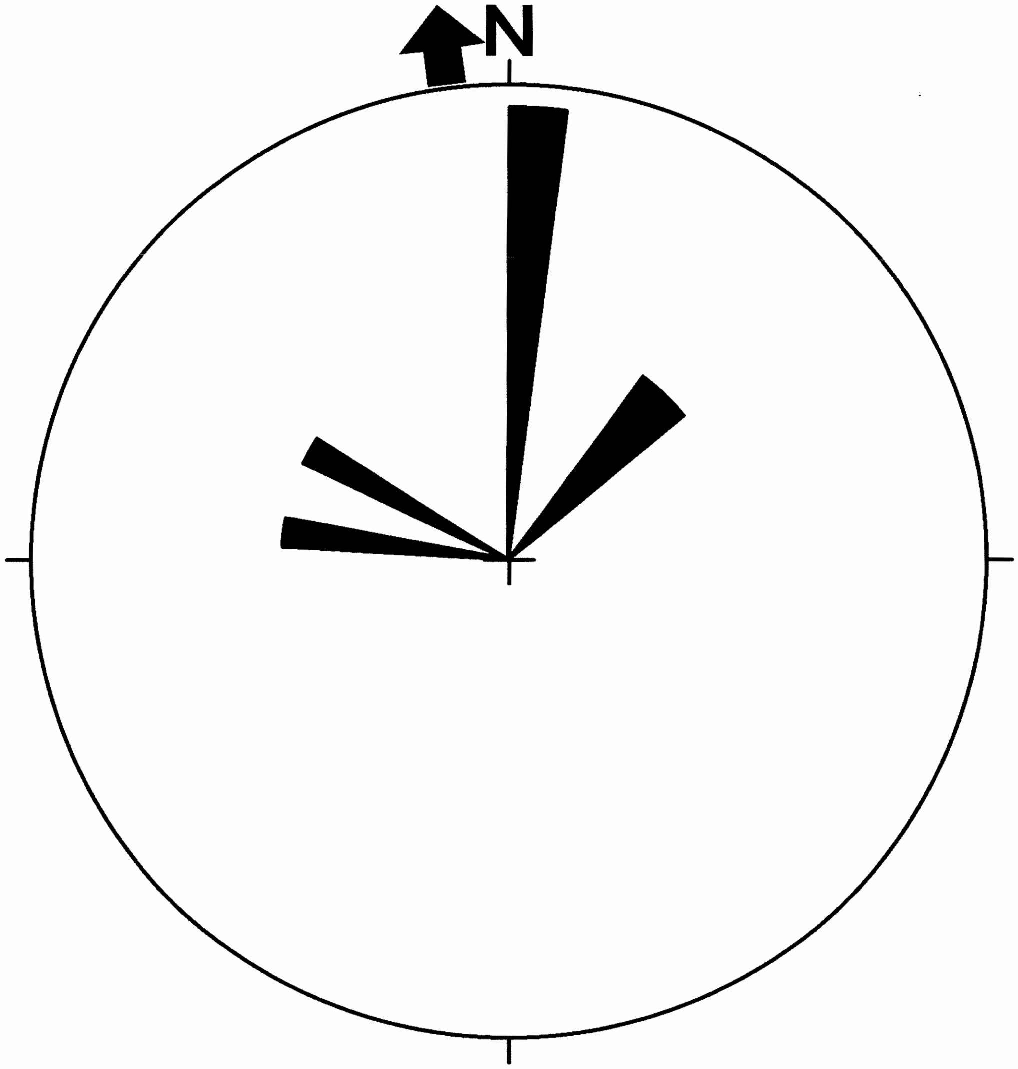
Fig 2.7 Paleocurrent data for whole section plotted on a Rose diagram. Paleoflow measurements are shown in table below according to lithological unit (see Appendix A). Arrow points to average paleoflow direction.

Bed #	**Ridge and Furrow**	**Parting Lineation** (not plotted above)	**Flute cast, other**
5	104°,18°,40°,60°,30°,70°		
9	20°,344°		
11 Channel Sand 1	117°,48°,196°,61°,59°,80°, 62°,50°	20°,46°	
17	185°,200°		
40	195°		
53	78°,2°,60°,280°		
62 Channel	40°,44°,296°		2°,274°



First Multistoried Sandstone			
N=8	Mean=74.95	R=0.741	

Fig 2.8a Paleoflow data for the 1st major multistoried channel sandstone (11 m upsection). Arrow points to average paleoflow direction.



Second Multistoried Sandstone			
N=6	Mean=352.52	R=0.671	

Fig 2.8b Paleoflow data for the 2nd major multistoried channel sandstone (98 m upsection) Arrow points to average paleoflow direction.

trough cross beds and asymmetrical rippling indicates a lower flow regime in the channel sandstones, with very rare upper flow regime indicated by parting lineations.

Past work on modern delta plain environments classify these multistoried sandstones as minor channel bodies formed in a coastal or alluvial plain setting (delta plain). The channel sandstones may indicate minor distributary channels which formed by crevassing (channel bank breaching) of major distributaries (Elliott, 1974; Fielding, 1986), or minor crevasse channels running perpendicular to distributary channels (Fielding, 1986; Tye and Coleman, 1989). During the crevassing process, sediment from a minor distributary channel is deposited through crevasse channels into numerous small, anastomosing streams which cut across the coastal plain or alluvial flood plain deposits (Tye and Coleman, 1989). Minor distributary channels show similarities to meandering streams with highly sinuous paths and some form of lateral accretion, but typically show no fining-upward cycles (Fielding, 1986). The crevasse channels are cut by erosive, turbulent flows emanating from small openings in distributary channel banks during a flood stage (Fielding, 1986). In a coastal plain setting, the channels eventually decelerate and settle into the deeper interdistributary waters depositing sheet-like crevasse splays (Fielding, 1984a) (Fig 2.9). Minor crevasse channels show evidence of being cut and filled during a single flood event, whereas others show a multistoried structure indicating episodic infilling.

2.2.2 Sheet sandstone (*Facies 2*)

The sheet sands vary from thin (10 cm to 1.0 m) to thick (1.0 to 3.5 m) bedded, light to medium grey, fine-grained bodies (Fig 2.2).

Thick-bedded sheet sandstones have undulating and planar-bedded surfaces, interbedded mudstone and siltstone, and can contain lenticular channel fills (1-2 m thick). The sandstones

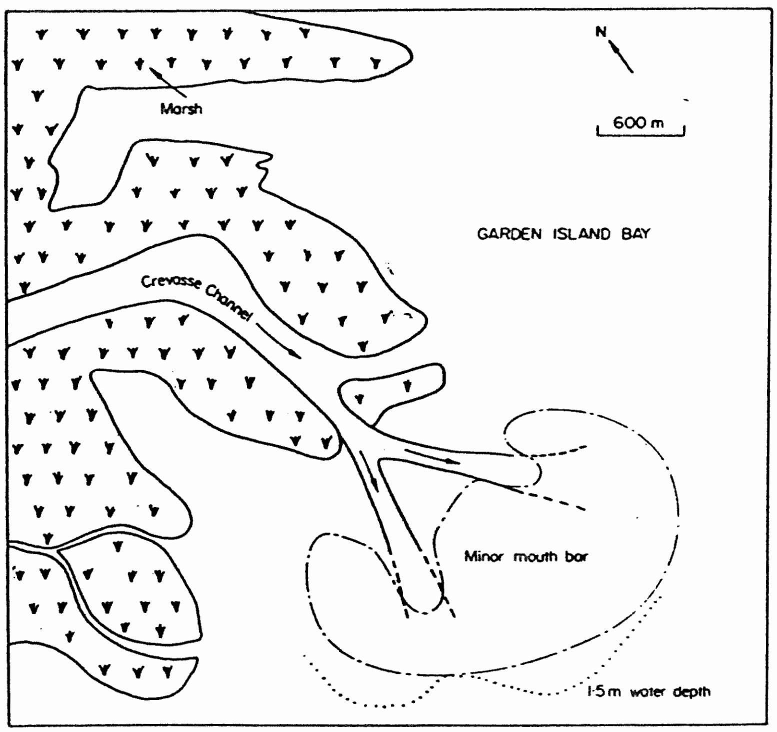


Fig 2.9 Crevasse channels decelerating and settling into deeper interdistributary waters depositing sheet-like crevasse splays (Elliott, 1974)

contain well defined parallel laminae, ripple cross lamination, current lineation, tool marks, and groove casts. Sparse paleocurrent flow indicators show fairly unidirectional flow. Carbonate nodules are rare to common in outcrop. Some beds gradually coarsen from siltstone to fine-grained sandstone resulting from an increase in flow velocity (Haszeldine, 1984).

Thin-bedded sheet sandstones show slightly undulating bedding surfaces, contain minor mudstone partings, and small lenticular channel fills or scours (10-50 cm thick). These sandstones contain parallel laminae and cross strata, and are commonly found interbedded within thick mudstone beds or heterolithic sand units (Fig 2.10).

The sheet sandstones contain various types of plant fossils, and are heavily rooted. The most common tree fossil is *Calamites*, usually found in situ (vertically in growth position) and averaging 5 cm in width. Less common are in situ sand-filled lycopsid tree trunks and impressions (averaging 10-25 cm in diameter). The larger sheet sandstones often contain scours caused by flow around standing lycopsid tree trunks (Fig 2.11). The most prominent root fossil is *Stigmaria* (5-10 cm width), rarely found attached to its original lycopsid tree trunk (Fig 2.12). These large roots commonly lie nearly horizontal with bedding and protrude abundant rootlets into the adjacent sediment.

Sheet sandstones are interpreted as crevasse splays deposited in interdistributary bays or lakes or on relatively dry floodplains. These sediment splays originate from minor crevasse channels, formed from the bank breaching (crevassing) of minor distributary channels during exceptional flood conditions. As the crevasse channel sediment flow decelerates as it enters deeper water and becomes unconfined, the transported sediment spreads to form lobe-shaped sand bodies (Elliott, 1974) (Fig 2.9). On open floodplains, the crevasse splays settle upon deceleration as sheet sands. Division of flow into anastomosing channels produces numerous sand lenses each separated by a

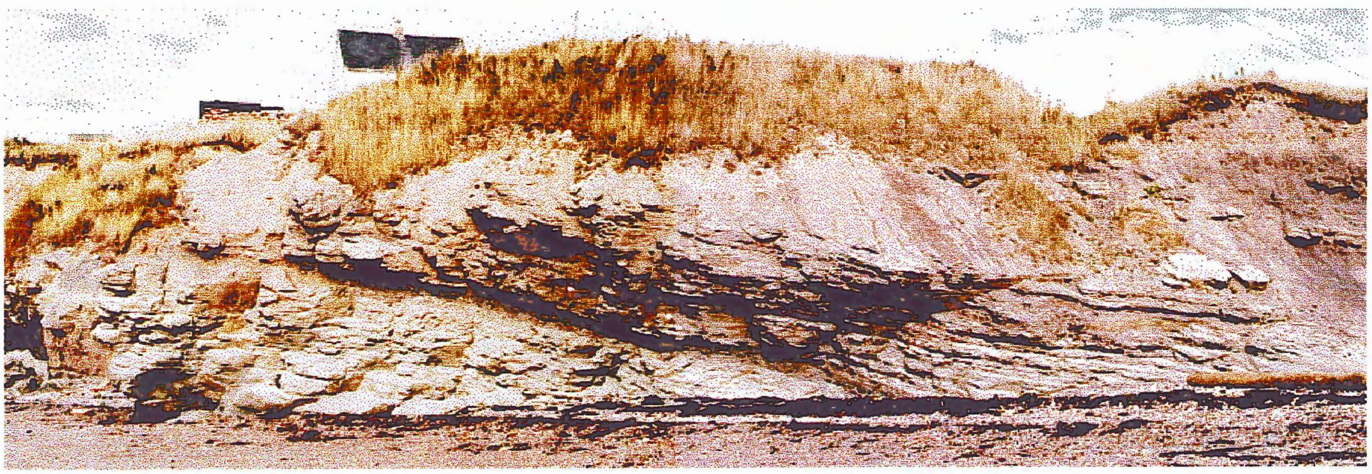


Fig 2.10 Thick sheet sandstone (crevasse splay) or channel with abundant in situ *Calamites*, lycopsids and interbedded mudstone. Unit has cross striae, and undulating bed surfaces. Unit found adjacent Bell's Brook near staircase (Cliff ~4 m high).

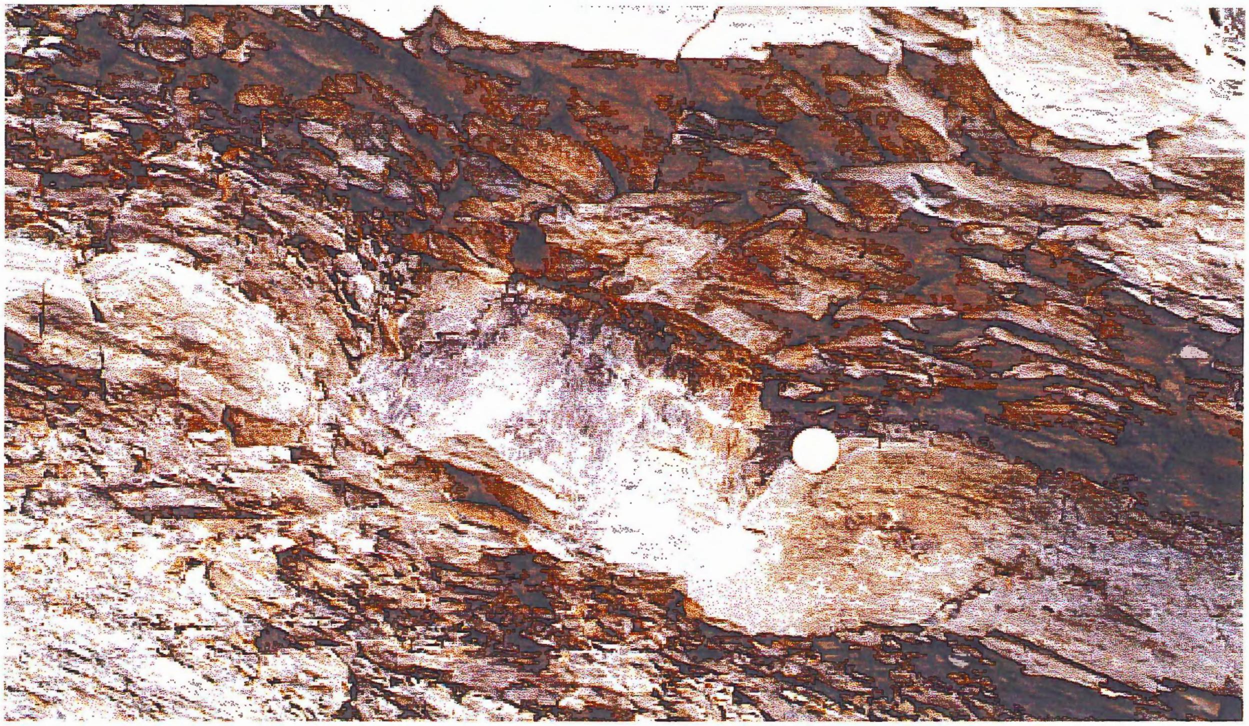


Fig 2.11 Sheet sandstone scoured from sediment flow around in situ lycopsid trunk (in middle of photo). Concave-upward bedding evident on the edges of the lycopsid trunk (~35 cm diameter).

Fig 2.12 Specimens of in situ *Stigmaria* root with main root stem and protruding rootlets (Scale 7 cm wide in top photo).

thin mudstone bed, while density currents deposit sheet-like sands (Elliott, 1974). *Calamites* and lycopsids are indicative of overbank deposits in shallow subaqueous conditions, unaffected by strong currents from the adjacent channels.

2.2.3 Heterolithic sandstone (*Facies 3*)

These sandstone units vary between 2 to 7 m in thickness (Fig 2.2) and contain numerous interbedded mudstone and siltstone beds (10-70 m thick) (Fig 2.13).

The sheet-like sandstone beds vary from 0.2 to 1.5 m thick (most beds average 0.25 m in thickness), are light grey, fine to medium-grained, and show undulating to planar bedding surfaces. Minor channel fills (0.5 m thick) are common and often contain fossil plant fragments. Platy bioturbated sandstones show traces of ripple cross-stratification and parallel lamination, can contain abundant carbonate (siderite) nodules, and abundant root fossils and traces (rare *Stigmaria*). Siderite nodules are regarded as a diagnostic indicator of methanic or post oxic environments which contain little or no H_2S (Pye et al., 1990). The nodular or root concretions often form in mudstones (Fig 2.14). The formation of siderite in the zone of sulphate reduction may result from a deficiency of bacterially-produced H_2S relative to the rate of iron reduction within the sediments (Pye et al., 1990).

The mudstone and siltstone beds are red to light grey, friable and platy, and commonly contain thin grey clay and carbonaceous shale layers. The clay and shale layers may represent rising groundwater levels or local inundation. The friable beds are bioturbated, hosting abundant root fossils and traces, and can contain in situ lycopsid trees (Fig 2.15), and *Stigmaria* rootlets. Platy mudstones rarely contain faint parallel laminae and may show faint bedding. Carbonate (siderite)

Fig 2.13 Heterolithic sandstone and mudstone unit in the middle of the section (in grey mudstone beds). Note the variance in bed style, from undulating to planar bed surfaces. Thickness of unit ~ 7 metres.

Fig 2.14 Abundant siderite nodules in platy mudstone within a heterolithic unit. Average diameter of nodules 1-15 cm.

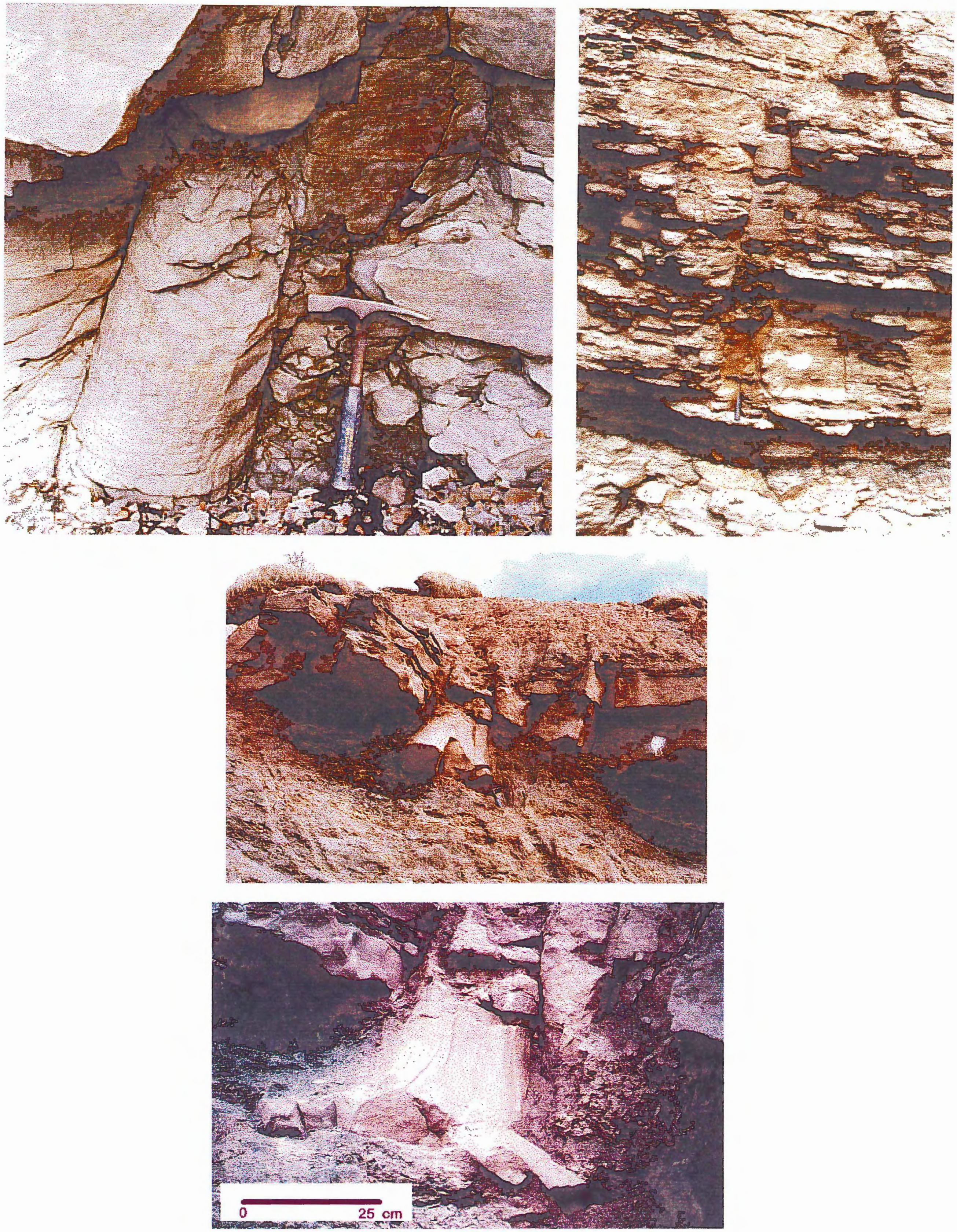


Fig 2.15 Various in situ lycopsid tree trunks in sheet (crevasse) sandstones and grey mudstones. The last lycopsid is near Bell's Brook and at the start of the section (~70 cm diameter).

nodules and root fillings are common to abundant, and root mottling (red-grey colour mottling) occurs in the mudstones and siltstones.

These thick heterolithic units are host to numerous plant fossils such as *Calamites* and in situ lycopsid tree trunks (also observed in sheet sandstones, Facies 2), and the sandstones often have rooted tops. The sand-filled lycopsid tree trunks, although prominent in the sheet sands, are rooted in the underlying mudstone beds, which contain their root stems (*Stigmaria*) and rootlets. Leaf fossil remains are rare to common in the sheet sands.

Two modes of origin are inferred for these deposits. (1) Some heterolithic sandstone could represent overbank levee deposits (stacked crevasse splays) bordering major and/or minor distributary channel deposits. These elongate deposits in modern environments, can be 10 km long, more than 2 km wide, and are at their thickest near the channel margin, tapering to zero at the distal edge (Fielding, 1986). The predominantly red mudstone (paleosol) beds and abundant rootlets in Joggins occurrences, suggest a slightly submerged soil-forming, and plant colonizing environment (Fielding, 1986), with a cyclic influx of fine-grained sand by sheet flow over the channel banks during flood stage (Coleman et al., 1964; Elliott, 1974). (2) Other occurrences have alternate light grey mudstone and sandstone units, and represent a more submerged, subaqueous environment (interdistributary bay) with less rooting influence and plant colonization (abundant carbonate nodules present in both sandstones and mudstones). Each sheet sandstone represents a crevasse splay with a sharp erosive base and may grade upward into the fines. The regular alternation of coarse- (sand) and fine-grained (mudstone) layers suggests a seasonal control on sedimentation (Fielding, 1986). Tye and Coleman (1989) described heterolithic sandstones and mudstones from backswamps in the Mississippi Delta (continuously flooded environment off the main distributary channels). In their lacustrine-delta model, silt- and claysized sediment introduced by overbank flooding of the distributary channels is associated with fine-grained sand deposited in the backswamp during occasional channel crevassing episodes. These deposits are stacked, thin, and upward-coarsening beds of ripple cross-laminated sand with rooted tops. The backswamp environment has abundant plant growth, and rooting is the dominant structure, ranging in size from large tree root traces to rootlets (Tye and Coleman, 1989). Carbonate minerals in the form of root fillings and/or nodules are usually associated with organic material in the section.

2.3 Mudstone Lithofacies (Table 2.2)

2.3.1 Grey clayey mudstone (*Facies 4a*)

These light grey (yellow stained) mudstones range from 0.2 to 1.0 m in thickness, are heavily bioturbated, well indurated to friable in texture, and invariably found underlying a coal and carbonaceous shale bed. Thin light grey carbonaceous shale layers are common, and plant (leaf) and root (*Stigmaria*) fossils are abundant (Fig 2.2).

This mudstone facies is classified as a "seat earth" or hydromorphic soil found below a prominent coal bed. These beds form in marsh settings of delta plains as organic-rich clays. Mack et al. (1993) classify light grey, organic-rich soils or underclays as *Gleysols*, found underlying a *Histosol* (coal). These rooted seat earths formed as hydromorphic paleosols modified by superimposition of *histosols* as the groundwater level rose, or diagenetically by ingress of organic acids from overlying peat (Tandon and Gibling, 1994).

Table 2.2: **Mudstone Lithofacies**

#	Facies Type	Average Thickness	Colour	Bed Style	Fossils	Other	Lithofacies Interpretation
4a	***Grey clayey mudstone***	0.2 to 1 m	light grey, yellow staining	bioturbated, friable, not stratified, some grey carbonaceous shale layers	heavily rooted, plant fossils evident, *Stigmaria* root	found underlying carbonaceous shale or coal beds	hydromorphic soil *Gleysol*
4b	***Grey platy mudstone***	0.2 to 1 m	light to medium grey or mottled (red-grey)	platy weathering, faint bedding, faint lamination	root traces rare to absent, some thin carbonaceous shale layers	nodular siderite concretions present	shallow water body, local rooted vegetation
4c	***Grey friable mudstone***	0.2 to 1.5 m	light to medium grey, or mottled, can have yellow staining	rooted, thin grey shaly layers, and carbonaceous shale layers, friable or blocky texture	can encompass lycopsid trunks, large roots (*Stigmaria*), plant fossils apparent	similar to seat earth mudstones (less rooted), nodular siderite concretions abundant	hydromorphic soil, higher vegetative influence than 4b
5a	***Red platy mudstone***	0.2 to 1 m	light to dark red (red-grey)	platy to chippy, silty layers, planar to undulating bed surfaces, thin grey carbonaceous layers common, conchoidal weathering	root fossils and traces common	nodular carbonate concretions common	oxidized soil, dryland, less rooting influence than 5b *Vertisol*
5b	***Red friable mudstone***	0.2 to 5 m	light to dark red, mottled texture (red-grey)	crumbly or chippy, thin grey organic clay layers common to abundant (usually found at the base of the bed), planar to undulating bed surfaces, no stratification	root fossils and traces common to abundant	nodular carbonate concretions abundant (5-25 cm width), rounded or flattened concretions	oxidized soil, dryland, abundant roots *Vertisol*

2.3.2 Grey platy mudstone (*Facies 4b*)

These light to medium grey mudstones range from 0.2 to 1.0 m in thickness, have platy weathering, and faint lamination (Fig 2.2). Root traces are rare to absent and thin carbonaceous shale layers are common. Nodular carbonate (siderite) concretions are also present (Fig 2.14). This mudstone facies is also a minor constituent in the heterolithic units (Facies 3).

Grey platy mudstones are interpreted as shallow water deposits with minor rooting influence. These fine grained mudrocks are similar to sediments that originate from distributary channels (Tye and Coleman, 1989) and settle out of suspension into a shallow water body (pond or lake) in the flood plain or backswamp. As a result, lamination may be formed, although bioturbation may mask these sedimentary structures. These mudstones are classified as a *Gleysol* paleosol where the surface or subsurface horizon experienced consistently low redox conditions (Mack et al., 1993). This type of horizon develops in areas of high water table. In an area that experiences a fluctuating water table, the horizon will experience alternate oxidation and reduction (Mack et al., 1993) indicated by red-green grey colour mottling. Smith (1991) from a petrographic study of Joggins paleosols refers to grey pedogenic mudstones as inceptisol-like. Carbonate nodules are common in the mottled beds of the thesis section, often containing roots which may also be a factor in the mottled appearance. Rust et al. (1984) inferred that in many cases mottling is due to reduction around roots even where evidence of roots is lacking.

2.3.3 Grey friable mudstone (*Facies 4c*)

These light to medium grey or mottled mudstone layers range from 0.2 to 1.5 m in thickness, have friable or blocky textures, and are rooted, with thin carbonaceous shale layers (Fig 2.2). These mudstones are less rooted than Facies 4a ("seat earth") and contain abundant nodular carbonate (siderite) concretions. They have rare plant (leaf) fossils, encompass lycopsid trunks (well preserved in overlying sheet sands, Facies 2), and contain large *Stigmaria* roots and rootlets.

Grey friable mudstones classify as a hydromorphic soil with a similar depositional history to Facies 4b, except that there is a higher vegetative influence. This mudstone also classifies as a *Gleysol*, and shows red-grey colour mottling. The mottles are typically small (1-2 cm), rounded to elongate in form, and often contain abundant carbonate nodules (5 cm diameter).

2.3.4 Red platy mudstone (*Facies 5a*)

These light to dark red mudstones range from 0.2 to 1.0 m in thickness, are platy to chippy in texture (conchoidal weathering), and contain silty layers. Bed surfaces are planar to undulating, faint parallel lamination is rare, and thin grey carbonaceous layers are common. Root fossils and traces and nodular carbonate concretions are also common (Fig 2.2).

These red mudstones classify as oxidized paleosol horizons in a subaerial environment, with little rooting influence. These deposits occur in strata interpreted to represent a dryland alluvial plain setting. Based on the Mack et al. (1993) classification, this type of soil horizon may be a *Vertisol* whose most prominent feature is homogenization of the profile by pedoturbation (shrinkage and swelling of expandable clays). Several other paleosol types are possible including *Argillisols, Spodosols, Oxisols* and *Protosols* (Mack et al., 1993). Prominent features are desiccation cracks, wedge-shaped peds, hummock and swale structures, slickensides and clastic dykes (Mack et al., 1993). The only features observed with certainty from this facies at Joggins are slickensides and desiccation cracks. Smith (1991) interpreted some red paleosols from Joggins as alfisol-like with a thin surface organic horizon and calcite concretions. Mack et al (1993) include alfisols in their *Argillisol* group.

2.3.5 Red friable mudstone (*Facies 5b*)

These light to dark red or mottled mudstones range from 0.2 to 5.0 m in thickness, are crumbly or chippy, and commonly contain abundant thin, light grey organic clay layers, usually found at the base of the bed (Fig 2.2). These grey carbonaceous shale layers may represent local ponding of groundwater levels in the soil horizon. Bedding surfaces are planar to undulating and no stratification is visible. Root fossils and traces are common to abundant, and nodular (rounded or flattened) carbonate concretions (5-25 cm width) are also abundant.

This mudstone facies also classifies as an oxidized paleosol horizon with abundant rooting and plant influence (unlike Facies 5a). These mudstones also follow the same paleosol classification found in Facies 5a, but can be termed as a more highly developed *Vertisol*.

2.4 Organic-rich Lithofacies (Table 2.3)

2.4.1 Carbonaceous shale (*Facies 6*)

The dark grey to black carbonaceous shale units range from 0.2 to 0.9 m in thickness, and show diffuse, platy layers with some coal stringers (Fig 2.2). Yellow or orange staining is common, and organic content is very high with abundant plant fossils and fragments (Fig 2.16).

This shale facies represents a clastic swamp deposit in the backswamp (flood plain) or overbank environment, where vegetation is well preserved in a shallow water body. These shales are closely associated with peat formation and coal development in a swamp setting.

2.4.2 Coal (*Facies 7*)

The black coal plies (yellow stained) range from 4 to 70 cm in thickness, and have a blocky, vitreous texture with high organic content and visible pyrite (Fig 2.17). Plant fossils and fragments

Table 2.3 **Organic-rich Lithofacies**

#	Facies type	Average Thickness	Colour	Bed Style	Fossils	Other	Lithofacies Interpretation
6	***Carbonaceous shale***	0.20 to 0.90 m	dark grey to black, yellow or orange staining	diffuse layers, platy, some coal stringers	plant fossils and fragments abundant, high amount of organics		shallow water body, vegetation well preserved (clastic swamp)
7	***Coal***	0.04 to 0.70 m	black, yellow staining	blocky texture, vitreous, finely banded	plant fossils or fragments visible under hand lens or microscopic-scale	some visible pyrite	mire: mature peat formation, high water level
8	***Limestone***	0.20 m	dark grey	undulating bed surfaces due to shell layers, fissile, platy	abundant shell fragments: bivalves, ostracods (1 cm or less in length)		probable brackish environment, relatively deep water (highest level of transgression)

Fig 2.16 Carbonaceous shale (B) with abundant plant material underlying coal beds (A).
Scale 7 cm wide.

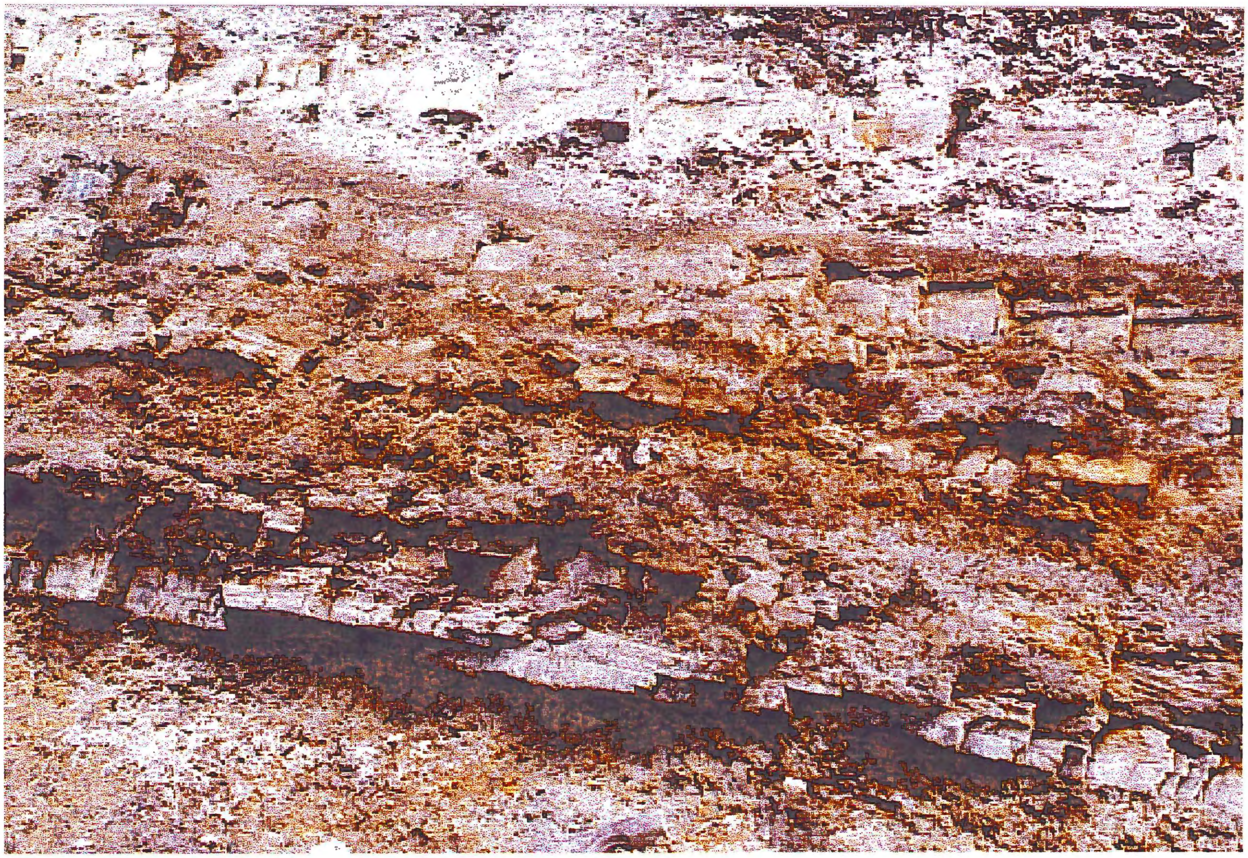


Fig 2.17 Close-up of the Queen Seam. Note the individual coal plies surrounded by carbonaceous shale partings (plant debris scattered). Coal plies 5-10 cm thick.

are typically only visible under a hand lens or microscope. The coal seams (e.g. Queen Seam) commonly have thick partings (10-30 cm) of dark grey or black carbonaceous shale which separate individual coal beds (Fig 2.2).

There are 8 coal horizons in the section, and only two seams which became economically feasible for mining. The Queen Seam (106 m upsection) is well exposed, ~95 cm thick and contains 3 coal plies separated by a 30 cm carbonaceous shale parting, and 30 cm mudstone with coal stringers and organic material (Fig 2.18). The Joggins Seam (129 m upsection) is poorly exposed due to mining activities and is barely visible through protruding shaft supports and rail ties (Fig 2.19). Logan (1845) describes the seam as ~1.5 m thick with thick coal plies and carbonaceous shale partings. Both seams were mined extensively until the mid-20th century in the Joggins area. The coals are of high-volatile bituminous rank with an average ash content of about 14-15% (Copeland, 1958, and Hacquebard and Donaldson, 1964; *cited in* Duff and Walton, 1973).

The coals represent mature peat formation in a mire setting where water levels are high. Peat formation occurs in the backswamp or marsh regions of a delta plain where clastic influx is reduced or non-existent. The carbonaceous shale partings indicate influxes of sediment into the swamp (Gibling, 1987).

The coals (classified as a *Histosol* by Mack et al., 1993) represent the compressed and metamorphosed remains of plants from an in situ peat (Haszeldine, 1984). Significant volumes of terrigenous organic-rich rocks (peats) can be preserved to form coals only when and where the overall increase in accommodation (function of subsidence and base level; for mires, base level is the groundwater table) approximately equals the accumulation rate of peat (Bohacs and Suter, 1997).

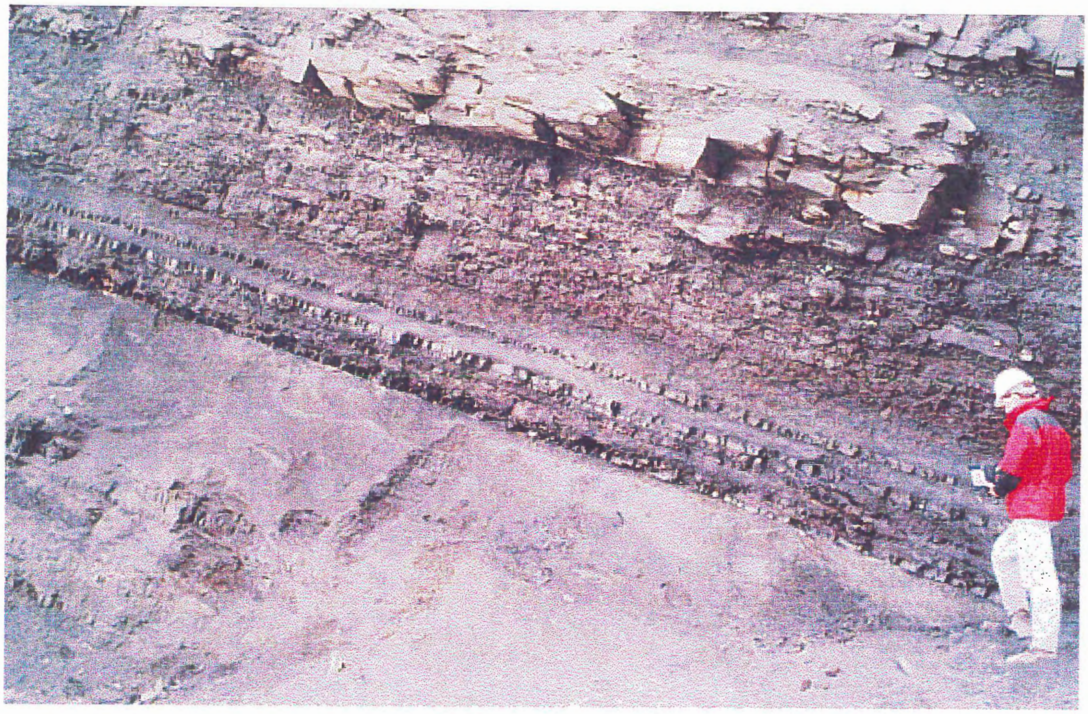


Fig 2.18 The main Queen Seam (mined beds), ~1 m thick with carbonaceous shale partings and organic matter. Excellent coastal exposure.

Fig 2.19 The Joggins Seam concealed (left side of picture). This seam is poorly exposed and the only remnants left of a mine are pit props, an old wharf and rail ties. The seam was ~1.5 m thick (Logan 1845) and was mined heavily until the mid part of the century. Note the crevasse (sheet) sandstone on the right-hand side of the photo.

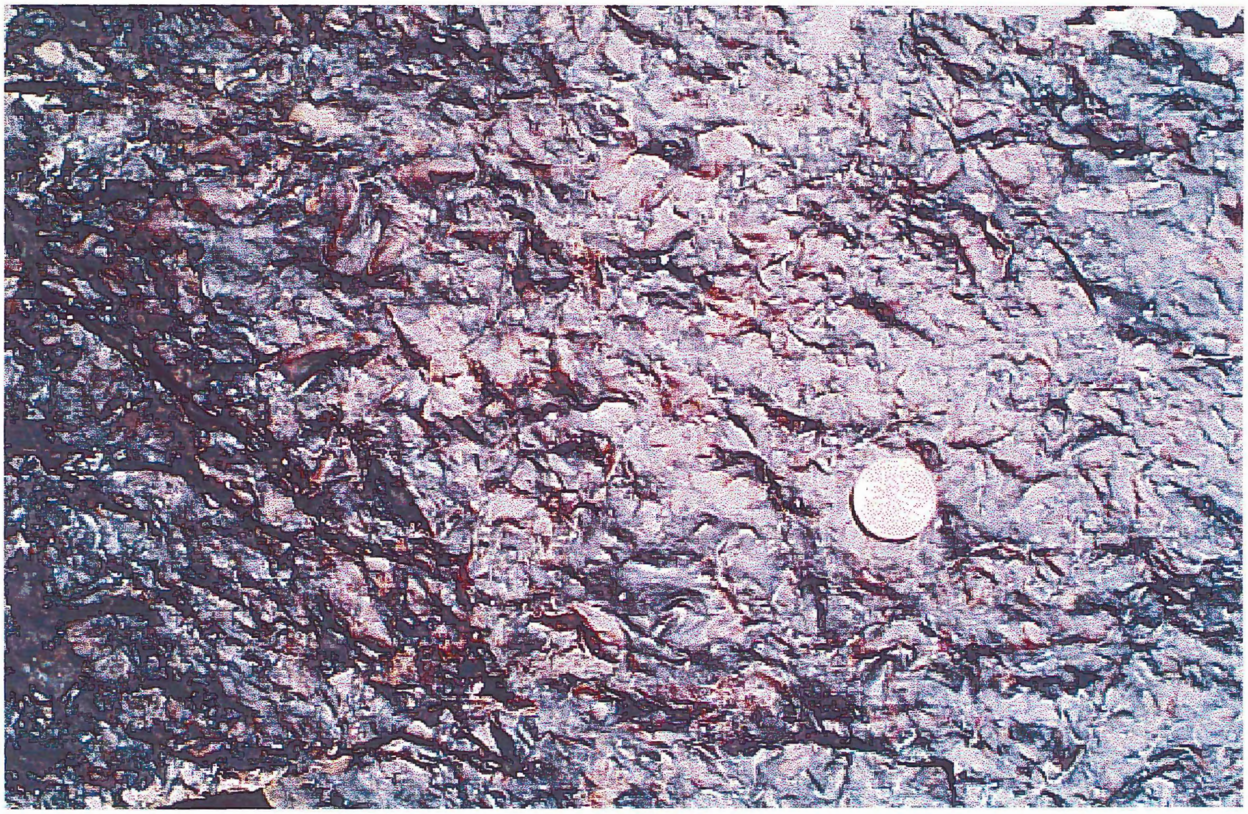


Fig 2.20 Close-up of the type of shelly, carbonaceous limestone found in the section. This piece found in scree contains abundant bivalves and ostracods in a shaly matrix.

2.4.3 Limestone (*Facies 8*)

The sole dark grey, carbonaceous, shell-rich limestone unit is 20 cm thick, and has an undulating bedding surface and wavy lamination resulting from layers of compacted bivalve shells (Fig 2.2). The limestone contains abundant shell fragments of bivalves (≤ 1 cm in length) and ostracods in a very fine-grained shale matrix (Fig 2.20) . *Naiadites* and *Curvirimula* have been identified in similar limestones within the Joggins Formation, but generic determinations were not made for this limestone.

The limestone bed found at the top of the section overlies a 12 cm coal bed, and represents a maximum transgressive level (Fig 2.21). The limestone formed in shallow water bodies (probably a few meters deep) on the flood plain, where a rise in the groundwater table caused peat swamps to be inundated to a depth too great for rooted vegetation to keep growing (Gibling, 1987).

Fig 2.21 Similar limestone bed overlying a coal seam with carbonaceous shale partings with abundant plant material (Joggins Section).

CHAPTER 3: FACIES SUCCESSIONS AND CYCLES

3.1 Introduction

Two facies successions dominate the thesis section: (1) a predominantly grey mudstone and sandstone "wetland" facies succession, and (2) a predominantly red mudstone and grey sandstone "dryland" facies succession. The wetland succession is heavily influenced by rising groundwater levels, swamp environments and standing water bodies, flood sheet flows, and generally deposition occurs in a subaqueous environment. The dryland succession can be described as overbank deposition in a subaerial environment. This facies succession is rarely influenced by the aqueous conditions mentioned above, and oxidized soil conditions dominate with cyclic sheet flow deposition of crevasse splays. The terms wetland and dryland are designated as relative degrees of drainage on the floodplain and many transitional strata were also observed.

The two successions alternate up section in regular intervals (Fig 3.1). The section begins with a 34 m thick wetland interval, followed by a 25 m thick dryland interval, a 17 m thick wetland interval, a 22 m dryland interval, and terminates with a 47 m thick wetland interval, which contains the major coal seams of the thesis section. This chapter describes each facies interval and the distinct cycles present in the section. Detailed interpretation of the facies successions and the origin of cyclicity is discussed in the next chapter.

3.2 Wetland Facies Succession

3.2.1 Coarsening-upward sequences and flooding surfaces

The wetland facies succession contains various coarsening-upward sequences (CUS) and organic-rich beds of carbonaceous shale and coal. Flooding surfaces (coal, limestone,

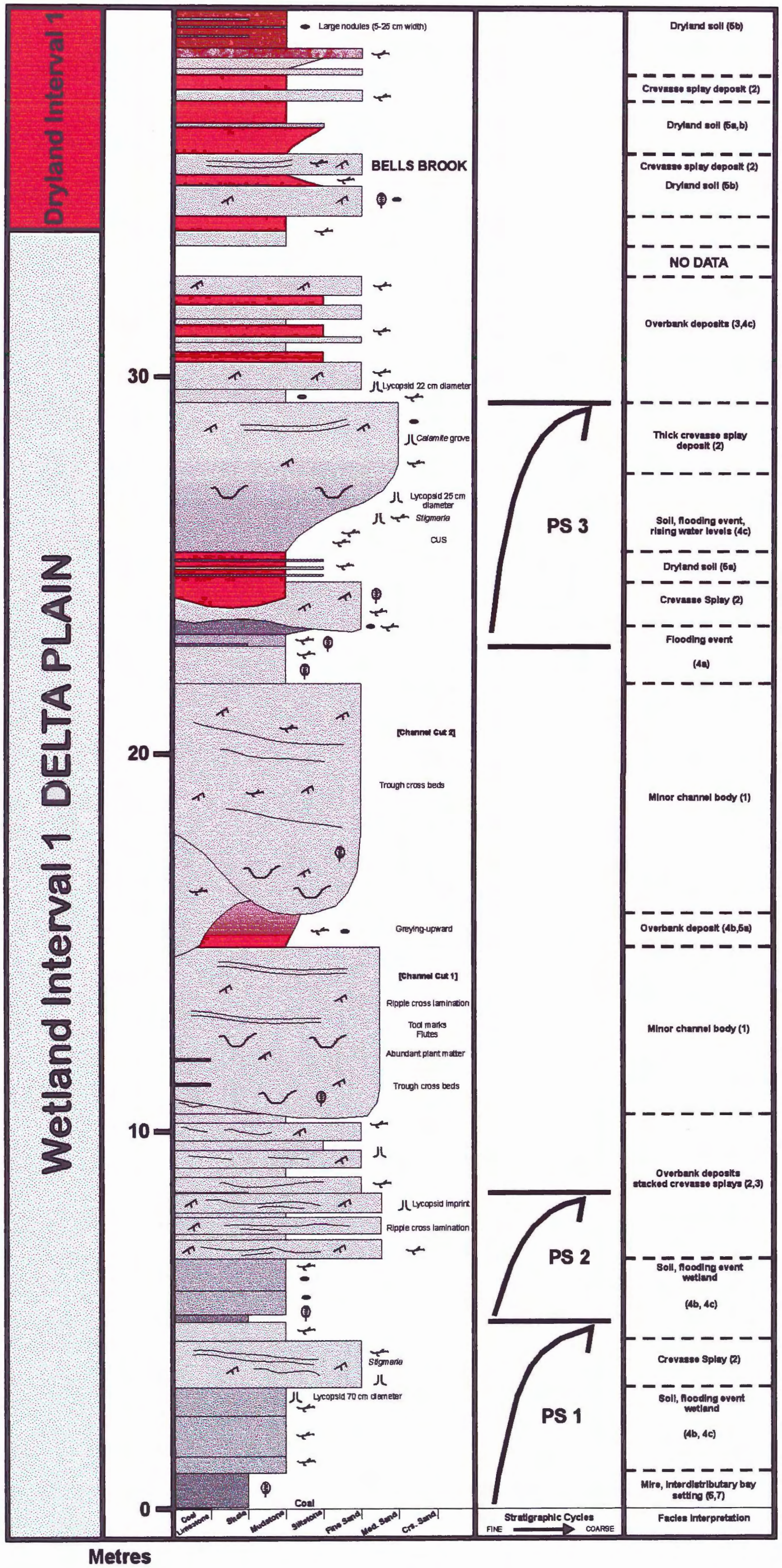
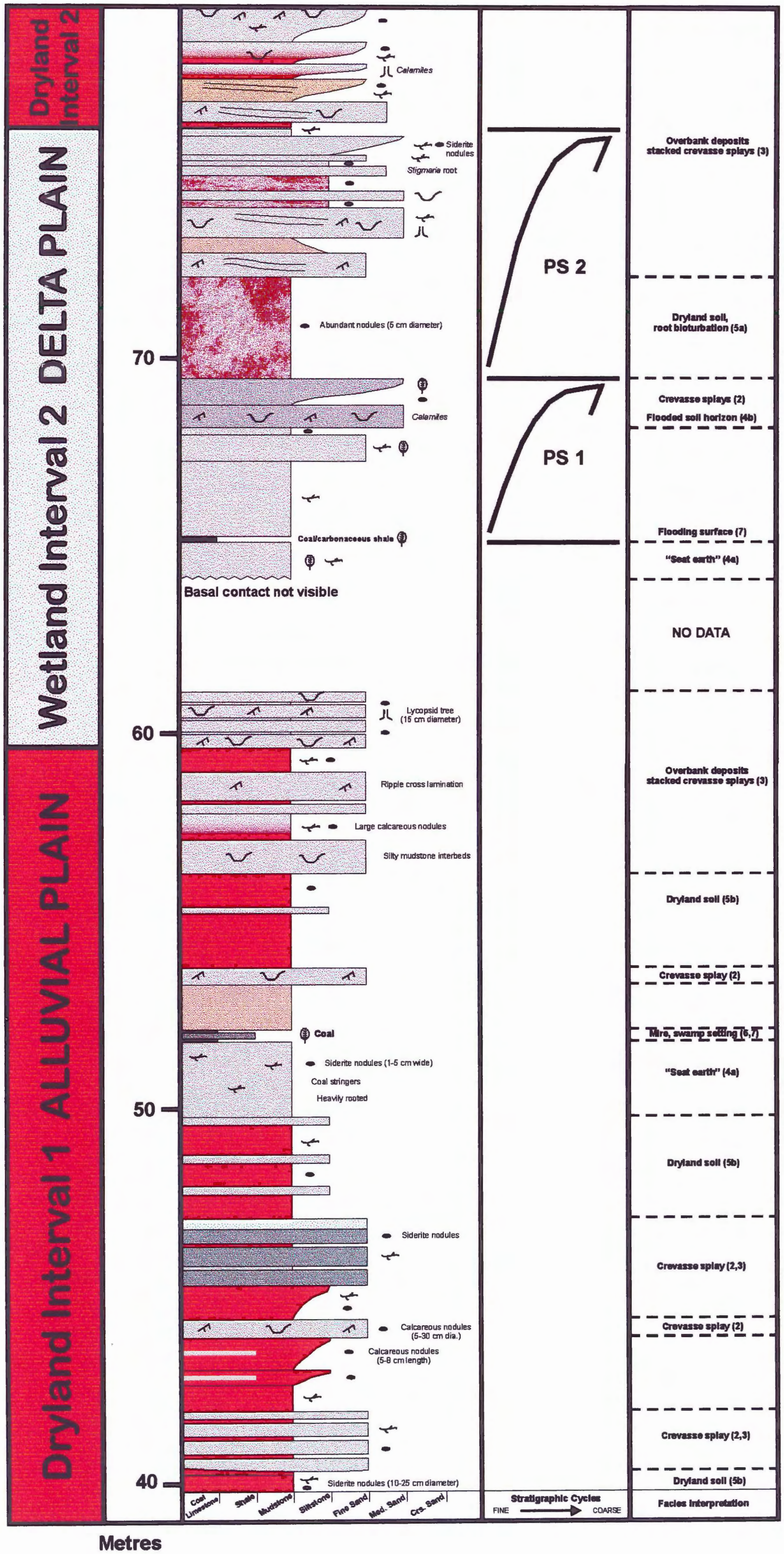
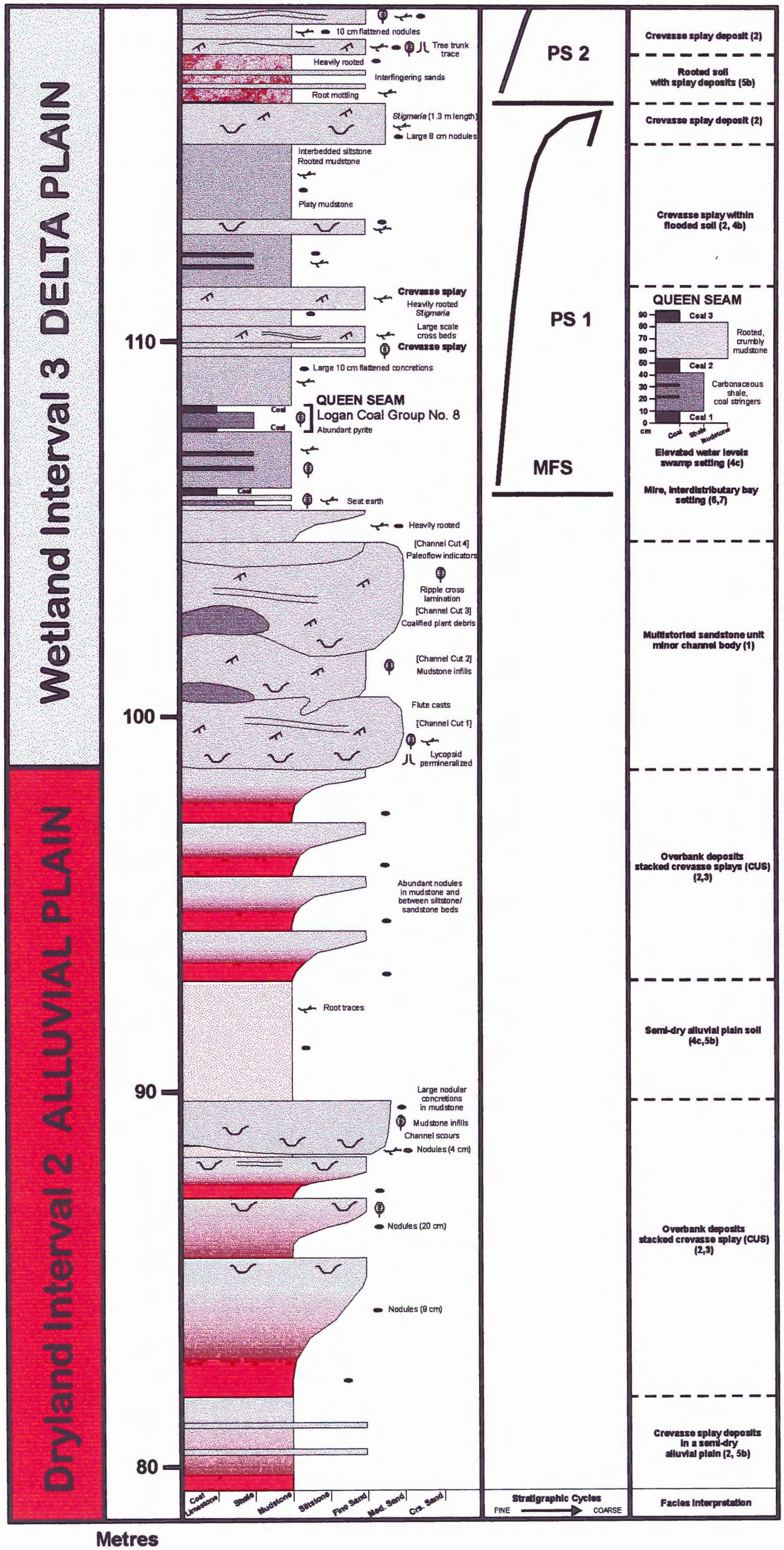


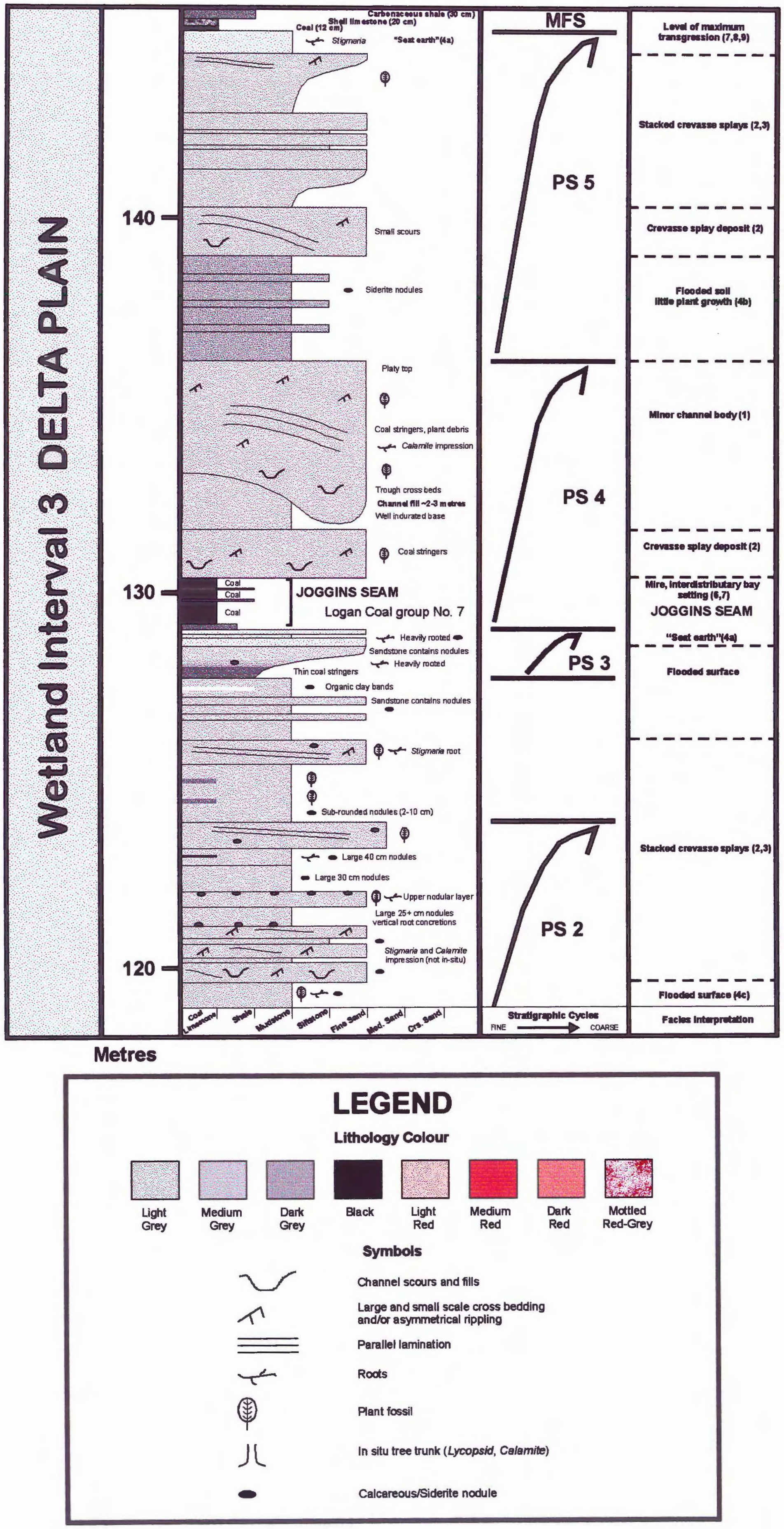
Fig 3.1 (Repeated) Facies successions column for the Joggins thesis section (145 m). Column divided into next four pages. Legend is on page 51. See stratigraphic column in back cover inset for full length version. *Note*: PS = Parasequence, MFS = Major flooding surface.



Dryland Interval 2
Wetland Interval 2 DELTA PLAIN
Dryland Interval 1 ALLUVIAL PLAIN
70
60
50
40
Metres
Calamites
Siderite nodules
Stigmaria root
Abundant nodules (5 cm diameter)
Calamites
Coal/carbonaceous shale
Basal contact not visible
Lycopsid tree (15 cm diameter)
Ripple cross lamination
Large calcareous nodules
Silty mudstone interbeds
Coal
Siderite nodules (1-5 cm wide)
Coal stringers
Heavily rooted
Siderite nodules
Calcareous nodules (5-30 cm dia.)
Calcareous nodules (5-8 cm length)
Siderite nodules (10-25 cm diameter)
Coal
Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
PS 2
PS 1
Stratigraphic Cycles
FINE
COARSE
Overbank deposits stacked crevasse splays (3)
Dryland soil, root bioturbation (5a)
Crevasse splays (2)
Flooded soil horizon (4b)
Flooding surface (7)
"Seat earth" (4a)
NO DATA
Overbank deposits stacked crevasse splays (3)
Dryland soil (5b)
Crevasse splay (2)
Mire, swamp setting (6,7)
"Seat earth" (4a)
Dryland soil (5b)
Crevasse splay (2,3)
Crevasse splay (2)
Crevasse splay (2,3)
Dryland soil (5b)
Facies Interpretation



Wetland Interval 3 DELTA PLAIN
Dryland Interval 2 ALLUVIAL PLAIN
110
100
90
80
Metres
10 cm flattened nodules
Tree trunk trace
Heavily rooted
Interfingering sands
Root mottling
Stigmaria (1.3 m length)
Large 8 cm nodules
Interbedded siltstone
Rooted mudstone
Platy mudstone
Crevasse splay
Heavily rooted Stigmaria
Large scale cross beds
Crevasse splay
Large 10 cm flattened concretions
QUEEN SEAM
Logan Coal Group No. 8
Abundant pyrite
Coal
Seat earth
Heavily rooted
[Channel Cut 4]
Paleoflow indicators
Ripple cross lamination
[Channel Cut 3]
Coalified plant debris
[Channel Cut 2]
Mudstone infills
Flute casts
[Channel Cut 1]
Lycopsid permineralized
Abundant nodules in mudstone and between siltstone/ sandstone beds
Root traces
Large nodular concretions in mudstone
Mudstone infills
Channel scours
Nodules (4 cm)
Nodules (20 cm)
Nodules (9 cm)
Coal
Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
PS 2
PS 1
MFS
Stratigraphic Cycles
FINE
COARSE
Crevasse splay deposit (2)
Rooted soil with splay deposits (5b)
Crevasse splay deposit (2)
Crevasse splay within flooded soil (2, 4b)
QUEEN SEAM
Coal 3
Rooted, crumbly mudstone
Coal 2
Carbonaceous shale, coal stringers
Coal 1
cm
Elevated water levels swamp setting (4c)
Mire, interdistributary bay setting (6,7)
Multistoried sandstone unit minor channel body (1)
Overbank deposits stacked crevasse splays (CUS) (2,3)
Semi-dry alluvial plain soil (4c,5b)
Overbank deposits stacked crevasse splay (CUS) (2,3)
Crevasse splay deposits in a semi-dry alluvial plain (2, 5b)
Facies Interpretation


Wetland Interval 3 DELTA PLAIN
Metres
140
130
120
Carbonaceous shale (30 cm)
Shell limestone (20 cm)
Coal (12 cm)
Stigmaria
"Seat earth"(4a)
Small scours
Siderite nodules
Platy top
Coal stringers, plant debris
Calamite impression
Trough cross beds
Channel fill ~2-3 metres
Well indurated base
Coal stringers
Coal
Coal
Coal
JOGGINS SEAM
Logan Coal group No. 7
Heavily rooted
Sandstone contains nodules
Heavily rooted
Thin coal stringers
Organic clay bands
Sandstone contains nodules
Stigmaria root
Sub-rounded nodules (2-10 cm)
Large 40 cm nodules
Large 30 cm nodules
Upper nodular layer
Large 25+ cm nodules
vertical root concretions
Stigmaria and Calamite
impression (not in-situ)
Coal
Limestone
Shale
Mudstone
Siltstone
Fine Sand
Med. Sand
Crs. Sand
MFS
PS 5
PS 4
PS 3
PS 2
Stratigraphic Cycles
FINE
COARSE
Level of maximum transgression (7,8,9)
Stacked crevasse splays (2,3)
Crevasse splay deposit (2)
Flooded soil
little plant growth (4b)
Minor channel body (1)
Crevasse splay deposit (2)
Mire, interdistributary bay setting (6,7)
JOGGINS SEAM
"Seat earth"(4a)
Flooded surface
Stacked crevasse splays (2,3)
Flooded surface (4c)
Facies Interpretation
LEGEND
Lithology Colour
Light Grey
Medium Grey
Dark Grey
Black
Light Red
Medium Red
Dark Red
Mottled Red-Grey
Symbols
Channel scours and fills
Large and small scale cross bedding and/or asymmetrical rippling
Parallel lamination
Roots
Plant fossil
In situ tree trunk (Lycopsid, Calamite)
Calcareous/Siderite nodule

carbonaceous shale or organic-rich grey mudstone) indicate the start of a coarsening-upward sequence which averages between 3 and 15 m in thickness (Fig 3.2b).

Most CUS begin with a thin coal or carbonaceous shale, but thick coal seams (Queen and Joggins Seam) in the upper section (105-130 m upsection) mark prominent flooding surfaces (Fig 3.2a). The sequence coarsens to light to medium-grey, rooted, nodular mudstones which commonly are organic-rich (plant fossils) and encompass in situ lycopsid tree trunks and *Stigmaria* roots. Thin, rooted crevasse splay (sheet) sandstones interfinger with the mudstones and also contain lycopsid tree trunks which are rooted in the underlying mudstone beds.

The sequence coarsens into a thick crevasse splay with rooted tops, *Stigmaria* and *Calamite* fossils, and in situ lycopsid tree trunks. In most instances, the CU sequences show thickening-upward trends within the sandstone. The CUS can also coarsen into rooted heterolithic sandstone units, which contain similar plant and tree fossils found in single crevasse splay. Most sandstone units show planar to undulating bed surfaces, trough cross bedding, parallel laminations, and minor channel scours. A medium-grained multi-storied channel sandstone (11 m upsection) cuts into the CUS and contains abundant tool marks, thick scour fills, and macerated plant matter at the base of the unit.

3.2.2 General description of the wetland succession

The thesis section contains two thick wetland intervals and a thin interval in the middle of the stratigraphic section. The wetland facies intervals show considerable variation within the section.

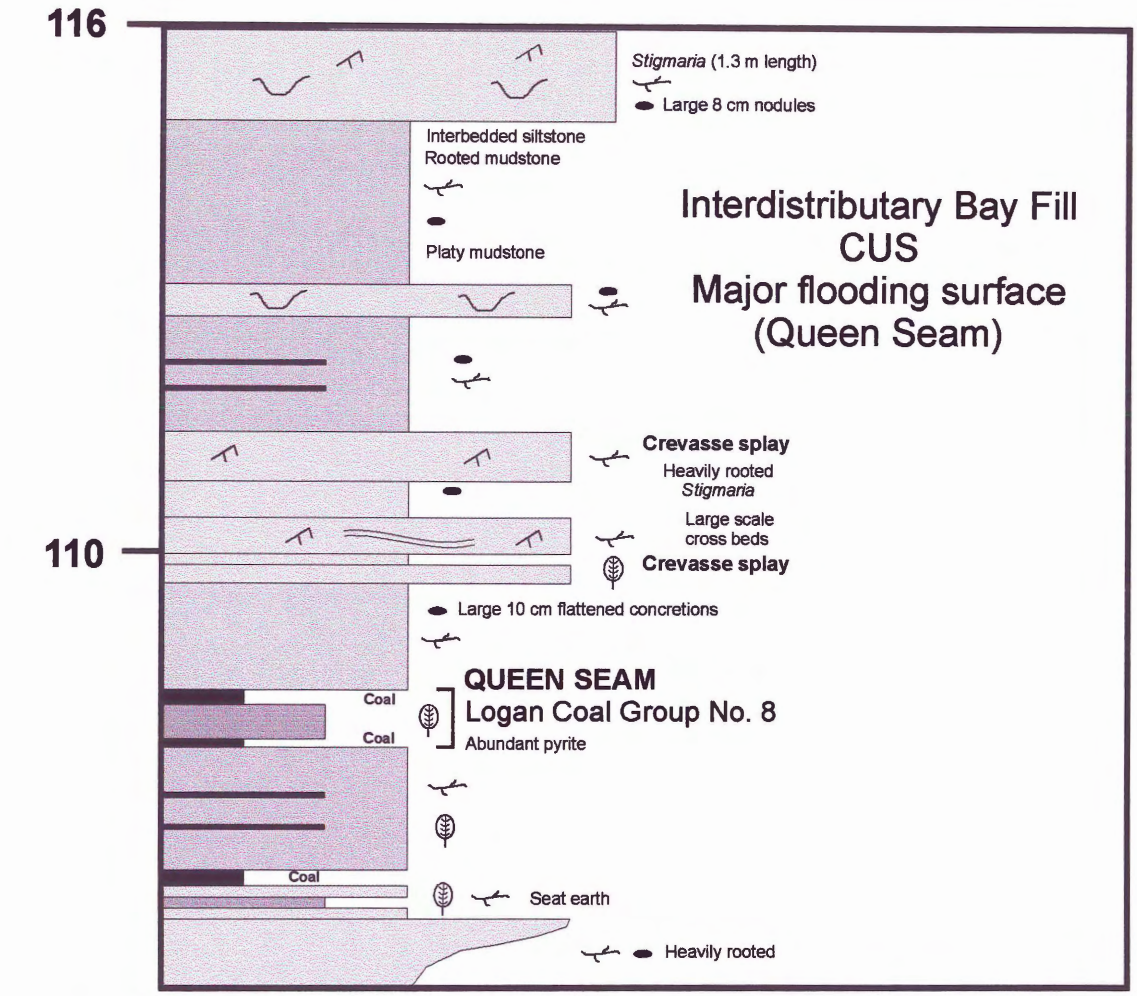


Fig 3.2a: Wetland interval 3, CUS from a major flooding surface (Queen Seam) Interdistributary bay fill deposit. Contains grey mudstone and sheet (crevasse splay) and heterolithic sandstones.

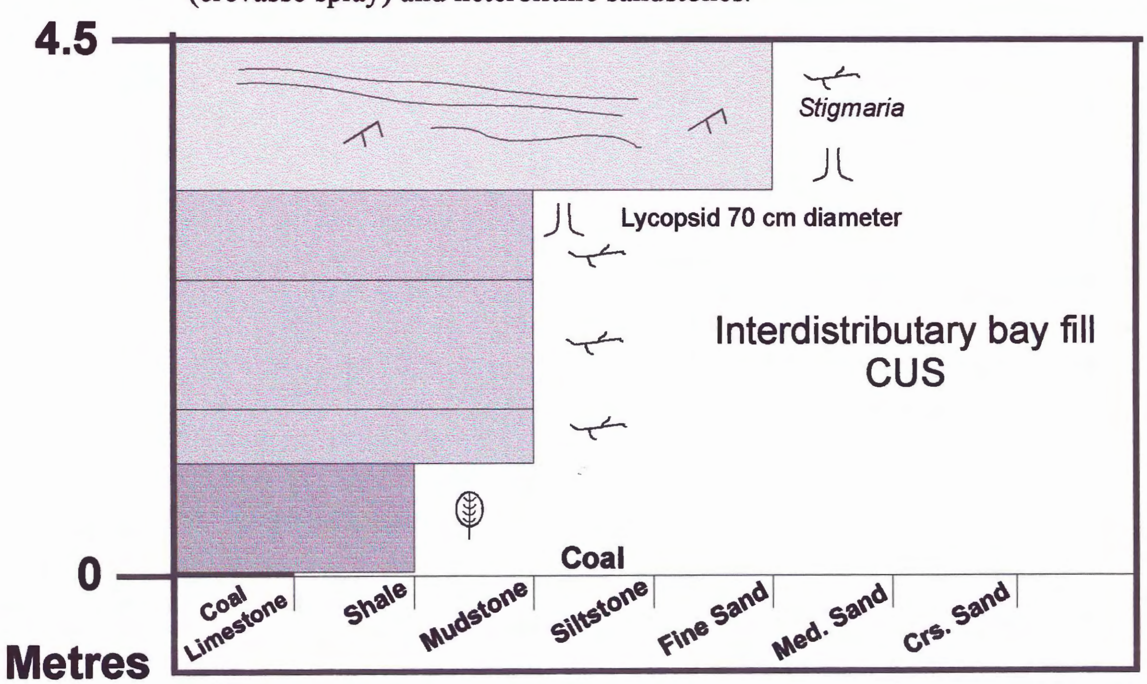


Fig 3.2b: Wetland interval 1, CUS from a flooding surface, Interdistributary bay fill deposit. Contains grey mudstone and sheet (crevasse splay) sandstones. One of the best example of a CU bay fill sequence in the

3.2.2.1 Wetland interval 1

The first wetland interval (0-34 m upsection) has four major coarsening-upward sequences bounded by a coal and carbonaceous shale flooding surfaces, contains abundant in situ lycopsids, *Calamites* and *Stigmaria* roots. This package contains a thick (~12 m) multistoried channel unit (Fig 3.3) and abundant crevasse splay deposits within light grey to medium grey mudstones and carbonaceous shales. A thick, coarsening-upward crevasse splay deposit (4.5 m) dominates the upper section of the first wetland interval, and is followed by a gradual transition into the red-dominated, dryland facies succession. Carbonate (sideritic and calcareous) nodules are rare, and root fossils are abundant in all lithologies. Plant (leaf) fossils are found only in organic-rich mudstones, carbonaceous shales and as macerated debris in the multistoried channel body.

3.2.2.2 Wetland interval 2

The second wetland interval is found in the middle of the section (59-76 m upsection), is bounded by two dryland intervals and contains one thin flooding surface (coal and carbonaceous shale bed). The upper part of this package (similar to the first wetland interval) coarsens from a coal bed into a light grey rooted mudstone, and into a series of fossiliferous medium-grey sheet sandstones. A second CUS coarsens from a mottled mudstone into a series of stacked sheet sandstones which contain interbedded thin, red-grey and mottled mudstones. Carbonate and calcareous nodules are more common in the upper sections, and in situ *Calamites* are common in the crevasse splay (sheet) sandstones.

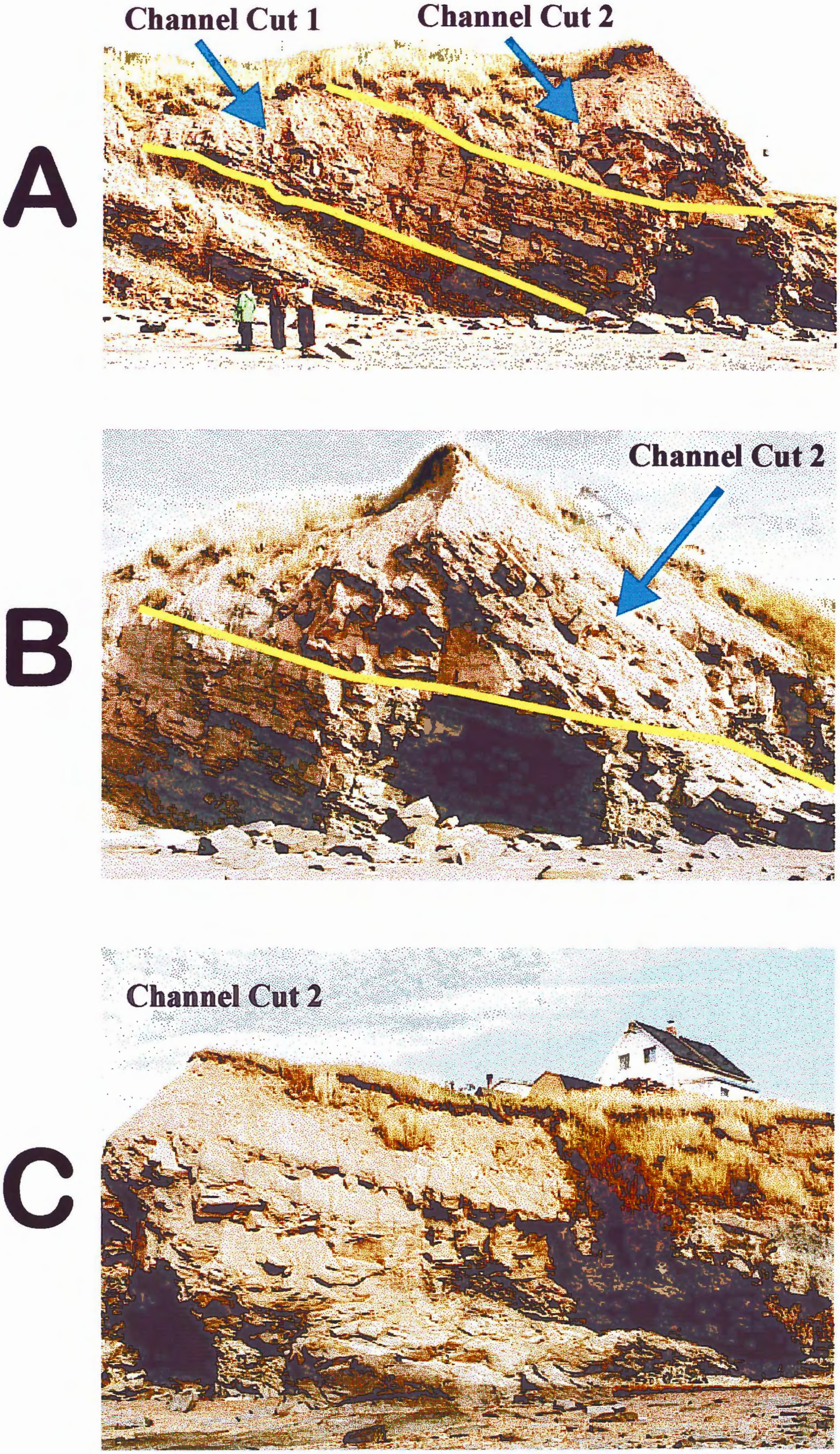


Fig 3.3: Thick multistoried channel sandstone (~8-9 m thick). Two channel cuts are prominent in the unit. Starting from Photo A, these pictures move upsection and are taken at different angles . Note: heterolithic base of sandstone in Photo A, beds thickening-upward into Photo B, interbedded mudstones and siltstones throughout, and friable beds at the top of the unit (Photo C). Cliff ~ 8-10 m high.

3.2.2.3 Wetland interval 3

The topmost wetland interval has five major CUS, and is found at the top of the stratigraphic section (98-145 m upsection). This interval differs greatly from the last two wetland intervals in that light-grey heterolithic sandstones and mudstones dominate, and the coal beds are much thicker (up to 70 cm) (Fig 3.4).

The base of the interval contains a 6 m thick multistoried channel sandstone unit, with thick mudstone-filled scours and macerated plant debris throughout (Fig 3.5). Flute casts and ripple cross lamination are abundant and permineralized plant material (tree trunks) is found at the base of the unit (Fig 2.4). This channel body marks the boundary with dryland interval 2. A series of thick coal beds (Queen Seam) with carbonaceous shale partings, and a heavily rooted "seat earth" overlie the thick channel body.

The Queen coal seam (90 cm thick) indicates the first major flooding surface in the interval, and the base of a 12 m coarsening-upward sequence (Fig 3.6). The first CUS contains rooted, medium grey mudstones with abundant carbonate and calcareous nodules. Several rooted crevasse splay (sheet) sandstones are found interbedded in the mudstones and gradually coarsen from a fine-grained to a medium-grained sandstone. *Stigmaria* roots and large 8-10 cm carbonate nodules are abundant in this sequence.

The second CUS begins with a carbonaceous shale flooding surface, and contains heterolithic sandstone units with light grey interbedded mudstones and siltstones (Fig 3.7). All lithologies have abundant carbonate nodules ranging in size from 20-40 cm, have *Stigmaria* roots, and contain abundant rootlets. Many of the sheet sandstones found in the middle of this CUS have large nodular layers composed of carbonate or calcareous concretions which formed parallel to the bedding surface. Mottled red-grey mudstones are common resulting from root penetration or

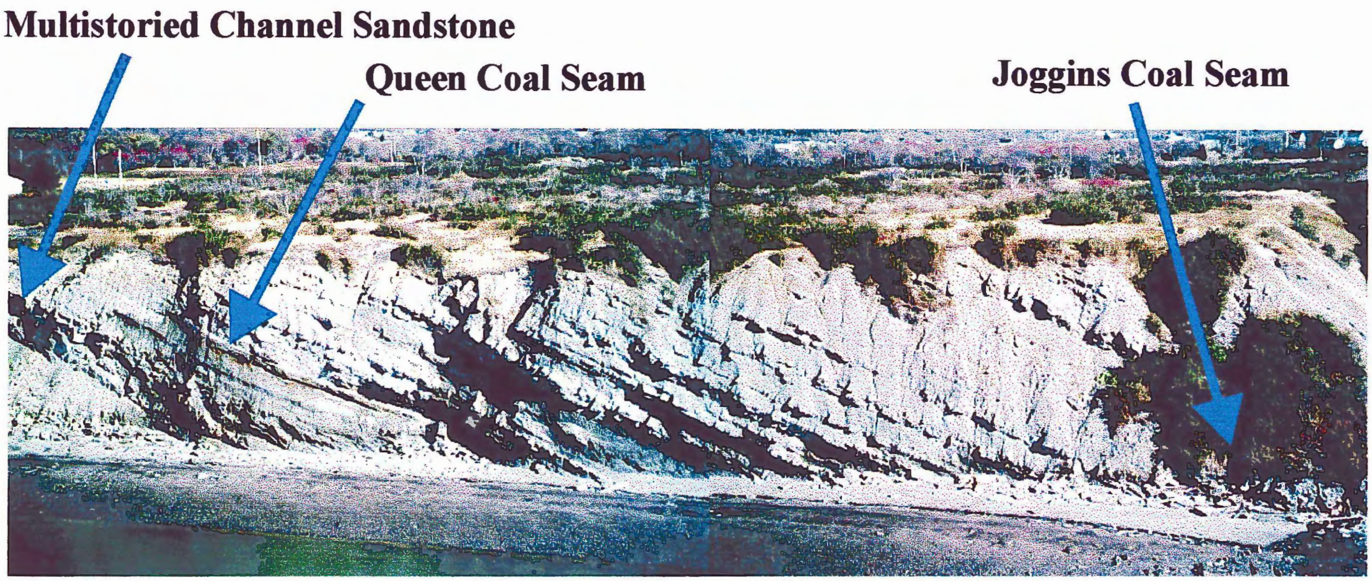


Fig 3.4 **Wetland Interval 3**, from the Queen Seam (left) to the Joggins Seam (right). Younging direction to the right. Photo taken by Ralph Stea (helicopter shots) for the Nova Scotia Department of Natural Resources. Cliff scale ~20 m.

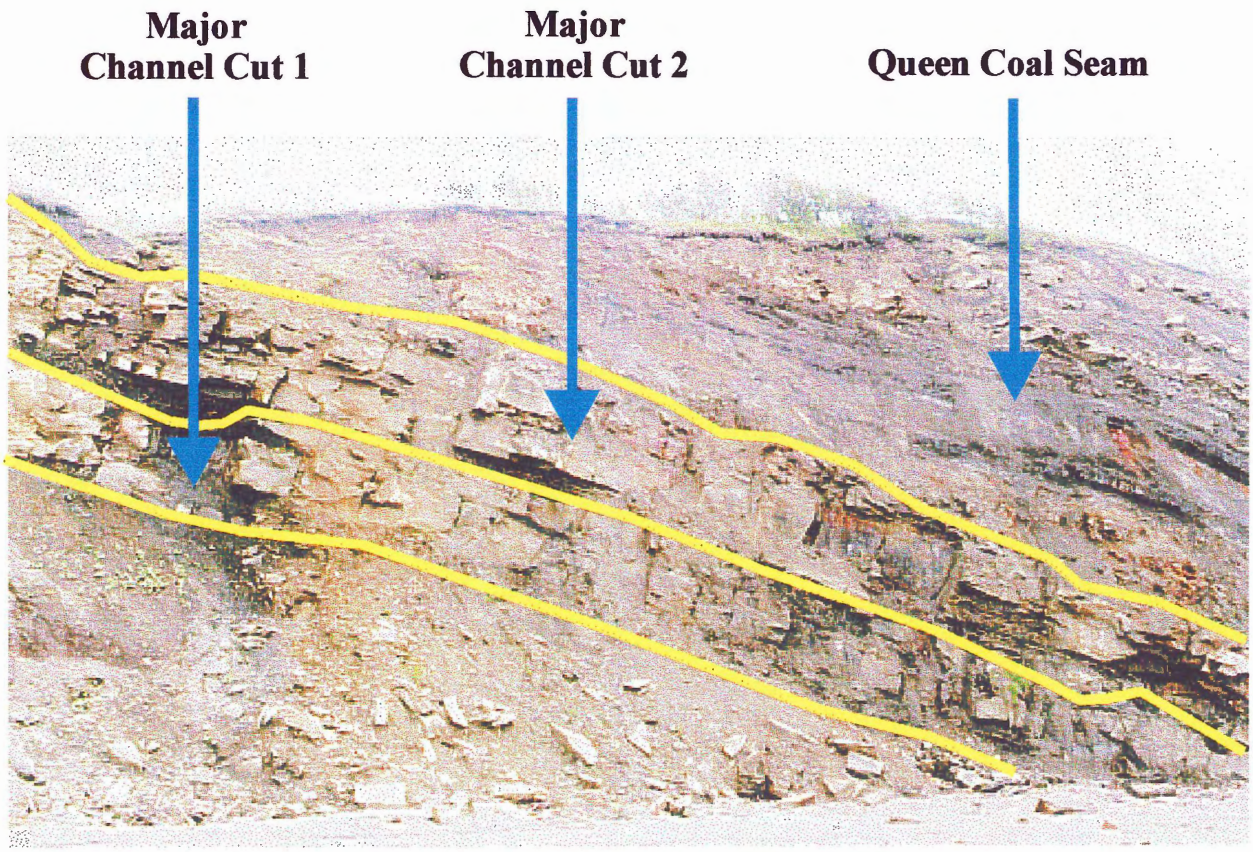


Fig 3.5: Second multistoried channel sandstone of section located in wetland interval 3 (~6 m thick in total with two major channel cuts). Notice the Queen Seam, first major flooding surface of the interval, above the channel sandstone unit.

Fig 3.6 Queen Seam (90 cm thick), separated by a mudstone bed (~1 m) thick. Channel sandstone located to the left of the seam and on the lower left corner of the photograph.

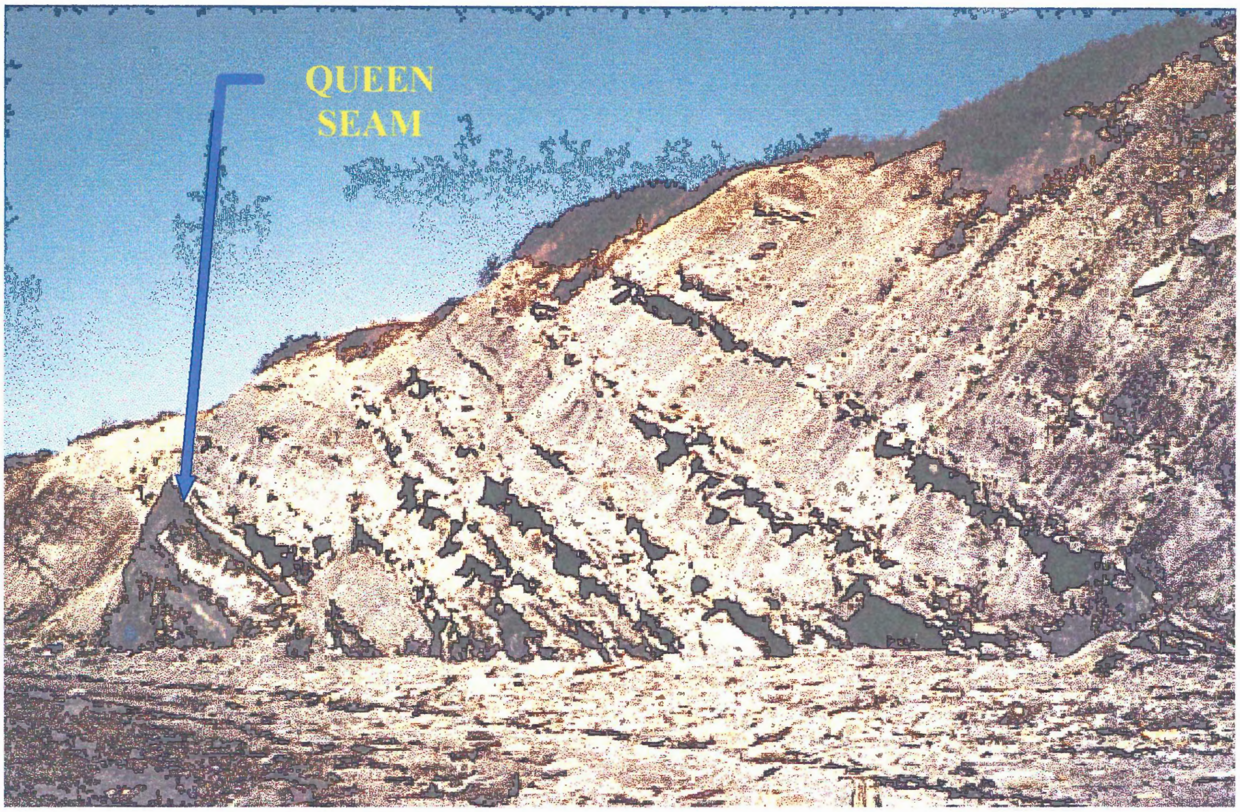


Fig 3.7 Heterolithic sandstone bodies located near the Joggins Seam in wetland interval 3. Notice: Queen Seam to the far left of the photograph.

changes in groundwater level. In situ lycopsid tree trunks and *Calamites* are rare to absent, but plant (leaf) fossils are very common in all lithologies.

The Joggins coal seam (1.4 m thick) forms the second major flooding surface of this interval which coarsens into a light grey mudstone and thin channel sandstone unit with abundant coal stringers and plant material (Fig 2.19). An additional CUS is present above this unit. The top part of this wetland interval contains a 12 cm coal bed abruptly underlying a 20 cm carbonaceous limestone, indicating a transgressive event and major flooding surface (Fig 2.21). This limestone represents the most significant flooding event in the stratigraphic section and indicates an inundation of the mature peat-forming surface.

	Lithology	**Sedimentary Structures**	**Fossils**	**Depositional Features** (*see* **Chapter 4** *for details*)
Wetland Succession (coastal plain)	light grey mudstone and fine-grained sandstone, carbonaceous shale, variably thick coal, and carbonaceous limestone	ripple cross laminations, scour fills, parallel laminae, tool marks in channel sandstone, abundant nodules in upper wetland interval	*Calamites* and *Stigmaria*, in situ lycopsid tree trunks, *Cordaites* (channel sandstones), roots	(i) regularly stacked CUS interpreted as interdistributary bay fills or interlobe basin fills, (ii) coal seams deposited in shallow water bodies (peat mires) in bay fill sequence, (iii) limestone deposited after inundation of peat mire during transgressive event
Dryland Succession (alluvial plain)	red mudstone and fine to medium grained, light grey sandstone, thin coal and carbonaceous shale, thin light grey carbonaceous shale or clay partings in mudstone	ripple cross laminations, scour fills, parallel laminae, tool marks in channel sandstone, CU sheet sandstone, abundant carbonate nodules throughout	abundant roots, rare plant material except in rare coal beds and in sheet sandstone, rare *Stigmaria*	(i) stacked crevasse splays (heterolithic units) represent overbank deposition on dry flood plain, (ii) red mudstones are interpreted as *Vertisols* (paleosol), (iii) CU crevasse splay due to prograding sediment flow on flood plain

Table 3.1 General description and depositional features of the wetland (coastal plain) and dryland (alluvial plain) facies successions in a delta plain environment.

3.3 Dryland Facies Succession

Two dryland intervals are present in the stratigraphic section, and show many lithological differences from the wetland facies succession. The dryland facies succession has red mudstones and siltstones with interbedded light grey sheet sandstones. Carbonaceous shales or coals are rare, and limestones are absent. This facies succession does not have any major coarsening-upward sequences, few flooding surfaces, and has abundant heterolithic sandstone packages (stacked crevasse splays in overbank deposits). Many mudstones coarsen on a fine scale (in contrast with the large CUS of the wetland succession) into red or light grey siltstones, and light grey sandstones.

3.3.1 General description of the dryland succession

3.3.1.1 Dryland interval 1

This dryland interval begins after a gradual transition from wetland interval 1, and contains rooted heterolithic sandstones and mudstones (Fig 3.8). Carbonate nodules are common (especially after Bell's Brook) in the red mudstones and light grey sheet sandstones. These nodules vary from 5-25 cm in length and are found sporadically in each lithology. Plant and tree fossils (e.g. lycopsid and *Calamites*) and *Stigmaria* are rarely preserved, but root traces and root concretions are common to abundant throughout the interval. Most sheet sandstones are thin (0.25-1.00 m) and intercalated with red mudstones. Stacked crevasse splay sandstones (1-1.5 m thick) punctuate the interval, especially towards the overlying wetland interval, and contain ripple cross lamination, undulating bed surfaces, and minor scours (Fig 3.9). The red mudstones commonly coarsen into red siltstone and are cut by sheet sandstones.

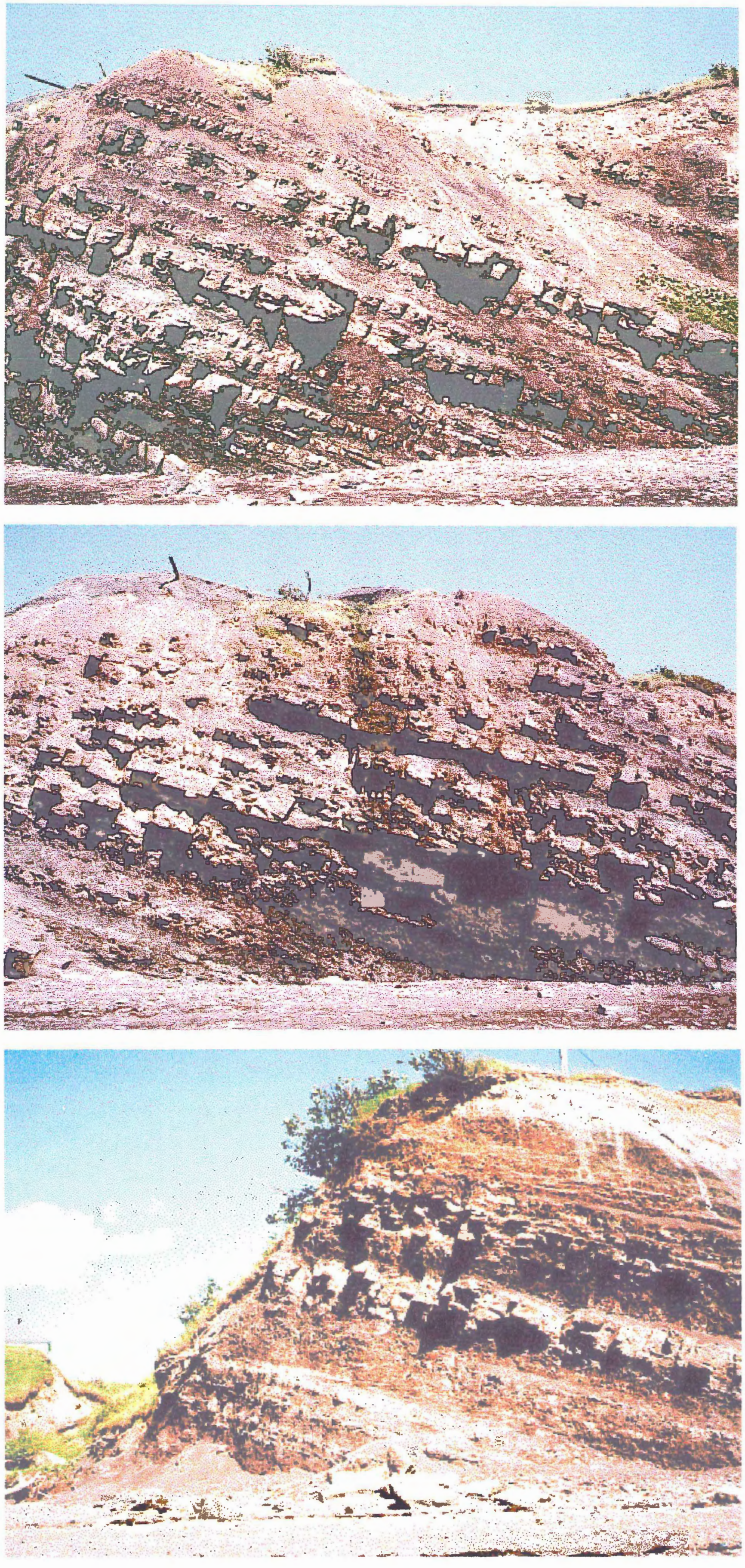


Fig 3.8 Series of photographs of the first heterolithic unit of dryland interval 1, predominantly red mudstones and grey sheet sandstones with calcareous nodules (Cliff height ~10-15 m).

Figure 3.9 Best example of a heterolithic sandstone and mudstone unit in the dryland facies succession (located in dryland interval 1). Stacked crevasse splays are evident and some show fairly planar bases. This body is near wetland interval 2. (Cliff height ~15-20 m)

This interval has a thin coal bed with a carbonaceous shale layer (30 cm thick in total), and abundant plant material (leaf fossils). A heavily rooted, 1.5 m thick "seat earth" underlies the coal beds, and contains coal stringers and siderite nodules (1-5 cm wide). The coal passes up into a light grey mudstone, and light grey sheet sandstone with undulating bed surfaces and cross-bedding. The coal represents a substantial rise in base level, and this "wetland" interval is interesting considering its presence in a predominantly dryland setting (see Chapter 4 for a detailed interpretation).

3.3.1.2 Dryland interval 2

This dryland interval differs greatly from the first interval. The red mudstone beds are thicker (up to 4 m) and tend to grey-upward into siltstones and sheet sandstones. The most prominent features of this interval are the abundant, thin CU beds of red mudstone to light grey sandstone. Similarly, this interval also contains numerous stacked crevasse splay units, and a thin coal bed (5 cm thick) which passes up into a medium grey mudstone and thin sheet sandstone (Fig 3.10).

This dryland interval overlies wetland interval 2 and begins with a thin coal bed (2-3 cm), and continues with abundant stacked crevasse splay (sheet) sandstones with thin, interbedded red and mottled mudstones. Abundant carbonate and calcareous nodules are present in all lithologies, often between the siltstone and sandstones beds of heterolithic units. Root traces and concretions are common, but not abundant in the red mudstones and sheet sandstones. *Calamites* and *Stigmaria* roots are rare in the lower crevasse splay sandstones, and absent in the upper thick heterolithic units. A 6 m thick multistoried channel sandstone cuts into this interval (98 m upsection), and marks the start of the last wetland interval (Fig 3.5).

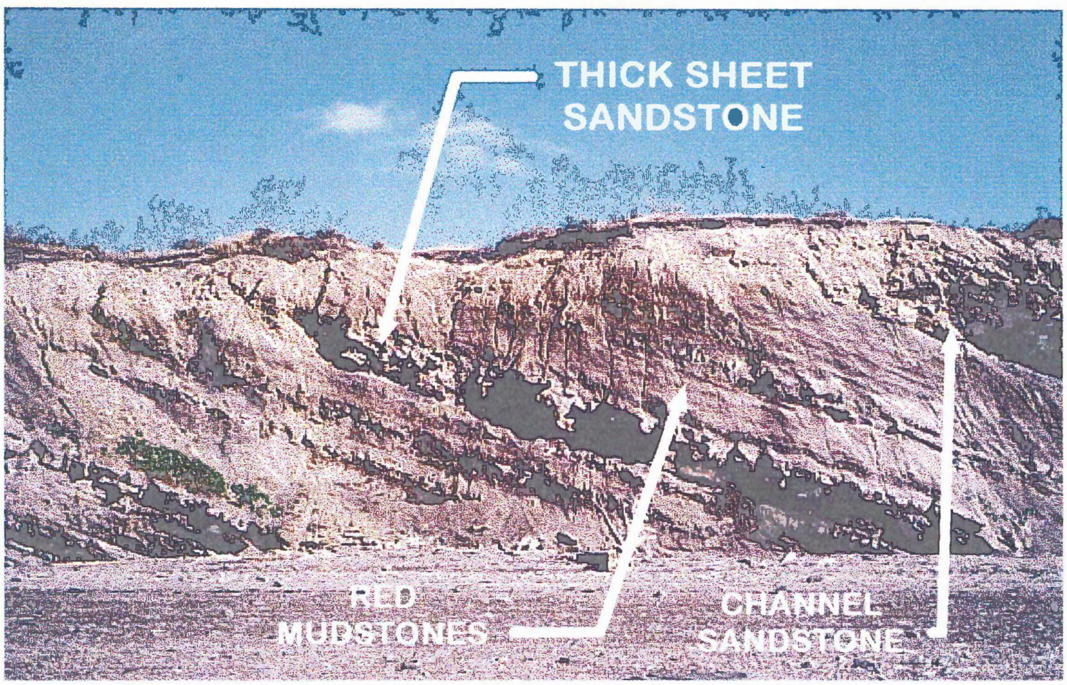


Fig 3.10 Dryland interval 2, with a thick crevasse sheet sandstone (~1.5 m thick) within prominent red mudstone beds. Note the start of the multistoried channel sandstone to the far right in the second photo. The first photo (starting from the left) shows repeated coarsening-upward sheet sandstones (from red mudstones) and thick red mudstone beds (~2-2.5 m thick). These CU bodies are also evident from a distance in the second photo, below the thick sheet sandstone.

CHAPTER 4: DISCUSSION AND CONCLUSIONS

DISCUSSION

4.1 Facies Model (Depositional Environment)

The presence of coals, rooted beds, plant and tree fossils, and the absence of any marine limestones and fauna indicate that the Joggins thesis section is a continental deposit. There is a lack of paleontological evidence (paleontological study beyond the scope of this thesis) within this section of the Joggins Formation to indicate a marine influence. The thesis section has two major facies successions: wetland succession and dryland succession, representing a *coastal or lacustrine plain environment* and *alluvial plain environment*. The wetland succession contains a grey mudstone facies with thick coal seams (flooding surfaces), limestone (maximum flooding surface), channel and sheet sandstones, and a series of coarsening-upward sequences (CUS). The dryland succession has a red mudstone facies with only thin coals, stacked and individual sheet sandstones, and a channel sandstone (Fig 4.1).

4.1.1 Wetland facies succession

The wetland succession generally is consistent with a coastal plain or lacustrine plain deposit (see Tye and Coleman, 1989; Gibling and Bird, 1994). This succession has many characteristics of a delta plain deposit, but the environment of deposition can only be inferred without accurate, regional geomorphic evidence. For the purpose of this interpretation, a general delta plain model is used to interpret the depositional history.

This facies succession occurs in a paleoenvironment interpreted as the non-marine part of a river-dominated delta (delta plain) and shows no evidence of marine influence and wave

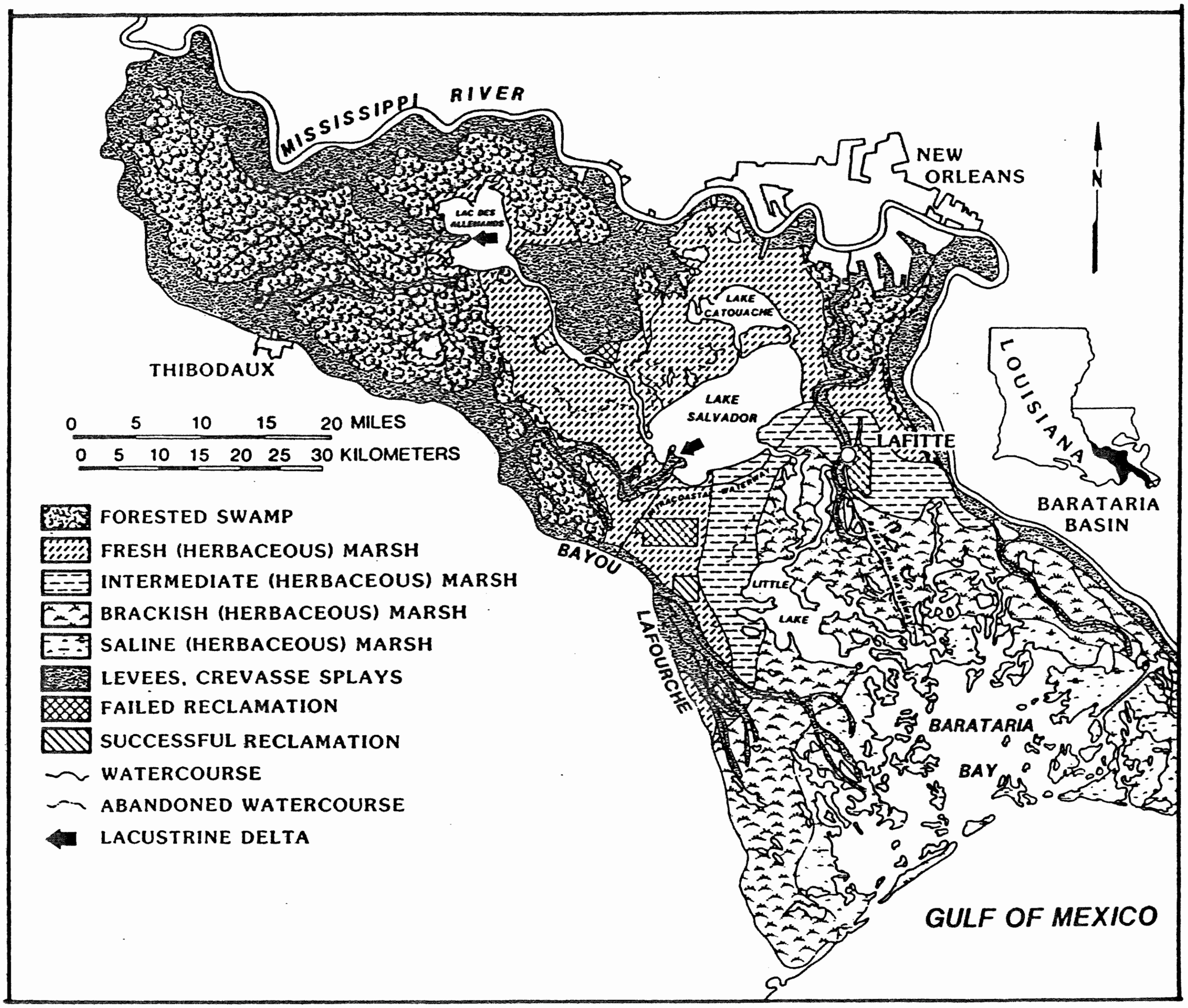


Fig 4.1 Hypothetical representation of the possible environment of deposition at Joggins, based on the Barataria Bay, interdistributary bay sequence (Mississippi Delta Plain). The thesis section may fall in the upper delta sequence near lacustrine environments and away from any marine influence (Kosters, 1989)

reworking. Chapter 2 interpreted each stratigraphic type as individual sedimentological bodies in a delta plain environment. The dominant features are overbank (flood plain) deposits such as crevasse splay (sheet sandstone) deposits, and grey mudstone, shale, coal and limestone. A minor channel sandstone in *wetland interval 1* cuts across the overbank (flood plain) deposits and represents a small-scale deltaic distributary channel (Elliott, 1974; Fielding, 1986; Gibling and Bird, 1994). The overbank deposits form small-scale cyclic CUS, beginning above a prominent coal bed or seam representing a flooded surface, or mire in which peat accumulated.

4.1.1.1 Interdistributary bay fills

The coarsening-upward sequences are indicative of interdistributary bay fills (Elliott, 1974; Tye and Coleman, 1989; Bhattacharya and Walker, 1992; Gibling and Bird, 1994), formed by the progradation of sediment from a distributary channel into a shallow interdistributary bay (coastal plain) or lake (Fig 2.9). Interdistributary bays are the areas between deltaic distributaries, and include coastal lakes and basins which constitute the delta plain (Coleman, 1964; Elliott, 1974). Prominent features are levees, crevasse sands, minor channels and extensive areas of vegetation (potential areas for peat growth and the formation of coal). The transport of sediment into these bays commonly leads to colonization of the abandoned surface by land plants such as *Calamites,* and lycopsid trees. The thicker crevasse splay lobes or channels are likely to form the top unit of the bay fill sequence, indicating sheet erosion (Elliott, 1974).

These deposits may also represent the progradation of delta lobes in areas close to major river mouths (observed on the Mississippi delta), and thickness of the units would depend on the scale of the delta and the water depth (Bhattacharya and Walker, 1992). But the small scale of the deposits and thin (2-10 m) CUS intervals do not indicate a typical Mississippi delta lobe progradation, and more closely resemble sediment deposition in small shallow water bodies, interlobe areas or lakes. According to Bhattacharya and Walker (1992), interdistributary and interlobe areas tend to be mud dominated, and contain stacked CUS which are much more irregular than the successions found in prograding deltaic lobes.

Fielding et al. (1988) suggest that as shallow water bodies (lake or bay) are filled by sediment from prograding delta lobes or distributary channels, a delta plain setting is established, and following abandonment the delta subsides and the cycle repeats. Peat formation will usually persist on the abandoned surface until the subsidence rate exceeds that of peat growth, leading to drowning. The next progradation of sediment then builds into the water body. Thin coals with carbonaceous shale partings and high ash content develop when clastic influx is great (Gibling, 1987). Thick coal seams develop only after a prolonged period without sediment influx (Kosters, 1989).

4.1.1.2 Peat formation

Peat formation in wetland deltaic environments occurs under low-energy conditions where sediment flow in the delta plain is segregated from peat-forming backswamps or mires. Kosters (1989) also indicates that deltaic peats accumulate in areas relatively isolated from clastic sedimentation, and the thickest deposits occur in the central parts of large abandoned interdistributaries or interlobe areas of the upper to central delta plain. Small-scale interdistributary bays between active distributaries of the prograding Mississippi delta, regularly experience daily flushing by river water and may be filled entirely by a crevasse splay, and therefore show thin poorly developed coal beds and other organic facies (Kosters, 1989). In the case of interlobe basins, which become isolated between distributary channels of different deltaic complexes, a long hiatus in clastic sedimentation allows for the formation of thick and extensive coal seams (Kosters, 1989). Gibling and Bird (1994) note in their study of the Late Carboniferous Sydney Basin that economic coals formed on extensive coastal platforms where low-gradient alluvial plains were drowned.

In deltaic settings, clastic influx must take place and occurs on two different time scales: 1-100 yr. (overbank flooding and crevasse splays), or 100-1000 yr. (delta-lobe switching) (Kosters, 1989). When overbank flooding is common, peat accumulation is often interrupted and diluted to organic-rich material such as carbonaceous shale. The thick economic coal seams (Queen and Joggins seams) formed in mires often influenced by clastic influx (formation of carbonaceous shale partings), but where overbank deposition was otherwise minimal. Thinner uneconomic, and inextensive coal seams (found in *wetland interval 1 and 2*) probably formed in shallow water bodies (1-2 m) during times of low groundwater levels. Rust et al. (1984) suggest in their study of the MacCarrons River Member (Springhill Mines Formation) stratigraphically higher than the thesis section, that the lack of thick coal seams results from low water tables and frequent progradation of crevasse splays over swamps, due to locally rapid basin subsidence.

4.1.1.3 Limestone formation

There is only one limestone in the thesis section and it is located at the top of the section immediately above a thin coal seam. As mentioned in Chapter 2, the limestone formed after the inundation of a peat-forming mire (mature *Histosol* horizon), resulting from a marked rise in relative base level (forming standing water bodies) in an interdistributary bay environment.

There was no detailed paleontological study done on this carbonaceous limestone which might indicate brackish water conditions during its formation, but Duff and Walton (1973) interpreted brackish limestones (similar to the limestone found in the thesis section) in the lower sections of the Joggins Formation (Lower Cove). Therefore the possibility of nearshore marine influence during the formation of this limestone cannot be ruled out. Paleontological work by Archer et al. (1995) in the lower section of the Joggins Formation between Little River (Lower Cove) and Bells Brook, suggests limited brackish water conditions. Some invertebrate trace fossils and agglutinated foraminifera found co-occurring in the strata indicate tidal influences and therefore the possibility of an estuarine setting. This interpretation cannot be made for the thesis section without proper paleontological evidence, but considering the close stratigraphic proximity (150-200 m) to the beds observed by Archer et al., it does remain a possibility and worth future investigation.

4.1.2 Dryland facies succession

The dryland facies succession classifies as an alluvial plain deposit. This succession contains a red mudstone facies (flood plain deposits), lacks major coal seams, and represents a drop in base level (groundwater) and well drained flood plain (Rust et al., 1984; Gibling and Bird, 1994). The red mudstone beds are mature paleosols that in some respects resemble vertisols formed where climate is strongly seasonal and groundwater levels are generally low (Gibling and Bird, 1994). The red colouration is found only in the mudstones and siltstones which contain abundant carbonate nodules, and the only vegetation present is root bioturbation, and leaf impressions.

In most cases, the contact between the grey mudstone (wetland facies) and the red mudstone (dryland facies) is fairly sharp (Fig 3.1) indicating a sudden change in relative base level (tectonic and eustatic factors discussed in section 4.2). Dryland interval 2 (~100 m upsection) is cut by a 6 m vertically-accreted channel sandstone which underlies a thick coal seam (Queen Seam), marking the start of a wetland interval. This major channel cut probably raised groundwater or surface water levels through overbank flooding, producing numerous shallow standing water bodies in the overbank facies and causing peat growth in newly formed mires. At this point the dryland facies succession disappears and the wetland delta plain succession dominates indicating a dramatic change in depositional environment.

There is only one significant coal seam in the alluvial plain succession and it occurs in the first dryland interval (50 m upsection). The coal seam is found within a 3 m grey facies (wetland) which represents a slight rise in groundwater level within the alluvial plain. The coal seam overlies a 2 m hydromorphic soil (seat earth) with abundant roots, coal stringers, and carbonate concretions. The coal seam has a thick (~20 cm) carbonaceous shale parting and two 7 cm coal beds with abundant plant material (leaf fragments), indicating that the peat mire (shallow water body) was prone to frequent clastic influx, and was not able to mature into an economic, low ash coal seam. The transition from a reddish-grey to red mudstone above the coal seam signifies a gradual drop in groundwater levels and the continuation of the dryland facies succession.

4.2 Cyclicity of Facies Successions

Tectonic and glacio-eustatic effects are factors in interpreting the formation and cyclicity of the wetland and dryland facies successions, and are usually interrelated. In this case, tectonic factors refer to basinal or local subsidence, the latter resulting from local fault activity. Glacio-eustatic factors include sea level fluctuations resulting from glacial retreat and advance. In determining the origin of cyclicity in the facies successions, allocyclic factors (tectonic, glacio-eustatic and climatic processes) often coincide with autocyclic factors (delta switching, channel migration and avulsion) (Read and Forsyth, 1989).

Many workers have recognized the distinct cyclicity of delta plain deposits throughout the Carboniferous and more recent times. One purpose of this study is to determine, through comparison with other coastal and lacustrine plain studies in North America and Great Britain, the reasons for the cyclicity of wetland (delta plain) and dryland (alluvial plain) facies successions. The ultimate factors which caused cyclicity in the thesis section can be postulated from the regional setting of the Joggins Formation and from previous work in similar depositional (delta plain) environments.

4.2.1 Autocyclic effects

Duff and Walton (1973) interpreted cyclic sequences in the lower part of the Joggins Formation as a result of periodic channel migrations (autocyclic events) superimposed on general basin subsidence (allocyclic events) of the delta plain. In their model, the supply of sediment is great enough that mudflats become established above the general level of the water table and reddening of the sediment is possible. Peat formation is minimal in this dryland surface (alluvial) resulting from the high level and rate of sedimentation. Eventually the channel moves away (by cut-off or avulsion), sediment supply decreases, and general subsidence of the area produces a wetland environment (delta plain) in which peat formation is possible. In some cases the subsidence continues and mires are overcome by rising waters producing calcareous limestones. Duff and Walton (1973) conclude that a marine transgression produced the limestone beds at Joggins. The Duff and Walton model, which invokes autocyclic events (e.g. channel switching) to explain small-scale cycles, can be applied to the wetland and dryland facies successions of the thesis section, but glacio-eustatic effects should also be examined in more detail.

4.2.2 Allocyclic effects

4.2.2.1 Tectonic effects

Rust et al. (1984) recognized the effect of basin subsidence and possible base level fluctuations (Springhill Mines Formation) on the formation of vertically accreting channel sandstones, coal seams, and abundant red mudstone beds. Elsewhere in the region, Gibling and Bird (1994) note that tectonism was active in the Maritimes Basin during the Late Carboniferous and that lateral facies variation may reflect differential subsidence over faulted basement rocks. The authors also suggest a glacio-eustatic influence (for the Sydney Basin), stating that Late Carboniferous sea-level fluctuations linked to Gondwanan glaciation (see Tandon and Gibling, 1994), have been estimated at several tens of metres, and that development of an alluvial setting would accompany a substantial base level drop in the coastal plain.

4.2.2.2 Tectono-eustatic and climatic effects

Relative base level fluctuations superimposed on basin subsidence are inferred to be the main allocyclic factors that influenced cyclicity in the thesis section. Basin subsidence was probably a "background" factor allowing long-term sediment accumulation, and may be applied to the formation of the numerous facies successions in the distal parts of the delta plain, together with relative base level fluctuations. The Cumberland Basin is bounded by major faults, and sudden downdrops from periodic fault movements ("punctuated subsidence") may have lowered the delta plain (from an alluvial dryland setting) producing flooding surfaces where peat growth and wetland conditions prevailed (coinciding with relative base level fluctuations). This tectono-eustatic step process may be evident in the stacked, coarsening-upward parasequences (interdistributary bay fills) and flooding surfaces which dominate the wetland succession. If long term tectonic effects such as uplift and basin subsidence were the major factors in determining cyclicity in the thesis section, then a gradual coarsening upward trend from red mudstones to thick channel sandstones, and steepening of the alluvial surface might be evident in the stratigraphic section (Rust et al., 1984). In fact, the thesis section does not show an overall coarsening-upward trend, and shows no concentrations of major channel bodies or continuous red beds.

Climatic changes (allocyclic) cannot be ruled out in causing cyclicity within the facies successions. Long-term dry seasons would produce a red bed succession as water tables lowered, decreasing the likelihood of peat growth and flooding surfaces. Long-term wet seasons would flood the delta plain creating numerous standing water bodies and increased peat growth in mires. Difficulty arises in interpreting these climatic effects as the sole causes of cyclicity, and therefore may coexist with tectonic and eustatic effects.

4.2.2.3 Model for relative base level fluctuations

This section provides a model for relative base level changes within the thesis section. The section contains relative lowstand and highland systems which accumulate during various phases of fall, rise and stabilization of sea level (Kosters and Suter, 1993). In the Exxon model, the maximum flooding surface (MFS) represents the top of the transgressive systems tract, and marks the boundary between two genetically different depositional episodes (Kosters and Suter, 1993). Parasequences are relatively conformable successions of genetically related beds or bedsets bounded by marine flooding surfaces or their correlative surfaces (Van Wagoner et al., 1990). Each "wetland" interdistributary bay fill deposit represents a parasequence, and the flooding surface is indicated by a coal bed. Progradation and abandonment of a single delta lobe within an interdistributary bay or lake creates a parasequence, and the stacking pattern of these parasequences may in some cases be related to sea level fluctuations (Kosters and Suter, 1993). It must be noted that there is no direct evidence that the thesis section was ever in contact with marine/brackish waters. Therefore, the discussion below makes references to relative base level fluctuations, which probably represent changes in groundwater or lacustrine levels in the measured section; these can be greatly influenced by eustatic changes. The term "coastal" may also refer to the marginal facies of a freshwater body.

The first wetland interval (*wetland facies interval 1*) represents a relative highstand of base level under which the coastal plain environment dominates. Relative base level progressively drops, transforming the wetland succession into a dryland succession (lowstand period). However, no distinct lowstand surface (e.g. mature paleosol, valley fill) was noted in the section. The highstand succession contains stacked parasequences (bay fills) which may indicate fluctuations in relative base level. The lowstand succession indicates the lowest position of relative base level. A transgressive period may be indicated by the upper red mudstone facies where alluvial processes such as overbank sedimentation and crevassing dominate. The first dryland interval (*dryland interval 1*) shows an abrupt transgression into the next flooding period (*wetland interval 2*). This thin wetland interval extends upward into another lowstand period, marking the second major drop in relative base level and the last dryland interval of the section (*dryland interval 2*). This dryland interval may also include a transgressive period, extending upward into a relative highstand separated by a third major flooding episode (Queen Seam). The last relative highstand (*wetland interval 3*) also contains stacked parasequences (bay fills) separated by thick (Joggins Seam) and thin flooding surfaces, indicating significant fluctuations in relative base level. The top of this wetland interval contains a major flooding surface (coal and carbonaceous limestone) representing a dramatic rise in relative base level and a major transgression within this parasequence set.

4.2.2.4 Effect of eustasy on delta plain hydrology and coal distribution

Variations in relative base level are usually accompanied by changes in delta plain hydrology (Kosters and Suter, 1993). These relative base level fluctuations greatly affect the depositional environment. For example, during a rise in base level, fresh groundwater may be recharged into the delta plain through bay-fill and overbank sediments which underlie the peat beds (Kosters and Suter, 1993), creating standing bodies of fresh water (mires) where high quality peatlands can form and extend laterally. Significant volumes of peat can be preserved to form coals only where the overall increase in accommodation (a function of base level and subsidence) approximately equals the accumulation rate of peat (Bohacs and Suter, 1997). In delta plain settings, the base level of deposition is the groundwater table. A large influx of sediment will dilute the organic matter and can kill the peat. In contrast, when the increase in accommodation greatly exceeds the peat production rate, the mires are inundated by lake or groundwater (Bohacs and Suter, 1997), and can produce limestones. Peat thickness is controlled by the ratio of the rates of accommodation and peat production. For example, above a critical threshold (normalized accommodation rate), mires can grow and thrive because of relatively stable conditions and rising groundwater levels (Bohacs and Suter, 1997). These mires quickly fill the local accommodation vertically and then spread laterally away from sediment influx. The Queen and Joggins Seams are thick and laterally extensive, but the abundance of carbonaceous shale partings in each seam indicates that the mires were prone to sediment influx and managed to thrive despite the stress.

The rise in groundwater base levels (due to relative base level fluctuations) results in the wetland facies succession represented by grey mudstones and waterlogged, fossiliferous sediments. As sea level stabilizes during highstand, groundwater discharges into the sea and is lost to the delta plain, eliminating thick, high quality peats (Kosters and Suter, 1993). As the sea level drops further, the delta plain environment settles into a lowstand condition, and the groundwater levels remain below the surface allowing a dryland (alluvial plain) facies succession to form with well developed paleosols. During the subsequent transgressive period, occasional fluctuations in relative base level may cause abrupt increases in groundwater levels allowing the growth of poorly developed peats in small water bodies with high sediment influx.

CONCLUSIONS

(1) The Joggins thesis section is interpreted as a fluvial to delta plain deposit and contains two major facies successions: *wetland facies succession* and *dryland facies succession*. The wetland facies succession represents a *coastal plain or lacustrine* environment. It comprises grey, rooted mudstone beds with stacked crevasse splay deposits (containing in situ lycopsid trunks, *Calamites* and *Stigmaria*), minor channel sandstone bodies, thin (1-10 cm) and thick (10-90 cm) coal seams, and one carbonaceous shelly limestone bed indicating a major flooding event. The main lithological feature of this succession is the repeated coarsening-upward sequences from mudstone to sandstone, deposited above prominent flooding surfaces (coal beds and carbonaceous shales). These deposits are interpreted as interdistributary bay fills or delta lobes in areas close to major river mouths. These coarsening-upward sequences are stacked in relatively regular intervals (forming a parasequence set) and may represent fluctuations in relative base level and subsidence. The dryland facies succession formed in an

alluvial plain environment and contains abundant red mudstone beds with carbonate nodules, stacked crevasse splay deposits, minor channel sandstone, and thin coal.

(2) The wetland and dryland facies successions alternate upsection in regular intervals on a scale of 10-47 m. Boundaries between the red and grey successions are gradational, and the strata comprise progradational (grey to red upwards) and retrogradational (red to grey) parasequence sets. Sequence boundaries could not be identified. The wetland intervals are interpreted as having formed during a relative highstand of base level while the dryland intervals represent lowstand periods of relative base level. These fluctuations in relative base level affected the groundwater hydrology of the delta plain environment. As relative base level rose, groundwater was probably recharged into the delta plain creating standing water bodies, bay fills and overbank deposits, and promoting peat growth. Low relative base levels created a dry, alluvial plain environment, diminishing peat growth. In this setting, minor flooding surfaces formed during occasional flood events or during wetter periods (climatic effects), producing thin rheotrophic peats with high clastic input.

(3) Cyclicity of the facies successions results from allocyclic and autocyclic factors, although the effects of the different processes are difficult to distinguish. Allocyclic effects that probably affected the basin during Joggins deposition include: (i) tectonic factors such as basinal or local subsidence (resulting from fault activity), (ii) glacio-eustatic effects causing relative base level fluctuations, and (iii) climatic effects such as dry or wet periods. Autocyclic effects include delta switching, channel migration and avulsion which often coincide with allocyclic effects. The preferred interpretation for the cyclic behavior of the facies successions is

fluctuations in relative base level (probably eustatic in origin) coinciding with sudden periodic subsidence (as opposed to continuous subsidence), resulting from fault activity in the basin. Furthermore, coupled with these tectono-eustatic effects are possible climatic changes on the delta plain which may have reddened the sediments during long-term dry seasons (low water table), and formed a wet environment during long-term wet seasons (high water table).

FUTURE WORK

Future areas of study include the carbonaceous limestone with bivalves and ostracods located at top of the section. An accurate interpretation of the trace fossil assemblages and agglutinated foraminifera is needed to determine if this limestone was formed in a brackish or fresh water environment. This study may indicate if this part of the Joggins Formation was also exposed to estuarine conditions and closer to marine influences than previously thought. Other work includes a thick concealed interval (~ 80-100 m) between the limestone and the cliff section measured by Tonelli (*in* 1997). This poorly exposed area borders the disputed boundary between the Joggins Formation and Springhill Mines Formation, but contains well exposed sandstone reefs. Finally, more extensive work should be done on the allocyclic effects (tectonic and glacio-eustatic) of cyclicity by comparing the section with other geological data in the Cumberland Group strata and determining correlations.

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APPENDIX A: DESCRIPTION OF LITHOLOGICAL UNITS

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
1	0.04	coal	sharp		black/yellow	seat earth, shaly		plant fossils, leaf fragments	coal stringers
2	0.90	carbonaceous shale/coal			black/dark grey and stained	diffuse layers, unbedded		plant fossils	yellow crystals, coal stringers
3	0.45	clay mudstone	sharp		medium grey	CU (mudstone to silty mudstone), friable		thin organic layers, roots, calcareous vertical roots	clay texture
4A CUS	1.07	mudstone	sharp		medium grey	blocky near top	minor stratification, interbeds of light grey shale	thin organic layers (mm)	vertical roots (1-3 cm wide)
4B CUS	0.75	silty mudstone	sharp (organic layer)		medium grey/ yellow stain	coarse interbeds of silty mudstone or siltstone	rooted shaly layers	large insitu tree, 70 cm diameter with roots	deep drowning event
5	1.25	sandstone	sharp	fine	light grey/brown	platy, bedded, lenticular (fills), blocky beds	planar/cross laminations, erosional bases, bioturbation	fossil traces, roots, fossil tree (1.5 m) insitu, Stigmaria root (5-8 cm wide)	paleo indicators
6	0.50	siltstone	gradational		light grey/ stain orange	FUS		root fragments	seat earth, heavily rooted
7	0.20	carbonaceous shale/coal	sharp		dark grey organic layer/orange	shale/mudstone/org anic layer		plant, root traces, leaf fragments	immature coal
8A	0.62	silty mudstone	sharp		medium grey/	thin organic layers, crumbly	2-3 cm carb. shale midsection	abundant root traces	siderite nodules
8B	0.85	silty mudstone	sharp		medium grey	platy and blocky		plant, root traces	siderite nodules
9	1.75	sandstone, interbedded mudstone	nodular	fine to medium	light grey/brown	blocky, semi-planar base, mudstone interbeds	ripple cross laminations, scour channels	tree imprint insitu , root traces	paleo, parallel/ cross lams.

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
10	2.50	sandstone, interbedded siltstone and mudstone	sharp	fine	light grey/ brown	blocky, lensoidal sand, minor CU from silty mud to sand	cross/parallel laminations	carbonaceous shale at base (1-2 cm thick)	fossil roots and Calamites
11A	4.00	channel sandstone	sharp and erosional	fine to medium	light grey	interbedded shale channel fills	flute marks, tool marks, current lineations, linear grooves, planar laminations, trough ripples	organic shale, coaly layers	paleo
11B CUS	3.00	siltstone, silty mudstone	sharp		grey siltstone, red mudstone	cut by overlying channel sand		root traces, rare plant fragments	siderite nodules, overbank deposit?
11C	4.00	channel sandstone	sharp erosional	fine	light grey/red	planar bedded, slumped deposit	cross laminations, ripples	root traces in slump, bark and fossil layers	multiple channel cut sequence, channel fill with slump body
12	1.00	silty mudstone	sharp		light grey/ green grey	heavily rooted		root traces, plant fossils	basal seat earth
13	0.30	mudstone	sharp		medium grey/ green grey	poorly bedded, basal black carbonaceous shale layer (lower 15 cm), blocky		abundant roots and plant fragments in shaly layers, almost coaly	heavily rooted, flooding event
14 CUS	0.40	silty mudstone to siltstone to sand	gradational		medium grey/ brown grey	shaly		abundant roots and root traces	nodules common, fast flood event
15	1.00	sandstone	sharp erosional	fine	light grey	lenticular erosional bed into lower sand, thins out, blocky beds, thin interbedded mudstones	ripples, cross laminations	plant, root fossils, traces	paleo

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
16	0.80	silty mudstone and siltstone interbeds	sharp erosional		red/ red-grey	3 siltstone interbeds		root traces, roots	nodular base
17A CUS	0.70	mudstone	gradational		medium grey/ red grey	heavily rooted, no bedding		vertical root traces	flood channel fill
17B CUS	0.50	siltstone	gradational		medium grey/red stain		planar laminations	root traces, Stigmaria	remnants of tree near base
17C CUS	2.75	sandstone	sharp erosional	medium	light grey/ red-grey	lensoidal channel base, planar beds,	trough cross beds parallel/cross laminations	Calamites insitu, large roots abundant, basal tree trunk insitu (25 cm diameter)	nodules common paleo
18	0.35	silty mudstone/ mudstone	sharp		light-medium grey	lensoidal features	minor bedding	root traces	abundant nodules
19	3.00	sandstone/ siltstone/silty mudstone	sharp		medium grey, some red layers	planar, interbedded red siltstone	cross bedding, basal scour grooves, rippling	insitu tree (22 cm diameter) within underlying unit, roots	
20	0.80	concealed							
21	0.40	mudstone	sharp		light grey/brown	crumbly, blocky	thin basal shaly layer	rare rooting	flood event?
22	0.40	mudstone	sharp		red/brown	crumbly, shaly	organic rich layer (0.5 cm)	roots and root traces	wavy base
23	0.80	sandstone/ siltstone	sharp	fine	light red-grey/ red-grey	planar top, interbedded mudstone, lenticular sands	scours, wavy contact, trough cross beds, rippling	plant fossils common	concretions common, erosional surfaces
24 FUS	0.30	siltstone to mudstone	sharp		red	friable		grey organic mudstone layer at base, heavily rooted	
25	0.55	sandstone	sharp	fine	light grey/brown	planar to wavy, uniform bed thickness	planar laminations, rippling	root fossils and traces	mudstone interbed
26 CUS	0.70	mudstone to siltstone	sharp		red	planar, crumbly			

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
27	0.10	siltstone	gradational	fine	medium grey	crumbly		fossil traces	
28	0.60	mudstone	sharp		red	crumbly, basal grey mud			colour change
29	0.30	sandstone	sharp	fine	light grey/ orange red	semi-planar (erosional base)		root traces, large root into basal mudstone	splay sand?
30	0.40	silty mudstone	sharp		red	CUS to sand, crumbly, unstratified,			
31	0.15	sandstone	gradational	very fine	red-grey/ orange		faint parallel and cross laminations	minor roots and traces	rounded orange concretions (siderite) abundant
32	0.30	mudstone/ siltstone	sharp		red-grey	CUS mudstone to siltstone, friable mudstone, non-stratified siltstone			colour change
33	0.25	sandstone/ siltstone	sharp	fine	red-grey to light grey	indurated, continuous bed, wavy base		root fossils and traces	mottled
34	1.10	mudstone	sharp		dark red	friable, crumbly, 3 medium grey carbonaceous shale and mudstone layers		minor root traces	large nodules (5-25 cm width)
35A	0.45	mudstone	gradational		red	basal grey organic clay		roots and traces common	abundant rounded calcareous nodules (10-25 cm dia)

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
35B	0.20	silty mudstone	sharp		red	cut by overlying sandstone, basal carbonaceous unit		rooted beds	channel scour, thins out
36	1.50	sandstone	sharp	fine	light grey to red-grey/orange weathered	3 interbedded units of red mudstone (friable) 10-30 cm and rooted	undulating surfaces	root traces	nodules, grey bands
37	0.70	mudstone	sharp		red	friable, chippy, uniform		large roots, heavily rooted	
38 CUS	0.40	mudstone to siltstone	gradational		red	mudstone chippy, grey bands of carbonaceous shale, non-stratified, blocky siltstone			calcareous nodules common
39 CUS	0.85	silty mudstone to siltstone	sharp		red to light grey	chippy mudstone, mottled stringers, grey carbon-aceous shale layers	carbonaceous shale between mud and silt	root traces (mottled)	calcareous nodules (5-8 cm length)
40	0.50	sandstone	sharp	fine	light grey/ brownish-grey	semi-planar beds, wavy base (undulating)	parallel and cross laminations		calcareous sandstone (cement), large calcareous nodules (5-30 cm dia), paleo
41 CUS	0.90	mudstone to siltstone	sharp		red/green grey			roots abundant	rounded concretions grey bands in base and midsection

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
42	1.50	sandstone/ mudstone	sharp	fine	greenish grey	interbedded red and grey silty mudstone, non-planar beds		root traces abundant from sand into interbeds	concretions (siderite)
43	5.00	mudstone, siltstone interbeds	sharp		red with interbedded grey	basal sandstone lenses, crumbly, upper 2 m: silty mudstone, orange stained, high organics, seat earth, coal stringers		organic shaly layers, heavily rooted	concretions abundant (1-5 cm wide)
44A	0.08	coal	sharp		black/orange-yellow stain	well formed, planar		plant fragments abundant	swamp surface
44B	0.17	carbonaceous shale	sharp		dark grey/ blue-grey			plant fossils common, coal stringers	orange yellow weathered
44C	0.07	coal	sharp		black/orange	planar		plant fossils	yellow stain
45	1.20	silty mudstone	sharp		reddish grey/ light grey	blocky/chippy texture, no stratification			rare concretions
46	0.45	sandstone	sharp	fine	light grey/ orange	lensoidal sandstone, thins out in some places	minor laminations, ripples		crevasse splay?
47	2.50	mudstone	sharp		red/green-grey	siltstone interbed, mudstone chippy, CUS in upper 1 m sand		remnants of Stigmaria in silt/sand, rooted silt/sand bed	calcareous nodules (5 cm length)
48A	0.90	sandstone	sharp	fine	light grey/ reddish-grey	siltstone and silty mudstone interbeds, erosional surfaces on sandstone			

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
48B	0.70	mudstone & silty mudstone	sharp		0.4 m= red mud, 0.3 m= light grey	CU from mudstone to silty mudstone, minor grey bands of organic shale, blocky and chippy		rooting	3 large concretions (calcareous nodules)
48C	1.10	sandstone	sharp	fine	light grey/ brown-grey	10 cm silty red mudstone interbed, massive sand and well indurated, overlying shaly partings, planar top and base	ripple cross laminations, ridge and furrow, large cross beds		
48D	0.65	mudstone	sharp		red	chippy, some silty parts, planar bed, angular clasts		rooted	abundant small rounded concretions
48E	1.50	sandstone	sharp	fine	light grey	planar bed, erosional scours or minor channels, well cemented, 3 interbeds of silty mudstone & siltstone	cross beds, ripples, small channels, wavy bedforms	large tree present in upper region (15 cm dia.)	rounded concretions in silty mudstone,
49	4.00	concealed	-	-	-	-	-	-	-
50A	0.15	coal/ carbonaceous shale	sharp		black			plant fossils	seat earth for 1 m below coal (no contact visible)
50B	2.00	mudstone	sharp					organics	

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
51A	0.70	sandstone/ siltstone	sharp	fine	light grey/ red-grey	planar beds, with interfingering siltstone (10 cm)	mudstone interbeds	plant fossils present, root traces	organic layer on top
51B	0.20	mudstone	sharp		light grey/ medium grey	platy		faint root traces	nodular concretions
51C	0.60	sandstone	sharp (erosional surface)	medium	medium grey/ brown	lensoidal beds	faint cross beds, large ridge and furrow, scours, parallel and cross laminations	Calamites (8 cm) and root fragments	nodules rare
51D CUS	0.70	mudstone to sandstone	sharp	v fine to medium	medium grey	friable mudstone, wavy planar sandstone beds	faint parallel laminations	plant fossils	nodules present
52	2.70	mudstone	sharp		mottled red-grey/ brown grey	CU to siltstone (base to 1 metre), friable mud, platy thin beds of siltstone	faint planar bedding	no visible fossils	abundant nodules (5 cm)
53A	0.65	sandstone	gradational	fine	light grey/ red grey	planar beds (0.20-0.65 m)	parallel laminations, minor cross beds	plant fossil impressions at base	paleocurrent evidence
53B	0.40	siltstone to mudstone	sharp	medium to v fine	red-grey/ green grey and red	FU from siltstone to mudstone, friable bed with planar color changes (red to grey)		thin organic layers in siltstone, root traces	rare nodules
53C	0.80	sandstone	gradational	medium	light grey/ green grey and rusty red	thickening bed, lensoidal erosional grooves within thin planar beds (10 cm), mudstone and siltstone interbeds	cross and parallel laminations	remnants of tree trunk (curved bedforms), rooting near base of tree	

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
53D	0.20	siltstone	sharp	fine	mottled red-grey	friable bed, mudstone interbed (thin)		root concretions	nodules (4 cm)
53E	0.25	sandstone	gradational with erosional grooves	medium	light grey/ red-grey	planar beds (0.25 m)	erosional grooves, some undulating sands	rare fossil fragments	
53F	0.40	siltstone		fine	mottled grey red/green grey and red brown	friable bed with grey siltstone beds (3 cm)	jointed		nodules common (8 cm)
53G	0.25	sandstone	gradational with erosional grooves	fine to medium	light grey/ red-grey	continuous undulating bedding surface, interfingering mudstones		Stigmaria root to basal unit	wet/dry flood event
53H	0.15	siltstone	sharp	fine	light grey/ red grey	friable bed pinched by sandstone grooves		root traces and fragments	nodules common
53I	0.15	sandstone	gradational with erosional grooves	fine	grey/red grey	blocky layer consolidating into underlying siltstone		root fragments	large nodules (12 cm)
53J	0.50	siltstone to sandstone	sharp	v fine silt to medium sand	grey/brownish grey	friable bed with grey siltstone layer coarsening up to a sand bed, nodular bed between silt and sand		roots and root traces	nodules common (siderite ~11 cm)
53K	0.20	mudstone	sharp		grey/green grey	overlain by carbonaceous shale, friable bed of mudstone, platy and blocky weathered		roots, root traces	

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
53L	0.18	mudstone	gradational		red/red brown	friable bed, blocky weathered		root traces, organic fragments	
53M	0.55	sandstone	gradational with erosional grooves	fine to medium	light grey/ green reddish grey	lensoidal concave up/down bed with thin interbedded mudstone	planar and cross laminations, ridge and furrow, platy		paleoflow evidence
53N CUS	0.60	mudstone to sandstone	sharp	v fine to fine	red and green grey/red and light grey	friable bed (mud 5 cm, silt 15 cm, sand 20 cm)	planar laminations in sandstone	organic fragments	small nodular concretions
53O CUS	0.40	mudstone to sandstone	sharp	v fine to fine	red to light grey/ red and green grey	friable bed	parallel laminations in sandstone	root fragments, Calamites in all lithologies	
53P CUS	0.60	mudstone to sandstone	sharp	v fine to fine and medium	red to light grey/red and green grey	25 cm well indurated sandstone	planar bedding, major, sharp erosional grooves underlying sandstone	root traces, and rare root fragments	small nodular concretions
53Q CUS	0.92	silty mudstone to sandstone	sharp	fine to medium	light grey/ green reddish grey	friable siltstone bed with thin organic layer, planar, dominant sandstone beds (75%)	erosional grooves, cross laminations,	large root fossils in siltstone	small nodular concretions common
54	2.50	mudstone	sharp		red to green grey/ red grey	friable mud, interbedded planar sandstones	parallel laminations in sandstone	root fossils	sandstone beds 70 cm thick in total

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
55A CUS	3.20	mudstone to siltstone	sharp	v fine	light red/green grey	siltstone (4 cm beds) and mudstone beds (>10 cm), friable bed with colour changes		root traces rare	small nodular concretions
55B CUS	0.50	sandstone	gradational with small channels	fine	light grey	interfingering siltstone, discontinuous planar bed, platy/blocky	faint trough cross laminations, mud infills between undulating surfaces		nodules (9 cm) in siltstone and some in sand
56 CUS	1.60	mudstone to sandstone	sharp	v fine to fine	light grey to red/green grey	interbedded, friable siltstone and mudstone layers, organic rich layers along siltstone, discontinuous sandstone planar bed with mudstone interfingering, grading up package	sandstone erosional grooves, undulating surfaces	plant impressions	nodules common (20 cm)
57A CUS	0.70	mudstone	sharp		red	platy basal mudstone with silty layers, friable top with nodules 3 cm below overlying unit	sandy lenses at base	grey carbonaceous shale layers near top	nodular rooted concretions (4 cm)
57B CUS	0.40	sandstone	sharp	fine	light grey/ green grey	discontinuous blocky bed with channel grooves (0.40 m), minor interbedded mud	undulating laminations, parallel laminations	sparse fossil fragments	

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
58	0.30	mudstone	sharp		red greenish grey	friable bed overlain by 1 cm organic layer, carbonaceous shale		root traces and root stems	nodules 4 cm
59	1.20	sandstone and mudstone infills	sharp	fine to medium	light grey/ red-grey	undulating beds, multi-channel fill sand with minor mud interbeds, major 3 m channel cut into underlying mudstone, mudstone infills between channels scour, erosional surface	channel scour (1.2 metres wide)	fossil impressions	large nodular concretions (12 cm) in mudstone
60	3.20	silty mudstone	sharp		light reddish grey/green reddish grey	friable bed with colour divisions, mottling mudstone, thin organic layers with yellow stain below overlying sandstone		root traces	1 cm nodules in mudstone
61	5.70	mudstone to siltstone to sandstone	sharp		light grey bands of siltstone and sandstone, red mudstone, mottled base	4 CUS sequences, sharp erosional base, friable beds, silt layers spaced 50 cm apart			abundant nodules in mudstone and along siltstone/ sandstone layers

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
62	6.00	sandstone with siltstone and mudstone interbeds	sharp	medium in sand	light grey/ brown grey	numerous major stacking channel sands with siltstone and mudstone interbeds, sandstone platy, 3 major fine intervals of dark grey mudstone and silty mudstone, lenticular beds or small scale channels, 4 major sandstones in unit, erosional scours abundant	large scale cross bedding, ridge and furrow, ripples, parallel laminations, flute casts	large tree found in basal channel sand, not insitu (length 1 m, diameter 20-30 cm), coalified plant or tree remains, plant fossils abundant and well preserved permineralized tree stump	non-calcareous cemented sandstones, paleo directions using ridge and furrow, and flute casts
63	0.85	silty mudstone to siltstone to fine sandstone	sharp	v fine to fine	light grey and mottled red/orange grey	CUS, silty mudstone to fine sandstone, blocky undulating sandstone		heavily rooted, (fossils and traces)	nodular concretions
64	0.40	mudstone to shale to seat earth	sharp		light grey/orange	FUS from mudstone to seat earth, dark grey shale layers		high organics, soil horizon, abundant plant fossils and roots	
65	0.20	coal	sharp		black/orange rusty colour	abundant pyrite, blocky			
66	1.50	mudstone/shale	sharp		medium grey/ stained yellow	planar bed, even thickness, minor grey carbon-aceous shale layers, platy		plant fossils evident heavily rooted	no concretions

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
67	0.70	coal with interbedded carbonaceous shale and shale (Queen Seam)	sharp		coal: black/orange shale: dark grey to black/orange	6 individual planar beds in unit with average thickness of 2-10 cm: coal, shale, coal, carbonaceous shale, coal, shale, coal sequence, shale crumbly		plant fossils uncommon in coal, but common in carbonaceous shale	*Logan Coal group No. 8* abundant pyrite (see notes)
68	1.30	mudstone	sharp		light to medium grey/red orange	platy near top, laminar 4 cm, some stratification and blocky		root traces and root fossils common	large 10 cm wide concretions (flattened)
69	0.80	sandstone, siltstone in upper 20 cm	sharp	fine	light grey/ orange	20 cm mudstone interbed (CU to sand), lenticular, not well indurated, wavy bedforms	large scale cross beds (5-6 cm amplitude), parallel/cross laminations, blocky beds	minor plant fossils, root traces abundant	
70	0.45	mudstone	sharp		light grey/ orange	crumbly		organic layer (middle)	calcareous nodules abundant (5 cm length)
71	0.60	sandstone	sharp	fine	light grey/ orange-brown	planar top and beds	cross beds, minor rippling	heavily rooted, large insitu root fossils (Stigmaria)	calcareous
72A	1.40	mudstone	sharp		medium grey/ orange-red	minor grey bands of non- and carbonaceous shale, (1-2 cm thick) platy mudstone	wavy bedforms	root traces and fossils, black carbon. shale	calcareous nodules abundant (2-5 cm length)

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
72B	0.40	sandstone/ siltstone lenses	sharp	fine	light grey	platy siltstone, lensoidal sands, surrounded by medium grey mudstone units 104 and 106	some rippling	roots abundant and traces common,	calcareous nodules abundant within siltstone and sandstone
72C	2.00	mudstone	sharp		medium grey/ orange	3 styles of mudstone: (1) bottom 60 cm, blocky, platy, (2) middle 1 m, chippy, some platy, rooted, light grey shale layers, (3) top 40 cm divided by light grey shale, blocky, silty, siltstone interbeds		rooting common, no fossils evident	nodular calcareous concretions
73	1.10	sandstone	sharp	fine to medium	light grey/ brownish grey	planar 40 cm sand with interbedded 15 cm siltstone, undulating, planar sand for 80 cm	channel groove, cross laminations, nodular shaped sandstone beds	insitu Stigmaria 1.3 m long, abundant root fossils	large nodules in siltstone (8 cm)
74	1.30	silty mudstone with inter-fingering lenses of sand	sharp	fine	red-grey mottled	friable bed, coaly shale at base		root traces, heavily rooted	nodules abundant in upper 70 cm
75	0.40	sandstone	sharp			undulating planar bed	large cross/parallel laminations	plant fragments at base, roots	vertical root nodules, tree trunk trace

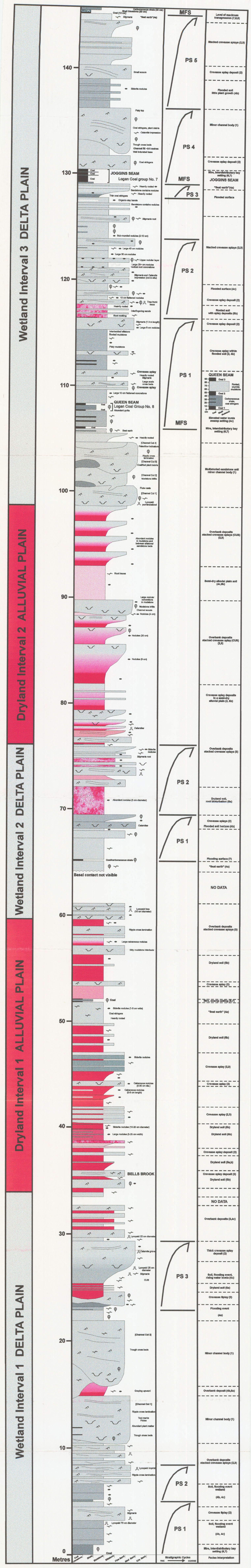
Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
76	0.40	silty mudstone	sharp		light grey/ light grey	friable, organic shale layer at top, nodular layers		root traces, vertical root extending down from upper unit	10 cm nodules, flattened
77	0.40	sandstone	sharp	fine	grey/green grey	planar bed with minor interbedded siltstone, bioturbation	parallel laminations	fossil fragments, insitu root traces	10 cm nodules
78	0.75	silty mudstone	sharp		light grey/ red-grey	friable bed with nodules, organic rich layer (0.12 cm up and <1 cm thick), platy yellow stained silt		root and plant traces	10 cm nodules
79	1.50	sandstone with mudstone/ siltstone interbeds	sharp	fine	light grey/ brown grey	planar base sand, interbedded siltstone (0.30 m), undulating sandstone bed, friable siltstone, minor grooves	trough cross laminations and parallel laminations	root and plant fossils abundant, remnant Stigmaria and Calamite impression (non-insitu)	large nodules in both lithologies
80	0.50	silty mudstone with nodular layer	sharp		grey/light grey	friable bed with 40 cm nodules near base, 0.30 m thin clay seam with underlying discontinuous and continuous nodular layer		organic rich layer along clay seam	vertical nodular root traces, large 25+ cm nodules
81	0.40	sandstone with nodular layer	sharp	fine	light grey/ red-light grey	planar beds, friable bed with nodular layer (0.15 m thick), yellow stain at base of siltstone, CU to sand		fossil fragments and plant fossils	nodular top (5-10 cm thick)

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
82A	0.70	mudstone	sharp	very fine	light grey/ light grey	basal organic rich layer, friable			large 30 cm nodules
83B	0.45	mudstone/shale	sharp	very fine to fine	light grey/ light grey	shaly organic layer (5 cm) with overlying massive discontinuous nodules, platy muddy siltstone		root impressions in organic layer, fossil traces in siltstone	40 cm nodules
84	0.70	sandstone	sharp	fine to medium	light grey/ red grey	planar sand beds with interbedded friable muddy siltstone	planar laminations	fossil fragments in sandstone	20 cm nodules in siltstone
85	1.55	mudstone	sharp	fine	light grey/ medium grey	friable bed with organic rich layer (10 cm thick)	grey organic shale interlayers	fossil traces in organic layer and nodular traces	sub-rounded nodules (2-10 cm length)
86	0.65	sandstone	sharp	fine	light grey/ brown	planar beds with interbedded siltstone	cross and planar laminations	fossil fragments in sandstone, insitu Stigmaria, root fossils	nodules in sandstone
87	1.65	silty mudstone and sandstone	sharp	fine	light grey/ orange	friable mudstone, nodular sandstone			organic bands in top 1 m of unit, abundant large nodules in mudstone, small in sand

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
88 CUS	0.85	carbonaceous shale/mudstone/ siltstone/nodular sandstone	sharp		dark grey to black shale, light grey mudstone	minor coal stringers		heavily rooted	rounded nodules in siltstone (1-10 cm)
89	0.45	sandstone/ mudstone interbeds (seat earth)	sharp	fine	light grey	seat earth		heavily rooted (upper 25 cm), insitu Stigmaria protruding from overlying coal seam	
90	1.37	coal/ carbonaceous shale (Joggins Seam)	sharp		black	base up: 15 cm coal/shale 61 cm coal 5 cm carbon. Shale 25 cm coal 5 cm carbon. Shale 25 cm coal			*Logan Coal group No. 7* * Note: lithology and thickness of seam taken from Logan (1845)
91	1.30	sandstone	sharp	fine	light grey	coal stringers and plant debris, lenticular beds, platy top	cross beds	fossiliferous	
92	1.50	silty mudstone	sharp		red				
93	1.4 to 3.00 max	sandstone	sharp	fine	light grey/ brown	well indurated base, platy top (upper 50 cm), variable thickness	channel sandstone, well formed cross and parallel beds, large scale rippling, trough cross beds,	abundant plant fossils, plant debris, root fossils, coal stringers, Calamite impression	
94	2.8	siltstone/ mudstone	sharp		medium grey/red	platy			siderite nodules
95	1.3	sandstone	sharp	fine	light grey	platy, undulating bedforms	rippled, cross beds, small scours, abundant parallel/cross laminations		

Unit No	Thickness (m)	Lithology	Basal Contact	Grain Size	Colour (fresh/ weathered)	Bed Style	Sedimentary Structures	Organic Content	Other
96 CUS	1.00	mudstone to siltstone to sandstone	sharp	fine sandstone	light grey	platy bedforms, wavy beds, partially concealed			
97	1.50	sandstone with interbedded siltstone	sharp	fine	light grey/ red-grey	platy interbeds of siltstone, well indurated to platy sandstone			
98 CUS	1.60	mudstone to siltstone to sandstone	sharp	fine sandstone	light grey	crumbly mudstone, laminated siltstone, platy sandstone	rippled sandstone, cross/parallel laminations	abundant fossil fragments	
99	0.60	seat earth	sharp		light grey			Stigmaria	* Note: lithology and thickness taken from Logan (1845)
100A	0.12	coal	sharp		black	vitreous coal, blocky and platy beds		no fossils seen	*Logan Coal group No. 6*
100B	0.20	shell limestone	sharp		dark grey	undulating shell layers		abundant shell fragments, bivalves, ostracods, shells (1 cm or less length)	
100C	0.30	carbonaceous shale							* Note: lithology and thickness taken from Logan (1845)

Total thickness of section: 145.64 metres for 139 lithological units



Stratigraphic Column of the Joggins Thesis Section

LEGEND

Lithology Colour

Light Grey · Medium Grey · Dark Grey · Black · Light Red · Medium Red · Dark Red · Mottled Red-Grey

Symbols

Channel scours and fills

Large and small scale cross bedding and/or asymmetrical rippling

Parallel lamination

Roots

Plant fossil

In situ tree trunk (*Lycopsid*, *Calamite*)

Calcareous/Siderite nodule

Stratigraphic column compiled by Paul Ténière

Stratigraphic Terms

PS: Parasequence (Interdistributary bay fill)
MFS: Major flooding surface

Notes:

Stratigraphic thickness of section: 145.64 m
Section begins at *Logan Division 4, Coal Group 13* and ends at *Logan Division 4, Coal Group 6*. Several stratigraphic references are made from Logan (1845).
All geological data (except Joggins Seam) mapped by Paul Teniere and Jeremy Tonelli in Joggins, Nova Scotia. Joggins Seam geological data from Logan (1845).
Stratigraphic column published for Dalhousie University undergraduate thesis (1998)