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# Alluvial sedimentology and basin analysis of Carboniferous strata near Joggins, Nova Scotia, Atlantic Canada

by

Michael Charles Rygel

Submitted in partial fulfilment of the requirements

for the degree of Doctor of Philosophy

at

Dalhousie University

Halifax, Nova Scotia

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## ABSTRACT

The Pennsylvanian Joggins Formation was deposited in the Cumberland Basin of Nova Scotia, a fault-bounded depocenter within the regional Maritimes Basin. Famous for its upright fossil lycopsid trees, the coastal exposure of this unit is widely regarded as the world's best exposure of coal-bearing Carboniferous strata. The newly redefined Joggins Formation comprises a small part of the 4,441-m-thick "Joggins section," which was measured by Sir William Logan during a 5 day period in June of 1842.

New seismic reflection data show that the Joggins Formation thickens towards the center of the Athol Syncline and thins on the flanks of the adjacent, salt-cored anticlines. These observations indicate that much Early Pennsylvanian subsidence in the Athol Syncline resulted from syndepositional flow of the underlying Windsor Group salt into the adjacent salt-cored anticlines (diapirs). This motif of ongoing, relatively gradual subsidence provides a mechanism to explain the exceptionally rapid accumulation of the Joggins Formation, as well as the lack of erosional sequence boundaries, basinward facies shifts, and other characteristics common to alluvial strata deposited in coastal areas.

Rivers sourced in the Caledonia Highlands and the New Brunswick Platform supplied sediment to this part of the basin during the Pennsylvanian. These rivers ranged from broad, sheet-like channel bodies in the Lower Cove redbeds, to the fixed, meandering, and multistorey channel bodies of the coal-bearing Joggins Formation. Statistical analysis of the width (W) and thickness (T) of the Joggins channel bodies shows that they represent distinct, but non-exclusive, areas in W-T space. Several multistorey channel bodies are present in the section, but high subsidence and sedimentation rates prevented rivers from extensively reworking preexisting fluvial deposits – thus preserving a remarkable amount of information about the rivers that formed them.

The heterolithic floodplain strata that encase these channel bodies contain a suite of hydrodynamic and decay-related sedimentary structures that formed where standing plants interacted with the sediment-laden floodwaters that regularly inundated the floodplain. These vegetation-induced structures are also present in the Mississippian Horton Group of Nova Scotia and New Brunswick, indicating that the fossil record of plant-sediment interaction may be much richer than previously recognized.

## ACKNOWLEDGEMENTS

Completion of this degree was largely due to the help and encouragement of numerous individuals who I would like to thank in the order in which they signed on to the cause. First, and perhaps most importantly, I would like to thank my mother, Karen Huber and my maternal grandparents, Charles and Shirley Morris. From day one, they stood firmly behind all my endeavors and made personal sacrifices so that I could take advantage of the educational opportunities that they never had.

Without the encouragement of Jack Beuthin in the late 1990s I would have not had the opportunity, nor the desire, to pursue this degree. He gave me a push in the right direction at a crucial time in my life. I would like to thank my wife Adrienne for her steadfast support and personal sacrifices. The stability and tranquility that she brought to my life has been a tremendous asset to me both personally and professionally.

Martin Gibling supervised this thesis and is thanked for stimulating discussions, countless hours spent revising chapters, and sage advice. The "long leash" approach allowed me to take the thesis in the direction I wanted and to gain valuable teaching and industry experience in the process. Thanks for everything Martin, I will look back on this thesis and my time in Nova Scotia with fond memories.

John Calder is acknowledged for helping me develop, shape, and communicate many of the ideas presented in this thesis – a contribution was given freely and largely on his own time. I am also indebted to my other co-authors: Sarah Davies, Howard Falcon-Lang, Murray Gingras, and particularly John Waldron and Brian Shipley. I appreciate their time and contributions to this thesis almost as much as I value their friendship.

My field work at Joggins was made possible thanks to the logistical assistance of John Reid, Sandy and Al Cooper. Brian Hebert kindly shared his personal fossil collection and knowledge of the section with me.

# CHAPTER 1: INTRODUCTION

## 1.1. OVERVIEW

The Joggins section is a 4.5-km-thick section of Carboniferous rocks exposed in a gently dipping coastal section along the Bay of Fundy in northwestern Nova Scotia. The Joggins Formation forms the medial, relatively fine-grained portion of this section and is exposed in a 500-m-wide wave-cut platform and 20-m-high sea cliffs which are constantly hewn and renewed by the Fundy tides. Widely regarded as the world's best exposure of coal-bearing Pennsylvanian-aged strata, the Joggins Formation contains 76 coal seams and over 63 forested horizons with standing lycopsids 5–6 m tall (Davies *et al.*, submitted).

Hailed by Charles Lyell (1842) as "the most wonderful phenomenon perhaps that I have ever seen," the natural laboratory of the Joggins cliffs was a "Coal Age Galapagos," that played a role in the careers of Charles Lyell, John William Dawson, William Logan, Abraham Gesner, Richard Owen, Othniel Marsh, and many other prominent Victorian geologists (Calder, 2003). The section is world renowned for fossil discoveries that include the oldest unequivocal reptile and the "tree stump fauna," a collection of over 200 faunal specimens representing 11 tetrapod and 5 terrestrial invertebrate taxa found within the upright trees (Calder, 1998). Discussed in Lyell's (1871) *Principles of Geology* and Darwin's (1859) *On the Origin of Species*, Joggins served as a proving ground for the principles of Uniformitarianism, the *in situ* botanical origin of coal, and the incompleteness of the fossil record. In recognition of its natural beauty, ongoing paleontological discoveries, and importance to the young science of

geology, the Canadian government recently included Joggins on its tentative list of candidate UNESCO World Heritage Sites.

Most of the research at Joggins since the work of Logan and Dawson has focused on the fossil record or mapping the distribution of the coal-bearing facies inland (Shaw, 1951; Copeland, 1959; Ryan *et al.*, 1991; see maps in Ryan and Boehner, 1994). Only recently have we made significant new inroads into understanding the sedimentological and basinal processes that were responsible for the deposition and preservation of this unique window into the Carboniferous world.

### 1.2. Present Research

This research program sought to characterize the nature and controls on Carboniferous alluvial strata near Joggins village, in the Cumberland Basin of Nova Scotia. Achieving this goal required a comprehensive understanding of sedimentary processes that acted on temporal scales of hours to millennia and spatial scales ranging from a few square centimeters to thousands of square kilometers (Fig. 1). With the sedimentological framework for the Joggins Formation essentially in place when my research began (Davies and Gibling, 2003), the most logical way to advance this goal was to focus on three aspects of alluvial sedimentation of increasing scope.

1. The fossil record of plant-sediment interaction
2. Fluvial sedimentology and basin analysis
3. Salt tectonics and seismic stratigraphy

These topics were disseminated through a series of peer-reviewed papers that were in various stages of the publication process at the time this thesis was submitted. Individual papers were modified to form many of the chapters in this thesis. A formal explanation

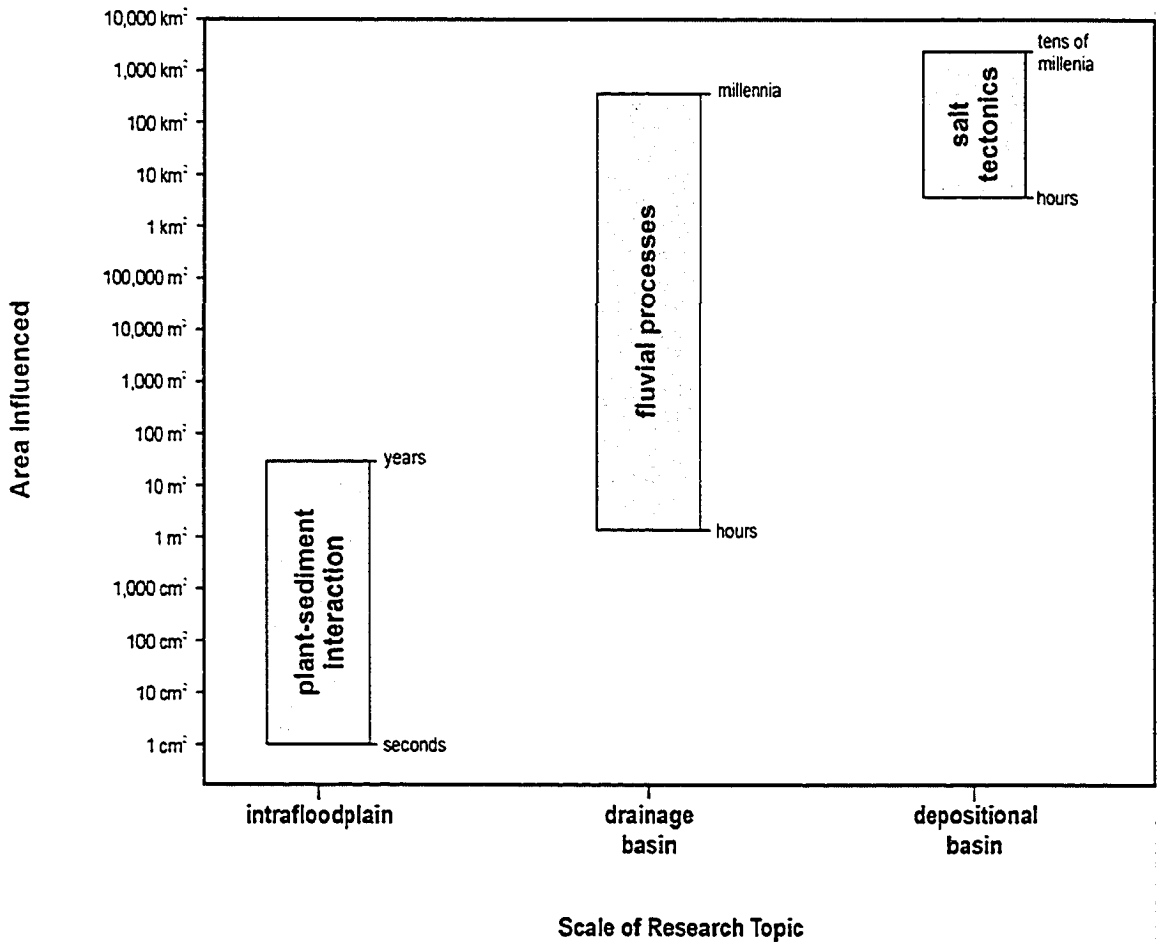



Figure 1: Diagram showing the different spatial and temporal scales of alluvial sedimentation examined in this thesis.

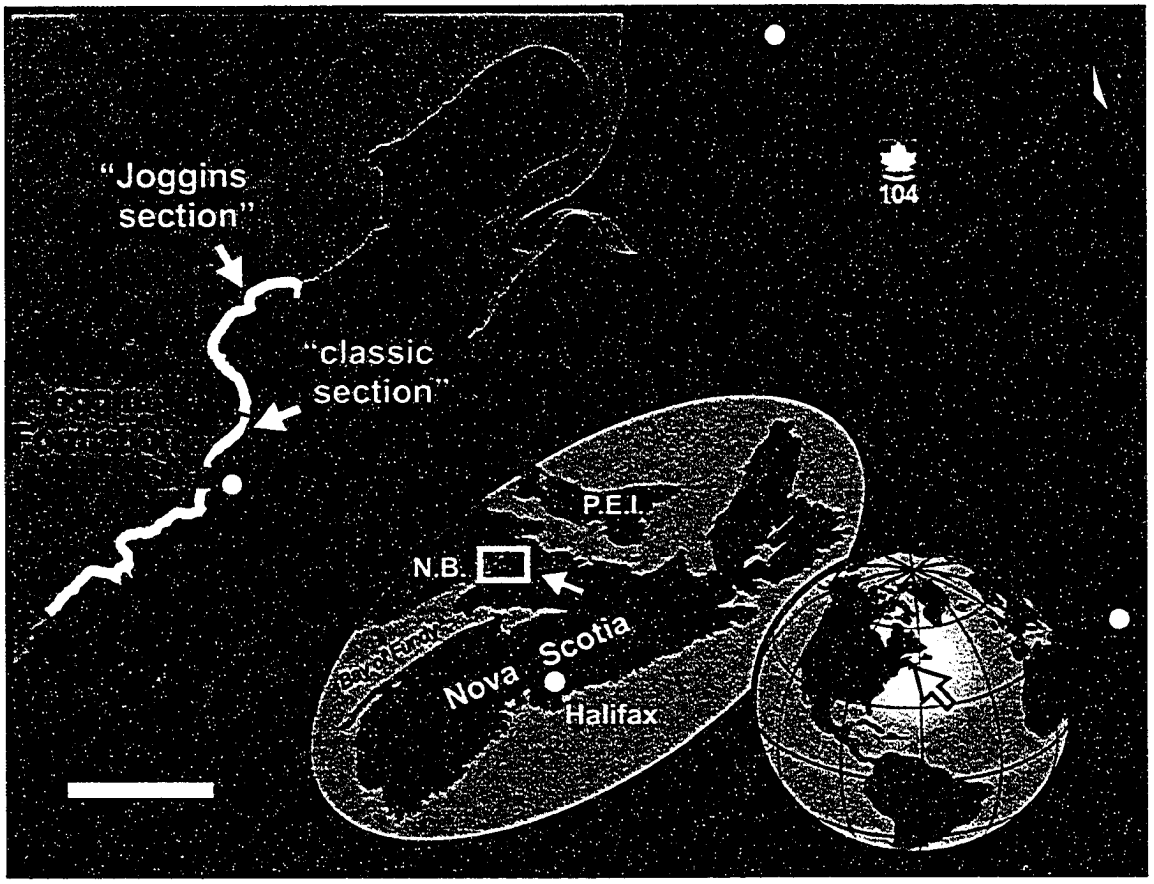



Figure 2: Location map showing Joggins and the place names associated with the Carboniferous strata exposed there.

of my contribution to each and a summary of their publication status are provided in Section 1.4 and Appendix 1. For all chapters based on a co-authored paper, a substantive portion of the research was conducted by the writer.

## 1.3. TERMINOLOGY

Historically, the "Joggins section" referred to the entire section of Carboniferous rocks measured by William Logan – some 4,441 m of strata exposed over a 30 km distance along the southern shore of Chignecto Bay (Fig. 2; Chapter 2). More recently, the "classic" Joggins section has been used to refer to the lower part of Logan's Division 4, the coal-bearing interval exposed in the cliffs between Lower Cove and Bell's Brook. Unless specified otherwise, the Joggins Formation as used in this thesis follows the terminology of Davies *et al.* (submitted): the coal-bearing interval extending from the base of Logan's Coal 45 to the highest limestone in Division 4. A complete account of the stratigraphic history of this formation is provided in section 3.4.1.

## 1.4. SUMMARY OF SEDIMENTARY RESEARCH AT JOGGINS

This thesis represents only a fraction of the body of research that has taken place at Joggins since the early 1990s – collectively, this effort represents the first comprehensive examination of the Joggins section since the pioneering work of Logan and Dawson in the mid- to late 1800s (Chapter 2). The coal-bearing portion of the basin fill was the subject of numerous mapping and stratigraphic studies in the twentieth century, resulting in a long and complex history of stratigraphic nomenclature. Aspects relevant to the coastal section are summarized in Chapters 2 and 3.

A few sedimentological studies did take place in the twentieth century, but they provided only a cursory overview of the depositional environments of the Joggins

section. In an examination of the cyclicity and fluvial systems of the classic section, Duff and Walton (1973) interpreted these strata as having been deposited in a large, northward prograding delta and concluded that most of the channel bodies formed in association with crevasse splays. The cyclic style of sedimentation was attributed to autocyclic delta lobe switching and channel migration.

Gibling (1987) noted that strata exposed near Joggins contained three coarsening upwards cycles, and that the Joggins channel bodies were remarkably narrow, suggesting that they formed as a network of stably-positioned, anastomosed channels. Ryan and Boehner (1994) revisited Logan's measured section and presented it as a graphic log. These authors documented a wide range of paleoflow measurements ranging from northeast to south and concluded that the Joggins channel-bodies represented a transition from a predominantly anastomosed to meandering channel morphology. Similarly, Falcon-Lang (1999) described both anastomosed and meandering type channel-bodies, both of which contained abundant fossil charcoal. Davies and Gibling (2003) remeasured the lower 600 m of the Joggins Formation and provided the first modern, comprehensive account of the cyclicity and sedimentology of these strata (review in Chapter 3).

## 1.5. Chapters and Contributions

### 1.5.1. Work not included as chapters in this thesis

Although an understanding of the facies and cyclicity of the Joggins Formation was presented in Davies and Gibling (2003), their work examined only the lower 600 m of coal-bearing strata in Dawson's Division 4. S.J. Davies measured the rest of Division 4, but the paper redefining the Joggins Formation (Davies *et al.*, submitted) awaited drafting of a detailed measured section.

Because the manuscript which presents the new Joggins measured section (Davies *et al.*, submitted) overlaps with Chapter 3 of this thesis, it was not included as a separate chapter. However, several of my contributions to this manuscript are included in this thesis:

- An electronically drafted version of the measured section based on the field notes of S.J. Davies (Appendix 4).
- A stand-alone section on the history of stratigraphic nomenclature for the Joggins Formation (Section 3.4.1).
- Supporting figures and tables (figures in Chapter 3).

Additionally, the closing remarks from Davies et al. (submitted) were modified and used to conclude Chapter 3.

### 1.5.2. Chapter 2

Chapter 2 is entitled *"Such a section as never was put together before": Logan, Dawson, Lyell, and mid-nineteenth-century measurements of the Joggins section*, by Michael C. Rygel and Brian C. Shipley. This paper was peer reviewd by Peter von Bitter, Rob Fensome, and an anonymous reviewer and accepted for publication in Atlantic Geology in February of 2005.

After the detailed measured section for the Joggins Formation (Davies *et al.*, submitted) was complete, it became obvious that the new thickness value of 915.5 m was significantly thicker (141.6 m) than Logan's measurements for the same interval. Chapter 3 summarizes my examination of Logan's original field notebooks in an attempt to determine what methods he used so that we could explain the discrepancies in thickness between his measurements and our own. I researched and wrote the majority of this

paper. My co-author, B.C. Shipley helped design the structure of the paper, revised all versions of the text, and provided valuable input on the historical accuracy of the content. John Calder provided feedback on the section that discusses the relationship between Logan and Dawson.

### 1.5.3. Chapter 3

Chapter 3 is a review paper entitled *Geological setting and paleoenvironments of the Joggins Formation* by Michael C. Rygel, Sarah J. Davies and Martin R. Gibling. This manuscript is intended as the background chapter in *Late Carboniferous Ecosystems of Joggins, Nova Scotia*, an upcoming Paleontological Society Guidebook edited by H.J. Falcon-Lang, M.R. Gibling, and J.H. Calder. This manuscript was submitted to the editors in July of 2003.

I conducted all the background research, drafted all the figures, and wrote the vast majority of the text in this manuscript. As previously mentioned, Appendix 4, sections 3.4.1 and 3.8. were modified from Davies *et al.* (submitted) – a manuscript that I co-authored but that is not included in this thesis.

### 1.5.4. Chapter 4

This manuscript, *Vegetation-induced sedimentary structures from fossil forests in the Pennsylvanian Joggins Formation, Nova Scotia* by Michael C. Rygel, Martin R. Gibling, and John H. Calder was peer reviewed by Frank Ettenson and Sean Bennett and published in the June 2004 edition of Sedimentology (v. 51, p. 531-552).

While examining the Joggins channel bodies, numerous channel-sized sandstone bodies formed around standing vegetation came to my attention. Several weeks of additional fieldwork revealed that these bodies representitives of several types of

structure that recorded the interaction between standing plants and alluvial sediment. These "vegetation-induced sedimentary structures" are one of the most distinctive features of the Joggins Formation and demonstrated that plants were able to localize both erosion and deposition on the Joggins floodplain. I was the primary author of this manuscript and solely responsible for the fieldwork and background research that it is built upon. J.H. Calder helped ensure the accuracy of the paleobotanical information.

### 1.5.5. Chapter 5

*Tournaisian forested wetlands in the Horton Group of Atlantic Canada* was authored by Michael C. Rygel, John H. Calder, Martin R. Gibling, Murray K. Gingras, and Camilla S.A. Melrose. This manuscript is a contribution to *Wetlands Through Time*, a Geological Society of America Special Publication edited by Stephen Greb and William DiMichele. The paper was peer reviewed by Hermann Pfefferkorn and Brigitte Meyer-Berthaud, and accepted for publication by the volume editors. I am awaiting final confirmation of acceptance from the GSA Editorial Office.

Building upon the initial description of sedimentary structures formed around standing plants at Joggins, an undergraduate thesis undertaken by C.S.A. Melrose and supervised by M.R. Gibling identified forested horizons in the Tournaisian Horton Bluff Formation and confirmed that similar structures were preserved there (Melrose, 2003; Melrose and Gibling, 2003). Presentation of this research at the 2003 NEGSA Meeting in Halifax (Rygel and Gibling, 2003) resulted in collaboration with M.K. Gingras on the Albert Formation of New Brunswick, where similar structures had been reported in an Atlantic Geoscience Society fieldguide (Gingras, 2002). These are among the world's earliest well preserved forested levels, and allowed me to test the broader relevance of the

styles of sediment-vegetation interaction documented at Joggins. These features may assist in identifying the former presence of standing vegetation where the trees themselves have not been preserved. I wrote the vast majority of the manuscript, conducted all the background research on the biota of the Horton Group, and collected the observations and measurements presented in the text. J.H. Calder contributed the section on wetland terminology, and visited the field localities to confirm/discuss paleobotanical and sedimentological observations. M.R. Gibling supervised the pilot study by C.S.A. Melrose.

### 1.5.6. Chapter 6

This chapter is a manuscript entitled *Fluvial systems of the Pennsylvanian Joggins Formation, Atlantic Canada: geomorphic and accommodation influences on channel body geometry and architecture*, by Michael C. Rygel and Martin R. Gibling. This work will be submitted to the Journal of Sedimentary Research in the summer of 2005.

In addition to providing practical information about the geometry of potential hydrocarbon reservoirs, understanding the fluvial sedimentology of the Joggins Formation also provides information about local conditions on the Joggins floodplain and the rivers that delivered sediment to it from the adjacent highlands and beyond. I wrote this manuscript and personally conducted the field work and background research upon which it is based.

### 1.5.7. Chapter 7

The paper *An early Pennsylvanian waterhole deposit and its fossil biota in a dryland alluvial plain setting, Joggins, Nova Scotia* was authored by Howard J. Falcon-Lang, Michael C. Rygel, Martin R. Gibling, and John H. Calder. This paper was peer

reviewed by Robert Gastaldo and Herman Pffefferkorn and published in the March 2004 volume of the Journal of the Geological Society (v. 161, p. 209-222).

The "Hebert beds" comprise five channel bodies and their associated genetically-related floodplain deposits. Building upon the initial description of faunal remains by Hebert and Calder (2004), H.J. Falcon-Lang coordinated the development of a manuscript that documented the floral and faunal remains in their paleoecological and sedimentological context. I contributed stand-alone sections to this manuscript that H.J. Falcon-Lang revised and incorporated with the rest of the text. Specifically, I was responsible for the sections on the description and interpretation of the sedimentology, photographs and taphonomic descriptions of the invertebrate and vertebrate material housed in the Fundy Geological Museum, as well as much of the research on *Archanodon* (a large bivalve) and modern/ancient waterholes.

### 1.5.8. Chapter 8

Chapter 8 is a manuscript entitled *Stratigraphy and sedimentology of Early Pennsylvanian red beds at Lower Cove, Nova Scotia, Canada: The Little River Formation with redefinition of the Joggins Formation* written by John H. Calder, Michael C. Rygel, R.J. Ryan, Howard J. Falcon-Lang, and Brian L. Hebert. This paper was submitted to Atlantic Geology in February of 2005.

Beginning in 1999, J.H. Calder (with the field assistance of B.L. Hebert) began measuring the section of redbeds exposed near the mouth of Little River in the village of Lower Cove, Nova Scotia (Logan's Division 5). This project complemented the work of S.J. Davies and together the two studies redefine the Joggins Formation and propose the Little River Formation. To expand upon J.H. Calder's measured section, I wrote stand-

alone section on the description and interpretation of the channel bodies in the Little River Formation, tied the air-photographs to the measured section, contributed a section on the history of stratigraphic nomenclature, and helped revise other sections of the manuscript written by J.H. Calder, and drafted all figures (excluding Appendix 5).

### 1.5.9. Chapter 9

This chapter is entitled *Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia* and was written by John W.F. Waldron and Michael C. Rygel. This paper was reviewd by Robert Gastaldo and John Calder and published in the May 2005 edition of Geology (v. 33, p. 337-340).

The text of the manuscript and the seismic interpretation represents an equal collaboration between J.W.F. Waldron and myself. After receiving training on how to use the Seisworks software in Waldron's lab, I interpreted the Cumberland Basin seismic lines with daily feedback and assistance from Waldron. I will be the lead author on a second paper (subsequent to this thesis) that will incorporate outcrop data from this thesis and will examine the history of the basin more fully.

# CHAPTER 2: "SUCH A SECTION AS NEVER WAS PUT TOGETHER BEFORE" - LOGAN, DAWSON, LYELL, AND MID-NINETEENTH-CENTURY MEASUREMENTS OF THE JOGGINS SECTION

*Michael C. Rygel and Brian C. Shipley*

## 2.1. ABSTRACT

William Edmond Logan assumed his duties as the first head of the Geological Survey of Canada in June 1843. Two previously overlooked field notebooks provide new insight into his first field project that summer: measurement of the "Joggins section", a classic Carboniferous locality in Nova Scotia. Inspired by reports of 40-foot-tall fossil trees, Logan spent five days measuring 14,570 feet 11 inches of strata exposed along the shore of the Bay of Fundy. Widely regarded as a meticulous, bed-by-bed measured section, closer examination reveals that many thickness values were calculated using paced distances. Realizing that his measured section was too detailed for scientific journals of the day, Logan published his work in a relatively obscure government publication where it went largely unnoticed for nearly a decade. Unaware of Logan's measured section, John William Dawson and Charles Lyell visited Joggins in 1852 and measured the section for themselves. Dawson later stated that the two sections contain only minor differences, but careful comparison shows that they have radically different descriptions and measurements for even the most distinctive beds. Dawson disguised these discrepancies in post-1855 editions of his book *Acadian Geology* by rewriting much of the measured section and abandoning many of his own observations. Although over 200 subsequent Joggins studies build upon these measured sections, the present study represents the first detailed examination of the sections and reveals previously unknown

discrepancies between two of the most important early geologic studies undertaken in Nova Scotia.

## 2.2. INTRODUCTION

Sir William Edmond Logan (1798-1875; Fig. 3), widely regarded as the "Father of Canadian Geology", began his prestigious Canadian career in earnest in June 1843 along the shores of the Bay of Fundy at "the Joggins." Appointed in 1842 as the first head of the Geological Survey of Canada, as the new institution eventually became known, Logan's mandate was to assess the mineral resources of the Province of Canada (the southern parts of modern Quebec and Ontario). He prepared for this undertaking by visiting coal-bearing Carboniferous outcrops in Nova Scotia and New Brunswick, then separate British colonies, before continuing north to search for coal in the older, poorly known rocks of the Gaspé Peninsula.

While in Nova Scotia, Logan measured the 14,570 foot 11 inch "Joggins section," a gently dipping coastal exposure along the southern shore of Chignecto Bay, near the present village of Joggins, Nova Scotia. Although this measured section is the framework upon which all subsequent studies have been built, the most specific information about Logan's time at Joggins is Harrington's (1883) report that "At the South Joggins he spent several weeks, and it was at this time that he executed his great section of the coal-measures which, as has been truly said, is 'a remarkable monument of his industry and power of observation.'" In this paper, we describe the events that brought Logan to Joggins and use his original field notebooks to provide the first detailed information about the construction of his famous measured section.

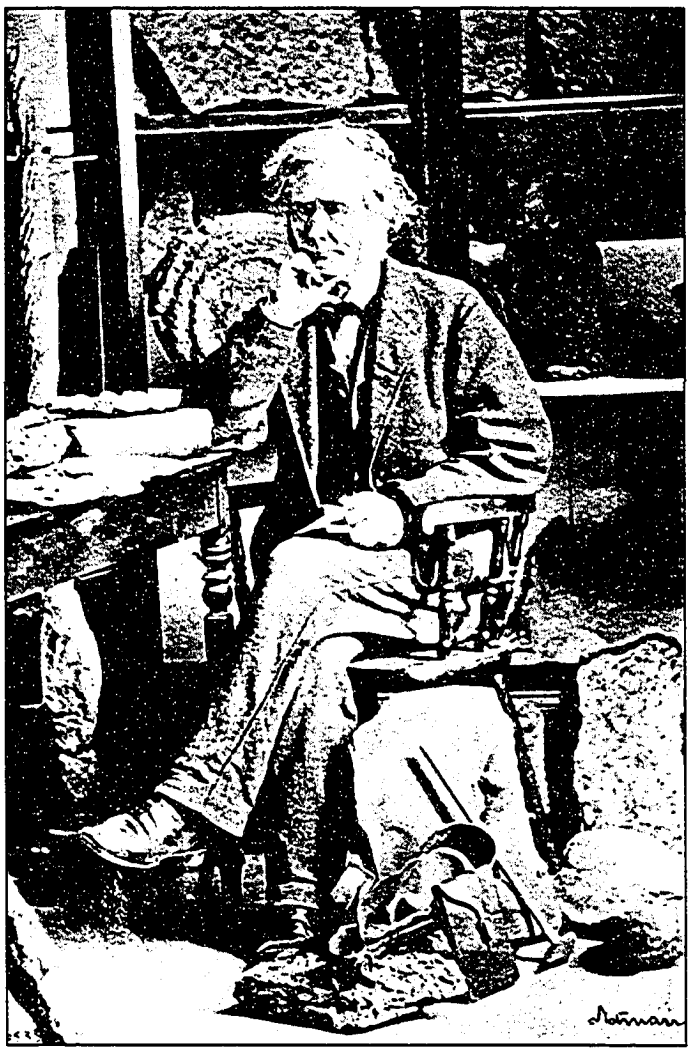


Figure 3: Sir William Edmond Logan, 1865. Photograph by William Notman, Montreal, Quebec; reproduced with permission of the McCord Museum of Canadian History, Montreal (accession number I-16533.1).

We then compare Logan's work to a little-known measured section of the "classic" Joggins section measured by John William Dawson and Charles Lyell nine years after completion of Logan's section. Despite Dawson's claim that the measured sections contain only "minor differences," careful scrutiny reveals that they provide very different descriptions and thicknesses even for distinctive beds. Our examination of Dawson's work clearly demonstrates that he disguised these discrepancies in post-1855 editions of *Acadian Geology* by abandoning many of his own observations. Lastly, we review the historical and scientific significance of the measured sections.

### 2.3. LOGAN'S INTEREST IN COAL

William Edmond Logan was born in Montreal on Friday, 20 April 1798. After attending high school in Scotland, Logan briefly attended Edinburgh University before joining his uncle's counting house in London in 1817 (Harrington, 1883; Alcock, 1948; Smith, 2000).

Logan's life changed direction in 1831 when he left London to work in his uncle's copper smelting business near Swansea, Wales. Logan was initially employed as an accountant and bookkeeper, but soon became interested in technical and scientific aspects of the business. In an 1833 letter to his brother he remarked that "Here I am, out of the world altogether, and attending to nothing else but the making of copper and the digging of coal from morning till night" (quoted in Harrington, 1883). Coal was the most heavily-used material in the smelting operation, and Logan soon became interested in its origin and distribution in the surrounding Glamorganshire coalfield (Torrens, 1999, we concur with Torrens in doubting the assertion by Christie (1995) that Logan's avowed interest in economic matters was purely deception). With his personally-purchased

compass and theodolite, Logan began to make detailed geologic maps of the area using the one-inch sheets of the Ordnance Survey as a base (Bailey, 1952), maps that Sir Henry De la Beche later adopted as official documents of the Geological Survey of Great Britain (Smith, 2000).

Logan's geologic prowess began to attract the attention of prominent figures of the day and he was elected as a Fellow of the Geological Society in 1837 (Torrens, 1999). Shortly thereafter, he stated his geological aspirations in a letter to his brother: "I take a great interest in the science, and some day or other I may appear in print ... If I ever return to Canada again I shall geologize there" (quoted in Harrington, 1883). Following the death of his uncle, and without any definite plan for future employment, Logan resigned his position at the copper works in 1838.

The years 1838 through 1841 were a period of intellectual and professional freedom during which Logan brought his investigation of the origin of coal to fruition. Although the botanical origin of coal became generally accepted during the early 1800s, there was still considerable debate about whether it was transported and deposited subaqueously (an idea termed the "drift' theory") or accumulated *in situ* (Stevenson, 1911). While Logan was mapping in Wales, coal miners brought the rooted underclays beneath coal seams to his attention (Torrens, 1999). Realizing that the stigmarian roots were part of the plants that made up the coal seams, Logan communicated his observations to the Geological Society of London in February 1840 and later published them as an abstract in the *Proceedings* (Logan, 1840) and in full in the *Transactions* (Logan, 1842).

The discovery that South Wales coal seams always occurred atop rooted seat earths (underclays) thus became Logan's claim to fame. The desire to extend the generality of this observation to other regions was a key motive of his actions over the next several years.

### 2.4. Logan returns to North America

Although free from daily business commitments, Logan still had to deal with many of his deceased uncle's affairs on both sides of the Atlantic (Torrens, 1999; Logan to De la Beche, 3 Dec 1841, De la Beche Papers). Obliged to sail for Canada in August of 1840, he decided to take this opportunity to examine the geology of eastern North America. Upon arriving in Nova Scotia, Logan took a stagecoach between Halifax and Pictou, recording as many impressions of the passing geology as he could (Logan, 1841). He continued on immediately to Quebec, and spent much of the next year examining the geology of the Montreal area (where his older brother James still lived), analyzing modern phenomena such as the accumulation of ice on the St. Lawrence River and a landslide south of the city (Logan, 1842, 1846). He planned to return to Britain in August 1841, but a delayed meeting in New York City allowed him enough time to visit the coalfields of eastern North America before his departure. While making arrangements to tour the eastern coalfields, Logan spotted Charles Lyell in the street and briefly met with him on Sunday, 15 August to discuss Logan's work on underclays, the Welsh coalfields, and Lyell's planned visit to Canada the following year (Harrington, 1883).

After a short visit to eastern Pennsylvania, Logan continued on to Saint John, New Brunswick, with hopes of meeting Abraham Gesner, a Maritime geologist and

physician. Finding that Gesner was in the field at Miramichi, Logan crossed the Bay of Fundy to investigate the geology near Windsor, Nova Scotia, where he made his famous discovery of tetrapod trackways (Dawson, 1855). The tour of Nova Scotia concluded with a week long excursion to the Pictou coalfield, during which Logan was "delighted" to have the company of William Dawson – a young and knowledgeable geologist from the area (Logan, 1841; Harrington, 1883). For Logan, the opportunity to confirm that the *Stigmaria*-bearing underclays he had first observed in South Wales also occurred in North America was a crucial step in establishing the superiority of his *in situ* theory of coal formation over the older, formerly generally-accepted theory of drift (Logan, 1842).

### 2.5. Birth of the Canadian survey

Much like oil today, coal was the single most important energy source during the nineteenth and early twentieth centuries. The industrial supremacy of Britain, and later the United States, was fueled by it (Zaslow 1975; Freese 2003). Coal provided energy for transportation, heat for homes, freed factories from the need for hydraulic power, and was crucial for the production of iron (Zaslow 1975; Freese 2003). Although the Province of Canada's economy in the first half of the nineteenth century was based largely on supplying raw materials, the province was keen to develop its mineral resources and secure its place in the transforming global economy. The British colony of Nova Scotia had Carboniferous coal deposits of economic value (Calder, 1985), but their geologic relationship to the rocks of Ontario and Quebec was unknown. Without the benefit of modern stratigraphic concepts, attempts to find and predict coal occurrences (even within known coalfields) were haphazard at best (Zaslow, 1975). Few people had

the necessary training to determine the extent of the coalfields, and securing and funding one of these individuals would require a national effort.

The need for a geological survey of Upper and Lower Canada became apparent in the early 1830s, but political unrest stalled serious planning for over a decade (Zeller, 1987). In September 1841, the government agreed to have a survey carried out, provided that it cost less than £1500. Shortly thereafter, Governor General Sir Charles Bagot began what was to be a very short search for the right candidate.

Logan first heard about the possibility of a Canadian survey in 1841, while preparing to travel to Pennsylvania and Nova Scotia (Zaslow, 1975). During his tour of the American coalfields, Logan wrote that "I have almost made up my mind, if I can make the necessary arrangements in business matters, to offer myself as a candidate to undertake the survey of Canada, and if I once begin, it will not be my fault if it does not go ahead" (Harrington, 1883). Shortly after the funds were allocated, lobbying by Logan's supporters on both sides of the Atlantic quickly convinced Sir Charles Bagot that Logan was the right choice for the job. In February 1842, Bagot asked the Colonial Secretary in London, Lord Stanley, to offer Logan the position if his letters of reference were favorable (Zeller, 1987). Four of the most influential British geologists wrote on Logan's behalf: British Geological Survey director Henry De la Beche, Oxford University's William Buckland, Geological Society president Roderick I. Murchison, and Adam Sedgwick of Cambridge University (Harrington, 1883).

Lord Stanley's undersecretary, G.W. Hope, offered William Logan the position of "Provincial Geologist" on 9 April 1842, an offer he accepted by letter on 14 April (Zaslow, 1975). Logan reported to Kingston, the Canadian capital, in late August to

negotiate the details of his employment, but a political crisis prevented him from meeting with the provincial government until several weeks later. In the interim, Logan went on several field excursions, met with individuals knowledgeable about the regional geology, and assembled a collection of the existing geological literature and maps (Harrington, 1883). With the government's permission, Logan returned to Britain for the winter of 1842-43 to fulfill several professional engagements and to review the existing geologic documents. Having completed a 5000-word "Preliminary Report" in December 1842, Logan spent the spring of 1843 in South Wales training his assistant, Alexander Murray (1810-1884), a retired naval officer and future director of the Geological Survey of Newfoundland, for their upcoming fieldwork in Canada. Murray departed for the flat-lying early Paleozoic formations of Canada West (Ontario) in April 1843 (Murray to De la Beche, 19 April 1843, De la Beche Papers), followed shortly thereafter by Logan who was destined for the deformed Paleozoic strata in the easternmost part of Canada, on the Gaspé Peninsula (Zaslow, 1975). If the Carboniferous deposits of the Atlantic colonies extended into Canada at any point, it would have to be here. Thus, the most logical starting point for the search for coal in the Province of Canada was the known coalfields in the British colonies of Nova Scotia and New Brunswick.

## 2.6. THE JOGGINS SECTION

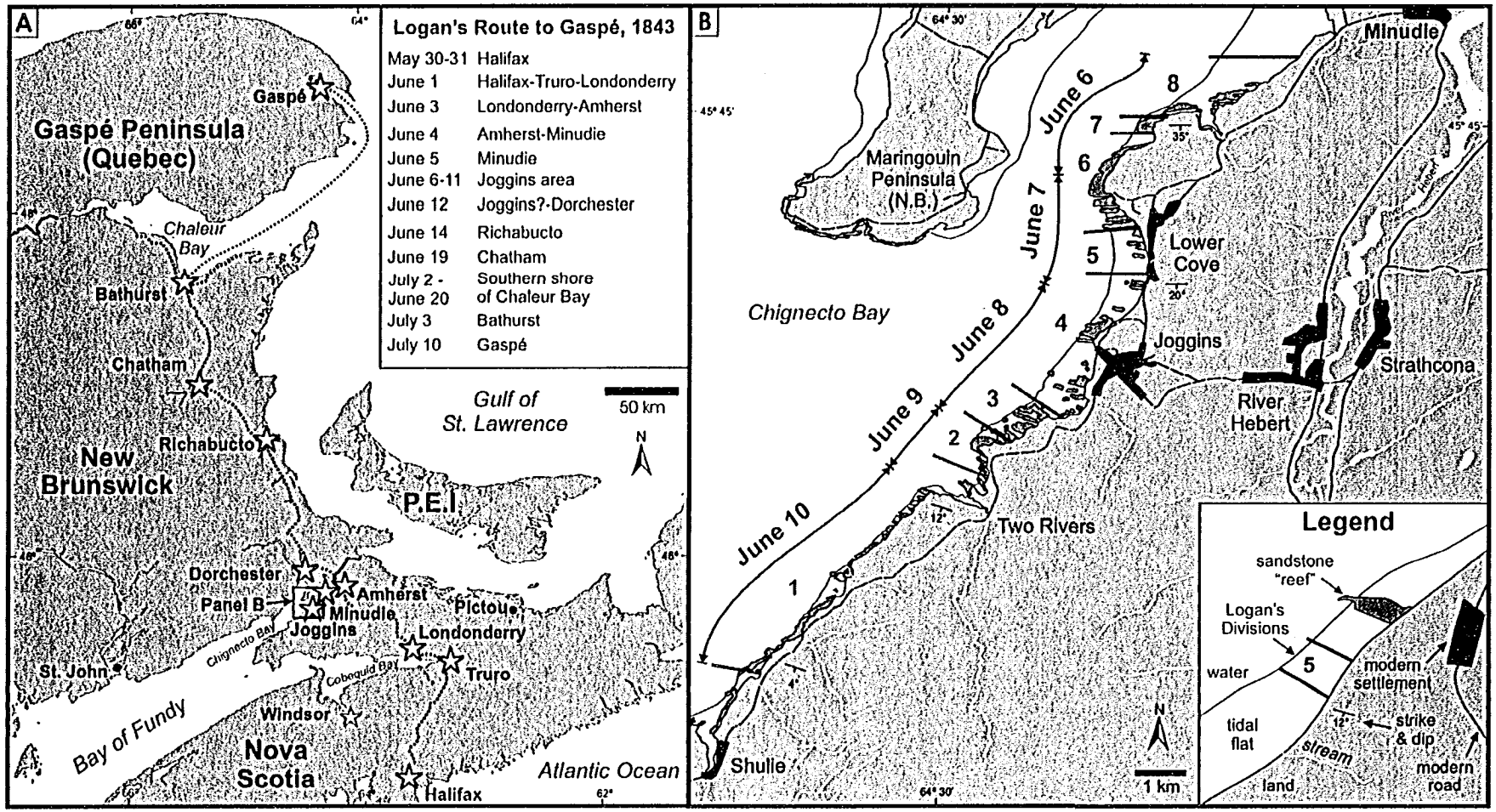
### 2.6.1. Introduction

Logan's personal journals and Geological Survey of Canada documents provide researchers with a wealth of information about his activities after his early-July arrival in Gaspé. Conversely, very little documentation exists for his month-long trip through Nova Scotia and New Brunswick en route to his final destination (Fig. 4A). The best

surviving records of this journey are Logan's two previously unexamined field notebooks (Logan 1843a,b) and a series of letters written to De la Beche around this time (see Sharpe and McCartney, 1998). We have used these resources to provide the first detailed account of Logan's visit to the Joggins section – an important, but poorly understood contribution to the geology of Nova Scotia.

Logan's primary goal for the summer of 1843 was to survey the strata of the Gaspé Peninsula to determine if they lay above or below the Carboniferous (Shipley 2002). Rather than sailing immediately to the Gaspé, Logan decided to take the overland route through Nova Scotia and New Brunswick to familiarize himself with known coal-bearing strata to the south. Logan had not visited Joggins on his two previous trips through Nova Scotia because it was off the main Halifax-Truro-Pictou transportation axis and because he missed the meeting with Abraham Gesner, who was well aware of its existence (Gesner 1836; Logan 1841a). Gesner accompanied Charles Lyell on his visit to the site in 1842, and Lyell's published account of his observations of fossil trees *in situ* there was helping to bring wider attention to this important area (Lyell 1843a, 1845; Wilson 1998; for other early accounts see Jackson and Alger 1828; Brown and Smith 1829).

Figure 4: A) Map showing major stops on Logan's journey to Gaspé during the summer of 1843. B) Map of the Chignecto coast showing Logan's daily progress on the Joggins section.


A
Logan's Route to Gaspé, 1843
May 30-31 Halifax
June 1 Halifax-Truro-Londonderry
June 3 Londonderry-Amherst
June 4 Amherst-Minudie
June 5 Minudie
June 6-11 Joggins area
June 12 Joggins?-Dorchester
June 14 Richabucto
June 19 Chatham
July 2 - June 20 Southern shore of Chaleur Bay
July 3 Bathurst
July 10 Gaspé
Gaspé Peninsula (Quebec)
Gaspé
Chaleur Bay
Bathurst
Chatham
Richabucto
New Brunswick
Gulf of St. Lawrence
50 km
N
P.E.I
Dorchester
Panel B
Amherst
Minudie
Joggins
Pictou
Londonderry
Truro
Chignecto Bay
Cobequid Bay
St. John
Windsor
Bay of Fundy
Nova Scotia
Atlantic Ocean
Halifax
B
Minudie
Maringouin Peninsula (N.B.)
June 6
June 7
June 8
June 9
June 10
Lower Cove
Chignecto Bay
Joggins
Strathcona
River Hebert
Two Rivers
Shulie
1 km
Legend
sandstone "reef"
Logan's Divisions
water
tidal flat
stream
land
modern settlement
strike & dip
modern road

Logan had communicated with Lyell about Nova Scotian geology immediately before departing for Canada in 1843. Lyell suggested that they look over a map of the region together and told Logan that the Geological Society was particularly interested in the observations they had both made on *Stigmaria* underclays (Lyell to Logan, 13 April 1843 & 27 April 1843, Logan Papers). Thus, Logan's trip to Joggins would provide the foundations for his official search for Canadian coal, allow him to pursue his research on the formation of coal, and to put his personal stamp on an increasingly important locality.

Upon arriving in Halifax at 10 a.m. on Tuesday 30 May 1843 aboard the *SS Acadia*, Logan spent much of that day and the next purchasing field supplies (knapsack, fishing basket, bird shot, etc.) and arranging to have his "traveling laboratory" sent on to Gaspé by boat. Logan's familiarity with Gesner and Lyell's work at Joggins is evident from his 31 May 1843 letter to De la Beche, in which he stated his first goal: "I shall pay a visit to the Joggins, where Lyell saw the vertical trees, & I shall endeavour to determine the thickness of the whole deposit there. Dr. Gesner says it is 5 miles thick & Lyell says that it dips one way for a distance of 35 miles" (De la Beche Papers). Logan left Halifax on 1 June, making his way toward the Bay of Fundy by foot and by coach. He arrived in Minudie on 4 June with the intention of starting work at Joggins the following day; but heavy rain caused a one-day delay, during which he measured sections in and around Minudie.

### 2.6.2. Logan's measurements

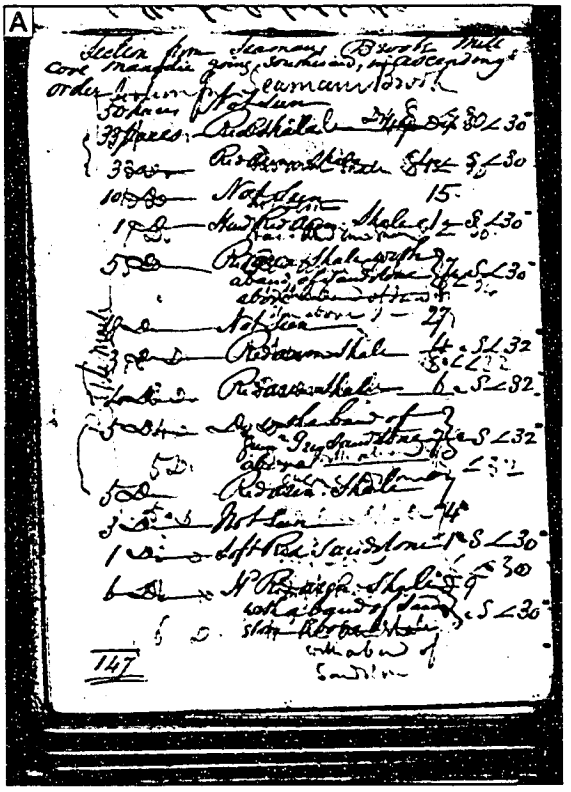
Logan measured 14,570 feet, 11 inches of strata exposed along the Chignecto coast between 6–10 June 1843 (Fig. 4B). From his starting point at Mill Cove, Logan worked up section, measuring about 3,700 feet of section in his first day and about 4,700

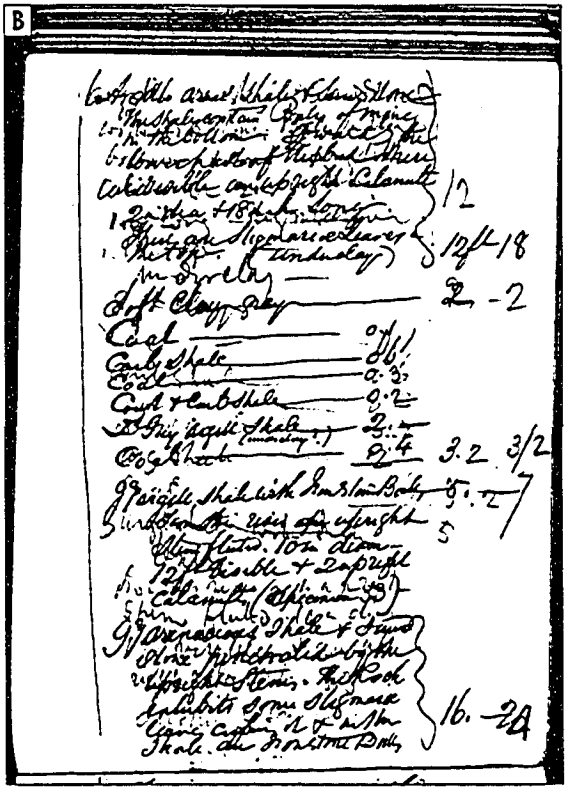
feet in his second. The accelerated pace of the second day was checked, however, as he entered coal-bearing strata; 3,900 feet of section between what would become Coal 34 (Division 4) and Ragged Reef Point were measured on Thursday 8 June. With dips of about 15° on the fourth day, the increasing horizontal distance per unit thickness became apparent because it took all of Friday 9 June to measure the ~1,360 feet of section from Ragged Reef Point to West Ragged Reef Point. After measuring an additional 868 feet on Saturday 10 June, Logan concluded his traverse, reasoning that the "dip is reduced by a very small angle, it is likely that a farther investigation would require a longer walk than I can afford" (Logan, 1843). Logan made no mention of his whereabouts on Sunday 11 June, but his notes indicate that he took the day off before moving on to Dorchester on Monday morning.

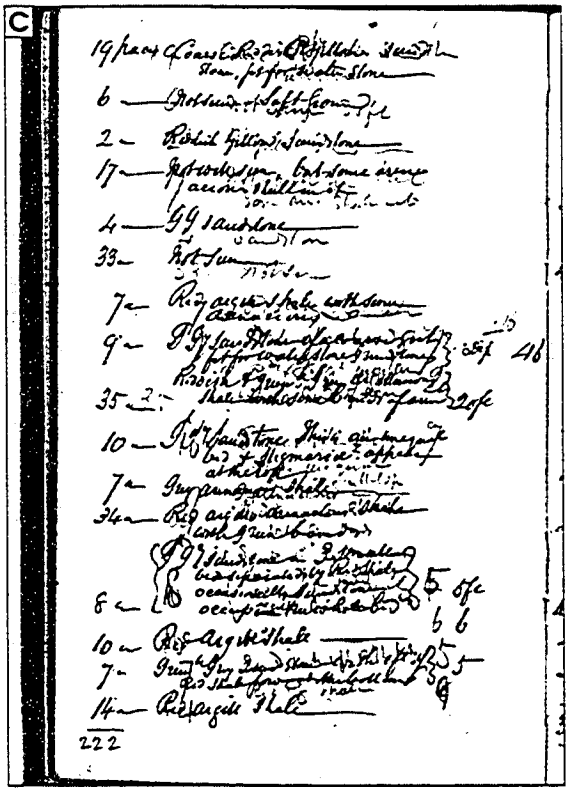
From a logistical perspective, the Joggins work differed significantly from his later work in Gaspé. A sparse population of settlers lived in the Joggins area by the early 1840s and Logan was able to find lodging with them for the duration of his stay, rather than having to make his own camp outdoors. Logistics were also simplified because Logan had only to provide for himself and a local assistant who he employed for three and three-quarters days. Realizing that his work in Nova Scotia was mainly reconnaissance, Logan did without the more complex surveying equipment employed in later projects (von Bitter, 1998) and used only his own pace, a compass, and basic field gear (e.g. measuring stick and hammer) to measure the section.

The field notebooks show that Logan continually adapted his methodology to suit the changing nature of the section. The first few pages of notes for 6 June record four

Figure 5: Pages from William Logan's field notebooks from Joggins (Logan 1843a, b). Lighter writing represents the original text (pencil); darker writing is the finalized text (ink). A) Logan's notes for the base of Division 8 showing the pace-lithology-thickness-dip style of note-taking used when pacing clastic intervals (6 June 1843). B) Logan's notes for part of Division 4 (8 June 1843). Note that Logan used the lithology-thickness style of note-taking for the coal-bearing interval, indicating that he measured these beds directly (no paces recorded). This contrasts with the over- and underlying clastic intervals where values are provided for both the thickness and the number of paces. C) Logan's notes for part of Division 2 with only pace and lithology recorded, a strong indicator that many thicknesses were calculated after Logan left the section (9 June 1843). D) Field sketch of an upright tree in Division 4 (7 June 1843).







types of information for each bed: number of paces, lithology, true thickness, and dip (Fig. 5A). Apparently realizing the enormity of his task, dip measurements become more infrequent (every few hundred feet of section) by the middle of the day. When evaluating Logan's work at Joggins it is important to remember that, although he considered the section bed-by-bed, he routinely grouped together what by modern standards would be several beds (see Davies *et al.*, submitted). Taken with other evidence (see below), the pace-lithology-thickness-dip style of note-taking records the process of pacing the horizontal extent of the beds, a measurement from which the true thickness was commonly calculated. With the transition to coal-bearing strata on 7–8 June, Logan began recording only the thickness and lithologic description for each seam and closely associated strata (Fig. 5B). The absence of pace counts for each bed represents a transition to direct measurement for these organic-rich intervals. For clastic intervals more than a few feet thick, Logan returned to pacing in order to determine bed thickness. Realizing that direct measurement was the most efficient way to proceed through gently dipping strata, Logan's notes from 10 June indicate that he adopted this methodology for measuring the redbed-dominated interval north of Two Rivers (Fig. 5C). Despite his rapid pace, Logan took the time to make several detailed sketches of particularly interesting features of the section (Fig. 5D).

Logan's habit of first writing his notes in pencil, only later inking them over, makes them difficult to read in places, but provides convincing evidence that he commonly calculated thickness values after leaving the section. Although clastic intervals are accompanied by notes on the number of paces, lithology, and thickness, only the first two values are always written in pencil (Figs. 5A-C). Conversely, coal-bearing

units always have lithology and thickness values written in pencil (Fig. 5B). Several beds observed on Friday 9 June are accompanied only by pace values (written in ink and pencil; Fig. 5C), demonstrating that paces were often the only measure of thickness collected in the field.

Indeed, it appears that Logan may not have inked over and finalized his Joggins notes until long after he left the section. In order to calculate the thickness of each bed, Logan had to multiply the number of paces by the length of his pace (our calculations indicate 2.9 feet) and the sine of the dip. No such calculations appear anywhere in his field notebooks, and it is unlikely that he would have had sufficient time to perform hundreds of trigonometric calculations after having spent lengthy days on the section. The absence of thickness values for observations on 9 June (Fig. 5C) indicates that the final calculation of bed thicknesses were made after he inked over the notes. Post-Joggins revision to the measured section is also apparent because numerous thickness values reported in the published version do not match the values in his notes, a discrepancy that either reflects a typographical error or, more likely, ongoing mathematical adjustments to the section. Logan hinted at post-Joggins calculation of thickness in a letter to De la Beche on 20 April 1844, mentioning that "since my return from field-work I have reduced all the measurements, and made out a vertical column" (De la Beche Papers).

Logan wrote to De la Beche several times about Joggins. Clearly delighted with his results there, he had first written to his mentor at the British survey while en route back from Nova Scotia to Canada. Writing from Bathurst, New Brunswick, just before he crossed Chaleur Bay into Gaspé, Logan said:

> I think I mentioned to you that I intended to visit the Joggins. I did so & spent a week putting together such a section as never was put together before. I measured and made a written description of every bed (& I don't suppose that in the whole distance there were 1500 feet not visible) occurring in 10 miles to a line directly across the strata, commencing with a dip of 45° in the lower part and ending (the change being gradual) with a dip of 4° in the upper. (Logan to De la Beche, 2 July 1843, Phillips Papers)

In this letter, Logan also mentioned that he was sending a box of Joggins fossils to De la Beche for analysis, and hoped that they would arrive safely. Although these fossils were undoubtedly collected to provide information about depositional environments for these strata, this aspect of Logan's plan was not destined for positive results.

### 2.6.3. Publication of Logan's measured section

With his observations and calculations neatly rewritten, the Joggins measured section was nearly complete by April 1844. Still awaiting feedback on the Joggins samples sent to De la Beche (also mentioned in the field notebooks), Logan wrote on 20 April, "My Dear De la Beche, How is it that you have never written to me? Did you get my letter from Bathurst, & did you get the Box of Specimens sent you from Nova Scotia?" Realizing the global significance of this section, he went on to explain:

> I am getting a written copy of it made for you, but it takes much time. It may be very useful to you in speaking of coal in general in your report. I mean to get the document published somehow or other, & I should be glad if you would allude to it publicly if it illustrates anything you may

have to say on South Wales. The detail will surprise you. You can make a public document of it if you like, by communicating it to the Geological Society. I am aware they would not print it; there is not poetry enough about it for their pages. But were it among their documents, you could then allude to it with more propriety, if you think it worth while. I cannot help thinking it will be considered very instructive in showing the composition of a coal-field. (De la Beche Papers)

By November 1844, the lines of communication had not improved. Just over two weeks before his "Report of Progress" for the previous year was turned in, a frustrated Logan outlined his situation in another letter to De la Beche:

In this one letter I have received from you, you speak of another previous dispatch which you have sent. This has never come to hand. You say nothing of any communication from me. So I am anxious to know whether you ever got my Joggins Section, & what you think of it. It is a work of no small labour & I hope something will come of it. Will it be useful to you in what you will have to say of the Welsh Coalfield. Perhaps you have not got it at all and I should like to know if such should be the case. A year & a half ago I sent you or rather put on the way of being forwarded to you a box of specimens from the Joggins; did this ever reach you? I have heard nothing of it since, not withstanding I have asked you three times to say, fish jaws and fish scales associated with Stigmariae were among the specimens (De la Beche Papers).

Unfortunately, Logan's hopes for close collaboration between the Canadian and British surveys proved to be impractical (despite the claim made by Christie, 1995). John Phillips, paleontologist to the Geological Survey of Great Britain, already had more work than he could handle, and the logistics of managing the rapidly-growing Canadian collection were impractical in the extreme. Although De la Beche appears to have sent Logan's Joggins fossils on to Phillips, nothing was ever published as a result (De la Beche Papers). In later years, Logan would make use of U.S. paleontologists such as James Hall of the New York survey, and eventually added his own paleontologist, Elkanah Billings, to the Geological Survey of Canada in 1856 (Zeller, 1987).

To publish his Joggins section, Logan turned instead to his mandatory annual report. Although Logan loathed having to submit yearly progress reports to the government (Shipley, 2001), the first installment provided him with a convenient vehicle for publishing a full copy of the Joggins measured section. The "Report of Progress for 1843", with its accompanying Joggins measured section, was presented to the government on 27 January 1845. These works, together with a letter from the Governor General, Logan's 1842 "Preliminary Report" and a report from Alexander Murray, make up the forty-five pages of Appendix W in the fourth volume of the *Journals of the Legislative Assembly of the Province of Canada 1844-5* (Logan 1845a,b,c).

The final version of the Joggins measured section covers seventeen pages and includes six figures (Logan, 1845). The 14,570 feet, 11 inches of strata in the section consist of 1,570 beds grouped into eight Divisions (following the original work, the "d" in "Divisions" is capitalized and each is designated with a number). Coal-bearing intervals were of particular interest, and Logan designated numbered "Coals" and "Coal

Groups" in each of the Divisions. Although Logan measured the section from bottom to top, he presented the published measured section in descending order so that the youngest (uppermost) strata fall within Division 1 and the oldest (lowermost) fall within Division 8. Logan was unhappy with the report's "awkward appearance" and made a point of telling De la Beche:

> If you had sent me the names of the shells, fish scales & jaw & plants which I forwarded to you all numbered, my section would have had a most learned air. I have sent a copy of the report to the President of the Geological Society. I hope he will be able to speak well of my name. I have been diligent; that I will say for myself. (Logan to De la Beche, 27 December 1845, De la Beche, Papers)

Ironically, because Logan sent his fossils to Britain, he was not even able to refer to them himself as he prepared the report (Logan to Lyell, 10 January 1853, Lyell, Papers). Logan was dissatisfied with the inclusion of his reports in a volume of government proceedings, complaining "who the devil ever reads a report" (Logan to De la Beche, 10 December 1846, De la Beche, Papers). His personally-distributed copies were not enough to counter the obscurity (outside of Canada), small print runs, and limited distribution of the Legislative Assembly's *Journals*, and so for many years after its publication Logan's geological work reached a much more limited audience than it should have (Shipley, 2001).

We present the first exact reproduction of Logan's measured section in Appendix 3. Poole (1908) republished the text portion of the section (in Proceedings and Transactions of the Nova Scotian Institute of Science - a journal that is itself rather

difficult to locate), but he did not have the original woodcuts and was unable to duplicate the figures that accompanied it. Although Poole's republication made the content of the section more accessible, his citation made the original nearly impossible to locate. Poole (1908) stated that the measured section was "published as an appendix in the first Report of Progress of the Geological Survey, for 1843, beginning at page 92, and extending to page 156, with figures on pages 157 to 159." By citing a rare offprint version of this report, rather than referring to its original place of publication in the Legislative Journal Appendices, Poole inadvertently obscured important information about the Canadian survey's early work: most of the geological literature in the last hundred years (even the Georef database) reference the section using Poole's misleading citation. With such convoluted information about the original work, most library photocopy requests are unsuccessful, resulting only in delivery of Poole (1908). We reintroduce the original measured section to the geological community by republishing it and by providing an accurate reference (Logan, 1845) to the most commonly available form. Additionally, the Canadian Institute for Historical Microreproduction's "Early Canadiana Online" project includes facsimiles of the original government document. The volume in which Logan's Appendix W appears is found at: http://www.canadiana.org/ECO/ItemRecord/9_00955_4_1; the Joggins section begins at image W-29.

## 2.7. Lyell and Dawson

### 2.7.1. Visits to Joggins

Logan was not the only Canadian geologist to publish a Joggins section. Another section was produced by John William Dawson (1820-1899), who first visited Joggins in

the 1830s. Dawson later recalled of this trip that "I returned in the evening to the quarryman's shanty, thoroughly fatigued, but loaded with fossils, delighted with the knowledge I had acquired, and with my enthusiasm for geology raised to a higher point than ever before" (Dawson, 1901). In the company of Abraham Gesner, the eminent British geologist Charles Lyell (Dawson's mentor) had made his first examination of the section in July 1842 (Wilson, 1998). Having personally witnessed a 25-foot-tall standing lycopsid trunk and discovering that Gesner once measured one 40 feet tall (Lyell, 1842); Wilson 1998), Lyell wrote to his sister that the Joggins fossil forests were "the most wonderful phenomenon perhaps that I have ever seen" (Lyell, 1842) Lyell's observations at the Joggins section were communicated to the Geological Society of London (Lyell 1843a, b) and featured prominently in his *Travels in North America* (Lyell, 1845). With both of their appetites thus whetted, mentor Lyell and protégé Dawson returned to the section together in 1852 to spend a few days exchanging ideas and investigating the preservation of standing trees (Sheets-Pyenson, 1996).

During this visit, the two lacked the advantage of Logan's measured section. During their five-day stay in September 1852 (Wilson, 1998), they examined much of the coal-bearing interval near Joggins village and measured their own 2,819 foot, 2 inch section. While breaking apart lycopsid casts in search of plant material, they stumbled across a diverse assemblage of animal remains, including reptile bones and land snail shells (Lyell and Dawson, 1853). Delighted with their discoveries, Lyell wrote to his father-in-law, Leonard Horner, on 12 September that "I never enjoyed the reading of a marvelous chapter of the big volume more" (Lyell, 1852).

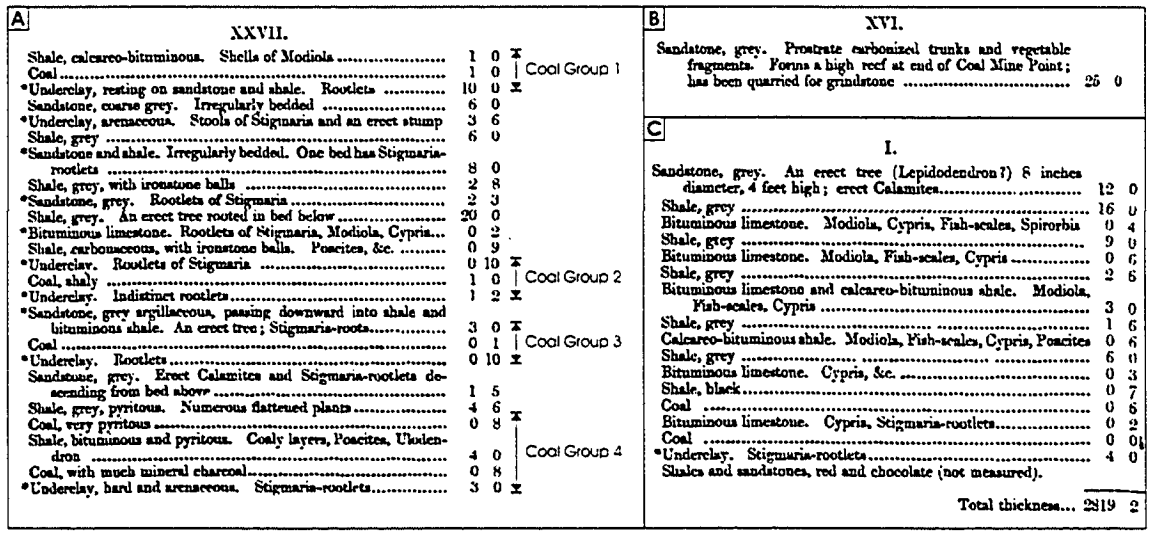
Following his visit to the Joggins section, Lyell became aware of Logan's measured section, but neither he nor Dawson could easily find any record of it in print. On 16 December 1852, Lyell requested a copy, to which Logan replied on 10 January 1853 that he had sent copies to the geological establishments in Britain and even to Lyell himself (Logan Papers; Lyell Papers). Logan's claim is supported by the fact that Leonard Horner (as President of the Geological Society of London) described Logan's section in great detail in his anniversary address to the Society (Horner 1846). This awkward exchange, described more fully by Shipley (2001), emphasizes both the inaccessibility of the measured section and the lack of communication between Logan on the one side, and Dawson and Lyell on the other. Sheets-Pyenson (1996, p. 24) speculated that there may have been personal friction between Logan and Dawson, noting that Dawson was not recruited for the Canadian survey and that Lyell often acted as their liaison even when they both lived in Montreal. Alternately, their less than perfect communication during the 1840's may simply have reflected their busy careers and the sheer press of sheer press of work that affected them. Whatever the case, after Dawson's appointment to McGill University in 1855, Harrington (1883) describes their relationship as close and cooperative – an observation supported by Logan's large donations to McGill University in his will.

With the benefit of additional observations during the following summer of 1853, Dawson finished the section by himself because Lyell had been called away to serve as commissioner to the New York Industrial Exhibition (Wilson, 1998). He then gave the

section to Lyell to communicate to the Geological Society of London on 2 November 1853 (Dawson, 1854). Dawson published his measured section as a list of lithologies and thicknesses that are subdivided into twenty nine "Groups" (later referred to as "Subdivisions", both of which are designated with Roman numerals). Dawson's measured section was accompanied by a five-page commentary on the sedimentology, a fourteen-page description of the Groups and, having eventually secured a copy, a précis of Logan's work. In comparing the two measured sections, Dawson mentioned that the "number of coals and bituminous limestones seen by us corresponds with that of Mr. Logan," and that any discrepancies arose from "different estimates of the limits of beds, from the obscuration of portions of the section, and from the circumstance that many beds called by us sandstones, or argillaceous sandstones, appear in Mr. Logan's section as arenaceous shales" (Dawson, 1854, p. 41). He also mentioned that his measured section corresponded to the lower part of Logan's Division 3 (Groups XXVIII and XXIX) and all of Division 4 (Groups XXVII through I). Despite the harmony implied by these comments, careful scrutiny reveals differences so profound that Dawson largely abandoned his own observations when he reproduced this section in post-1855 editions of *Acadian Geology* (Fig. 6).

### 2.7.2. Comparison of the measured sections

Lateral changes in bed thickness and ongoing erosion of the cliffs (up to 50 m in the last 150 years) makes detailed comparison of Logan and Dawson's sections with the



A

XXVII.

| | | | | |
|---|---|---|---|---|
| Shale, calcareo-bituminous. Shells of Modiola | 1 | 0 | ⧗ | Coal Group 1 |
| Coal | 1 | 0 | | |
| *Underclay, resting on sandstone and shale. Rootlets | 10 | 0 | ⧗ | |
| Sandstone, coarse grey. Irregularly bedded | 6 | 0 | | |
| *Underclay, arenaceous. Stools of Stigmaria and an erect stump | 3 | 6 | | |
| Shale, grey | 6 | 0 | | |
| *Sandstone and shale. Irregularly bedded. One bed has Stigmaria-rootlets | 8 | 0 | | |
| Shale, grey, with ironstone balls | 2 | 8 | | |
| *Sandstone, grey. Rootlets of Stigmaria | 2 | 3 | | |
| Shale, grey. An erect tree rooted in bed below | 20 | 0 | | |
| *Bituminous limestone. Rootlets of Stigmaria, Modiola, Cypris... | 0 | 2 | | |
| Shale, carbonaceous, with ironstone balls. Poacites, &c. | 0 | 9 | | |
| *Underclay. Rootlets of Stigmaria | 0 | 10 | ⧗ | Coal Group 2 |
| Coal, shaly | 1 | 0 | | |
| *Underclay. Indistinct rootlets | 1 | 2 | ⧗ | |
| *Sandstone, grey argillaceous, passing downward into shale and bituminous shale. An erect tree; Stigmaria-roots | 3 | 0 | ⧗ | Coal Group 3 |
| Coal | 0 | 1 | | |
| *Underclay. Rootlets | 0 | 10 | ⧗ | |
| Sandstone, grey. Erect Calamites and Stigmaria-rootlets descending from bed above | 1 | 5 | | |
| Shale, grey, pyritous. Numerous flattened plants | 4 | 6 | | |
| Coal, very pyritous | 0 | 8 | ⧗ | Coal Group 4 |
| Shale, bituminous and pyritous. Coaly layers, Poacites, Ulodendron | 4 | 0 | | |
| Coal, with much mineral charcoal | 0 | 8 | | |
| *Underclay, hard and arenaceous. Stigmaria-rootlets | 3 | 0 | ⧗ | |

B

XVI.

| | | |
|---|---|---|
| Sandstone, grey. Prostrate carbonized trunks and vegetable fragments. Forms a high reef at end of Coal Mine Point; has been quarried for grindstone | 25 | 0 |

C

I.

| | | |
|---|---|---|
| Sandstone, grey. An erect tree (Lepidodendron?) 8 inches diameter, 4 feet high; erect Calamites | 12 | 0 |
| Shale, grey | 16 | 0 |
| Bituminous limestone. Modiola, Cypris, Fish-scales, Spirorbis | 0 | 4 |
| Shale, grey | 9 | 0 |
| Bituminous limestone. Modiola, Fish-scales, Cypris | 0 | 6 |
| Shale, grey | 2 | 6 |
| Bituminous limestone and calcareo-bituminous shale. Modiola, Fish-scales, Cypris | 3 | 0 |
| Shale, grey | 1 | 6 |
| Calcareo-bituminous shale. Modiola, Fish-scales, Cypris, Poacites | 0 | 6 |
| Shale, grey | 6 | 0 |
| Bituminous limestone. Cypris, &c. | 0 | 3 |
| Shale, black | 0 | 7 |
| Coal | 0 | 6 |
| Bituminous limestone. Cypris, Stigmaria-rootlets | 0 | 2 |
| Coal | 0 | 0½ |
| *Underclay. Stigmaria-rootlets | 4 | 0 |
| Shales and sandstones, red and chocolate (not measured). | | |
| Total thickness... | 2819 | 2 |

Figure 6: Selected intervals from Dawson's (1854) measured section. A) Group XXVII, which corresponds to the top of Logan's Division 4 and the top of the newly redefined Joggins Formation. Labels showing Coal Groups added for comparison with Fig. 7. B) Group XVI, Coal Mine Point. C) Group I, which corresponds to the base of Logan's Division 4 and contains the base of the newly redefined Joggins Formation.

modern coastal section problematic. Despite these changes, comparison of cumulative thicknesses and beds with relatively constant thicknesses (e.g. coals, limestones, and some sandstones) makes certain comparisons possible. Logan reported a thickness of 2,533 feet, 7 inches for the interval between the top of the limestone in Coal Group 1 and the base of Coal 45, whereas Dawson's measured section gave a thickness of 2,616 feet, 8 inches for the same interval, which is 83 feet, 1 inches (3.3%) thicker than Logan's estimate. This comparison is based on the questionable assumption that Dawson correctly matched his measured section to Logan's. The calcareo-bituminous shale at the top of Group XXVII (Fig. 6A) almost certainly corresponds to Logan's bituminous limestone, but Dawson's judgment that the lowest coal in Group I matches Logan's Coal 45 is problematic because the bituminous limestone that Dawson observed in Group I (Fig. 6C) is a lithology that last occurs in Logan's Coal 44. If Dawson did mismatch the base of the sections, the difference between the measured sections increases to 191 feet, 9 inches, an increase of 7.6% over Logan's thickness. Regardless of the exact correlation, the cumulative thicknesses of the measured sections match remarkably well given the brevity of their field work.

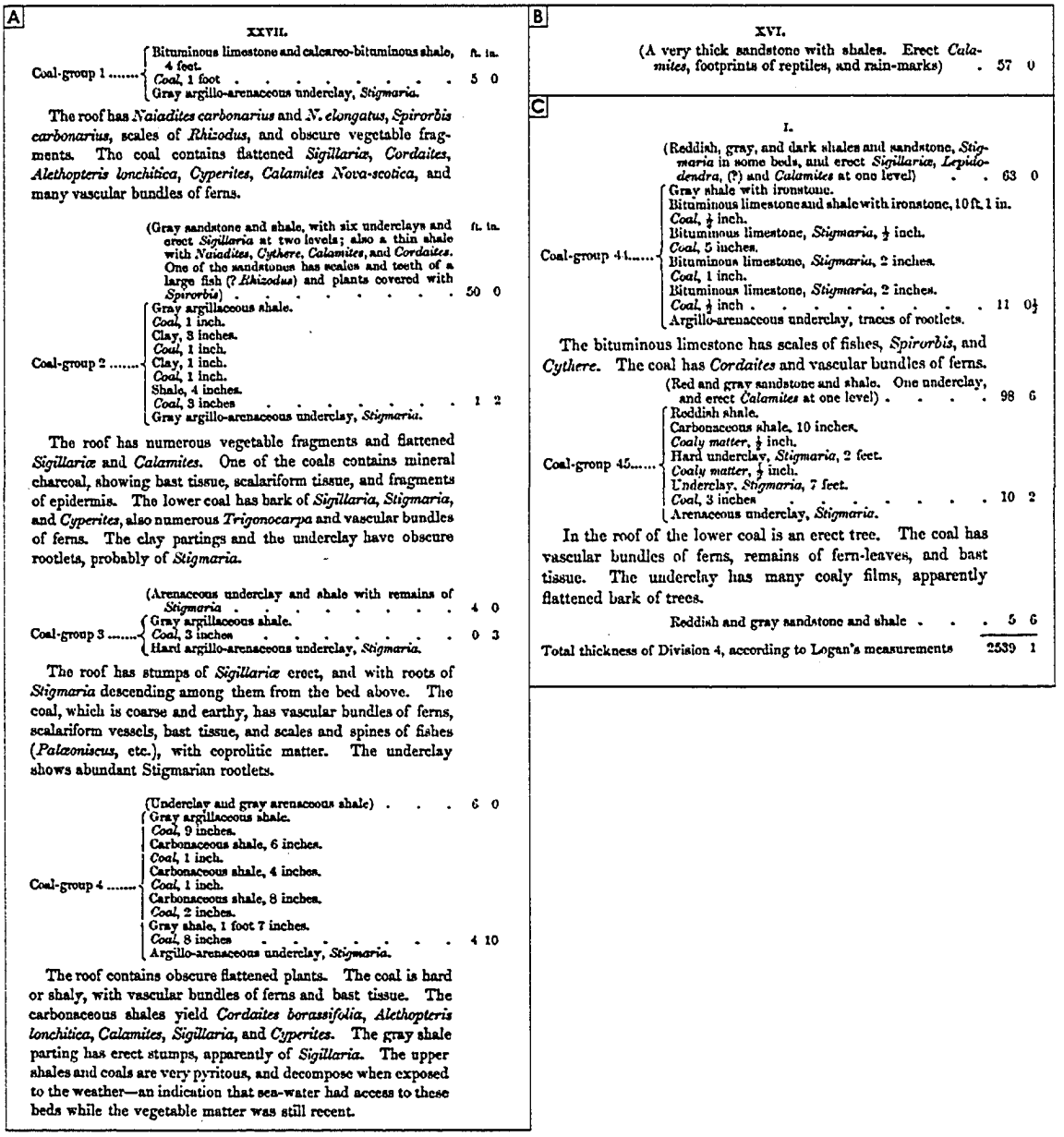
Contrary to Dawson's statement, both measured sections contain coal seams that are not present in the other. Dawson recorded Bell's Brook within a 12-foot shale. Depending on its exact placement within this interval, the brook is separated from the next overlying coal by 28 to 40 feet of clastic sediment; however, Logan placed Coal 10 within 6 feet of the brook. (note that Davies *et al.* (submitted) were unable to find Coal 10). Conversely, coals mentioned in Dawson's Groups XVII (8-inch seam), XV (4-inch

seam), and XI (4-foot seam) are not reported by Logan (note that the 8-inch and 4-foot seam are exposed today; the location of the 4-inch seam is uncertain).

Unlike the cumulative thickness values, bed-by-bed comparison of the measured sections shows that even distinctive beds have very different descriptions and thicknesses. For example, Logan's measured section has Division 4 capped by a 4-foot bituminous limestone atop a 1-foot coal (Coal Group 1); the same interval is described by Dawson (Group XXVII; Fig. 6A) as having a 1-foot coal overlain by 1-foot calcareo-bituminous shale. (Note that Davies *et al.* (submitted), record a 0.38 m [1 foot, 3 inch] limestone at this level.) Logan's Coal Group 4 consists of an 8-inch coal overlain by 1 foot, 7 inches of argillaceous shale and 2 feet, 7 inches of interbedded coal and carbonaceous shale, whereas Dawson describes the same interval (near the base of Group XXVII; Fig. 6A) as having two 8-inch coals separated by 4 feet of bituminous shale with coaly layers. Both measured sections specifically mention the Coal Mine Point headland; Logan quotes the thickness of the sandstone there as 30 feet, but Dawson (Fig. 6B) gives it as 25 feet. (Note that Davies *et al.* (submitted), give the thickness of the sandstone portion of Coal Mine Point as about 7.6 m [25 feet] thick.)

### 2.7.3. Reconciliation

Without explanation, a very different version of the Joggins measured section appears in later printings of *Acadian Geology* (Dawson, 1868, 1878, 1891). At first glance, it appears as if Dawson simplified his measured section and incorporated Logan's numbers; closer inspection reveals that he abandoned many of his own observations and thicknesses in favor of Logan's. The nature of these changes is easily illustrated by comparing Dawson's 1855 and 1868 versions of Subdivisions I, XXVI, and XXVII with



A

XXVII.

| | | ft. | in. |
|---|---|---|---|
| Coal-group 1 | Bituminous limestone and calcareo-bituminous shale, 4 feet. | | |
| | *Coal*, 1 foot | 5 | 0 |
| | Gray argillo-arenaceous underclay, *Stigmaria*. | | |

The roof has *Naiadites carbonarius* and *N. elongatus*, *Spirorbis carbonarius*, scales of *Rhizodus*, and obscure vegetable fragments. The coal contains flattened *Sigillariæ*, *Cordaites*, *Alethopteris lonchitica*, *Cyperites*, *Calamites Nova-scotica*, and many vascular bundles of ferns.

| | | ft. | in. |
|---|---|---|---|
| | (Gray sandstone and shale, with six underclays and erect *Sigillaria* at two levels; also a thin shale with *Naiadites*, *Cythere*, *Calamites*, and *Cordaites*. One of the sandstones has scales and teeth of a large fish (? *Rhizodus*) and plants covered with *Spirorbis*) | 50 | 0 |
| Coal-group 2 | Gray argillaceous shale. | | |
| | *Coal*, 1 inch. | | |
| | Clay, 3 inches. | | |
| | *Coal*, 1 inch. | | |
| | Clay, 1 inch. | | |
| | *Coal*, 1 inch. | | |
| | Shale, 4 inches. | | |
| | *Coal*, 3 inches | 1 | 2 |
| | Gray argillo-arenaceous underclay, *Stigmaria*. | | |

The roof has numerous vegetable fragments and flattened *Sigillariæ* and *Calamites*. One of the coals contains mineral charcoal, showing bast tissue, scalariform tissue, and fragments of epidermis. The lower coal has bark of *Sigillaria*, *Stigmaria*, and *Cyperites*, also numerous *Trigonocarpa* and vascular bundles of ferns. The clay partings and the underclay have obscure rootlets, probably of *Stigmaria*.

| | | | |
|---|---|---|---|
| | (Arenaceous underclay and shale with remains of *Stigmaria* | 4 | 0 |
| Coal-group 3 | Gray argillaceous shale. | | |
| | *Coal*, 3 inches | 0 | 3 |
| | Hard argillo-arenaceous underclay, *Stigmaria*. | | |

The roof has stumps of *Sigillariæ* erect, and with roots of *Stigmaria* descending among them from the bed above. The coal, which is coarse and earthy, has vascular bundles of ferns, scalariform vessels, bast tissue, and scales and spines of fishes (*Palæoniscus*, etc.), with coprolitic matter. The underclay shows abundant Stigmarian rootlets.

| | | | |
|---|---|---|---|
| | (Underclay and gray arenaceous shale) | 6 | 0 |
| Coal-group 4 | Gray argillaceous shale. | | |
| | *Coal*, 9 inches. | | |
| | Carbonaceous shale, 6 inches. | | |
| | *Coal*, 1 inch. | | |
| | Carbonaceous shale, 4 inches. | | |
| | *Coal*, 1 inch. | | |
| | Carbonaceous shale, 8 inches. | | |
| | *Coal*, 2 inches. | | |
| | Gray shale, 1 foot 7 inches. | | |
| | *Coal*, 8 inches | 4 | 10 |
| | Argillo-arenaceous underclay, *Stigmaria*. | | |

The roof contains obscure flattened plants. The coal is hard or shaly, with vascular bundles of ferns and bast tissue. The carbonaceous shales yield *Cordaites borassifolia*, *Alethopteris lonchitica*, *Calamites*, *Sigillaria*, and *Cyperites*. The gray shale parting has erect stumps, apparently of *Sigillaria*. The upper shales and coals are very pyritous, and decompose when exposed to the weather—an indication that sea-water had access to these beds while the vegetable matter was still recent.

B

XVI.

| | | | |
|---|---|---|---|
| | (A very thick sandstone with shales. Erect *Calamites*, footprints of reptiles, and rain-marks) | 57 | 0 |

C

I.

| | | | |
|---|---|---|---|
| | (Reddish, gray, and dark shales and sandstone, *Stigmaria* in some beds, and erect *Sigillaria*, *Lepidodendra*, (?) and *Calamites* at one level) | 63 | 0 |
| Coal-group 44 | Gray shale with ironstone. | | |
| | Bituminous limestone and shale with ironstone, 10 ft. 1 in. | | |
| | *Coal*, ½ inch. | | |
| | Bituminous limestone, *Stigmaria*, ½ inch. | | |
| | *Coal*, 5 inches. | | |
| | Bituminous limestone, *Stigmaria*, 2 inches. | | |
| | *Coal*, 1 inch. | | |
| | Bituminous limestone, *Stigmaria*, 2 inches. | | |
| | *Coal*, ½ inch | 11 | 0½ |
| | Argillo-arenaceous underclay, traces of rootlets. | | |

The bituminous limestone has scales of fishes, *Spirorbis*, and *Cythere*. The coal has *Cordaites* and vascular bundles of ferns.

| | | | |
|---|---|---|---|
| | (Red and gray sandstone and shale. One underclay, and erect *Calamites* at one level) | 98 | 6 |
| Coal-group 45 | Reddish shale. | | |
| | Carbonaceous shale, 10 inches. | | |
| | *Coaly matter*, ½ inch. | | |
| | Hard underclay, *Stigmaria*, 2 feet. | | |
| | *Coaly matter*, ½ inch. | | |
| | Underclay, *Stigmaria*, 7 feet. | | |
| | *Coal*, 3 inches | 10 | 2 |
| | Arenaceous underclay, *Stigmaria*. | | |

In the roof of the lower coal is an erect tree. The coal has vascular bundles of ferns, remains of fern-leaves, and bast tissue. The underclay has many coaly films, apparently flattened bark of trees.

| | | | |
|---|---|---|---|
| | Reddish and gray sandstone and shale | 5 | 6 |
| Total thickness of Division 4, according to Logan's measurements | | 2539 | 1 |

Figure 7: Dawson's (1868) version of the intervals shown in Fig. 6. A) Group XXVII, which corresponds to the top of Logan's Division 4 and the top of the newly redefined Joggins Formation. B) Group XVI, which contains Coal Mine Point. C) Group I, which corresponds to the base of Logan's Division 4 and contains the base of the newly redefined Joggins Formation.

each other (Figs. 6 and 7) and with Logan's measured section (Appendix 3). A comparison of the coals in these intervals reveals that Dawson adopted Logan's observations for coals and immediately adjacent strata. This interval also demonstrates that Dawson sometimes used Logan's thicknesses for thick packages of interbedded clastic strata. Dawson also made it impossible to compare thicknesses between the revised version of his measured section and Logan's by excluding the thickness of many units immediately above (shales) or below (underclays) coals (Figs. 7A and C). Although Dawson stated at the end of the measured section that the "total thickness of Division 4, according to Logan's measurements" is 2,539 feet, 1 inch, the sum of all the values he listed is actually 2,583 feet, 3 inches (which is a minimum value because of the missing thicknesses for units above and below coals).

Fortunately, Dawson inserted text blocks with his own observations to supplement Logan's basic lithologic descriptions. More importantly, he also inserted several of the coals that Logan missed. These additional coal-bearing packages are designated with a letter suffix (e.g., Coal Groups 13a, 15a, and 29a). The only explanation of the overlooked seams is given with regards to Coal Group 29a: "My measurements in this part of the section differ somewhat from those of Sir W.E. Logan, who, I suppose, had not a good opportunity of examining the two last coals. The coal 29a is now mined by an adit from the shore, called the 'New Mine'" (Dawson, 1868).

Logan's decision to abandon his own measurements was unfortunate because, if number of hours per unit thickness is any indication of quality, Dawson and Lyell certainly had the superior measured section. We are not aware of any documentation explaining why Dawson chose to abandon his own observations in favor of Logan's, but

it seems likely that Dawson made this decision to abandon his measurements for the sake of simplicity and to publicize the largely unknown work of his colleague from twenty-five years earlier. Certainly, it made no sense to have two competing sections, and Logan was the senior geologist and had published his version first. Although Dawson's revised version has only limited value as a bed-by-bed measured section, it does contribute a wealth of paleontological and interpretive information, something almost completely lacking from Logan's measured section.

## 2.8. Significance of the Measured Sections

Our findings dispel the notion that Logan produced a bed-by-bed measured section accurate to fractions of an inch, but highlight other aspects of his work that are even more remarkable. Logan measured more than 14,570 feet 11 inches of section in only five days. This monumental feat was accomplished in spite of the access problems caused by the Fundy tides and without the aid of a trained field assistant. Logan's thicknesses for Divisions 4, 5, and 6 are surprisingly close to the values reported by recent detailed studies (Table 1), an impressive accomplishment considering the brevity of his visit and the inherent difficulties with pacing in rough, irregular terrain. Sixteen decades later, Logan's measured section remains the only complete measured section of the strata exposed along the Chignecto coast. The three studies listed in Table 1,

| Division | Present name | Logan's thickness | Thickness (m) & Author | Difference from Logan's thickness |
|---|---|---|---|---|
| 4 | Joggins Formation | 773.9 m (2,539 ft. 1 in.) | 915.5 m (Davies *et al.*, submitted) | 141.6 m (+18.3%) |
| 5 | Little River Formation | 634.6 m (2082 ft.) | 635.8 m (Calder *et al.*, Chapter 8) | 1.2 m (+0.2%) |
| 6 | Boss Point Formation | 987.8 m (3,240 ft. 9 in.) | 1074 m (S. Johnson & C. St. Peter, pers. comm.) | 86.2 m (+8.7%) |

Table 1: Summary of measured thicknesses for Logan's Divisions 4, 5, and 6.

combined, comprise just over half of the interval covered by Logan in his five-day traverse.

The Joggins measured section constructed by Logan, and the modified versions that appeared in post-1855 editions of Dawson's *Acadian Geology*, are the foundation upon which all subsequent studies were based. The sections and the discoveries made while constructing them are featured in some of the most important scientific works of the nineteenth century, including Darwin's (1859) *On the Origin of Species* and in Lyell's (1862) *Principles of Geology*. Regardless of the stratigraphic rank and exact thickness assigned to Logan's Divisions, 160 years of revisions make it clear that Logan essentially got the major lithostratigraphic divisions correct at his first attempt (Fig. 8). With the redefinition of the Joggins Formation and the establishment of the Little River Formation (Calder *et al.*, Chapter 8; Davies *et al.*, submitted), many of the stratigraphic boundaries exposed along the coast now correspond almost exactly to the contacts between Logan's Divisions (Fig. 8). The balance between "lumping" and "splitting" may well shift in the future, but Logan's observations will continue to form the framework upon which the nomenclature is built.

When Logan measured the section at Joggins in June 1843, it was done for his own specific reasons, as he underwent the transition from a gentlemanly amateur to an official government geologist. Nevertheless, it remains one of the single greatest contributions to the geology of the Maritimes. Although our research shows that Logan's section should no longer be considered a detailed, bed-by-bed measured section, the story behind its construction shows that it remains "a remarkable monument of his industry and power of observation" (Harrington, 1883).

Figure 8: Major changes to the stratigraphic nomenclature applied to the section along Chignecto Bay. Current scheme incorporates Davies *et al.*, (submitted), Calder *et al.* (Chapter 8), Calder (1995), and Susan Johnson and Clint St. Peter (pers. comm., 2003). Circled numbers correspond to the following surfaces: 1) base of Ragged Reef Point, 2) base of lowest gray sandstone, 3) base of lowest conglomerate, 4) highest siderose mudrock, 5) base of sandstone 168 feet, 2 inches above base of Division 3. Asterisk denotes modern boundary that corresponds to one of Logan's Division boundaries.

Logan (1845c)
Dawson (1868)
Bell (1912)
Bell (1914)
Bell (1943)
Shaw (1951)
Copeland (1959)
Belt (1964)
Kelley (1967)
Ryan et al. (1991)
Current Scheme
Division 1
Division 2
Division 3
Division 4
Division 5
Division 6
Division 7
Division 8
Upper Coal Fm.
Div. 1
Div. 2
Div. 3
Div. 4
Div. 5
Div. 6
Div. 7
Div. 8
Middle Coal Formation
Millstone-grit Series
Upper Coal Measures
Upp. Grindstone Div.
Middle Grindstone Division
Upper division (grey)
Lower division (reddish)
Middle Coal Measures
Upper red measures
Lower Grindstone division
Lower Cong. div
Millstone-grit or Lower Coal Measures
Windsor Series
Shulie Formation
Joggins Formation
Boss Point Formation
Windsor Formation
Cumberland Group
Riversdale Group
Canso Gr.
undifferentiated
Joggins member
Boss Point Fm.
Claremont Fm.
Shepody Formation
Middleboro Fm.
Map Unit #11
#10
#10a
Boss Point Fm. (#8)
Claremont Fm. (#7)
Shepody Fm. (#6)
Maringouin Fm (#5)
Facies C (upper coarse)
Facies B (lower fine, coal-bearing)
Facies A (lower coarse)
Riversdale Group (not studied at the fm.scale)
not studied
Coarse Fluvial Facies
Cumberlandian strata
Rivercsdalian strata
Boss Point Fm.
Claremont cong.
Shepody Fm.
Maringouin Fm.
Cumberland Group
Riversdale Group
Boss Point Fm.
Claremont Fm.
Canso Group
Mabou Gr.
Ragged Reef Fm.
Springhill Mines Fm.
Joggins Fm.
Boss Point Fm.
Claremont Fm.
Shepody Fm.
Middleb-orough Fm.
Springhill Mines Fm.
Joggins Fm.
Little River Fm.
Boss Point Fm.
Claremont Fm
Shepody Fm.
Middleb-orough Fm.
Mabou Gr.
top of Logan's section
highest siderose mudrock (same as 45)
top of highest bit
base of Coal 45
top of "South Reef"
lowest bit & top of cl.
lowest cong.
base of first grey sd.
covered
bed nearly horizontal
highest gray shale
highest carb. shale
highest limestone
base of bit 5'6" below lowest thick (6 cm) coal
top of "south reef"
lowest bit & top of cl.
highest greenish sd. in Div. 8
covered

## 2.9. ACKNOWLEDGEMENTS

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# CHAPTER 3: GEOLOGICAL SETTING AND PALEOENVIRONMENTS OF THE JOGGINS FORMATION

*Michael C. Rygel, Sarah J. Davies and Martin R. Gibling*

## 3.1. ABSTRACT

The Pennsylvanian Joggins Formation was deposited in the Cumberland Basin of Nova Scotia, a fault-bounded depocenter within the regional Maritimes Basin. In the Pennsylvanian, Nova Scotia was situated at the heart of tropical Euramerica and served as a crossroads for biotic exchange between North America and Europe. This 915.5-m-thick unit accumulated in the Langsettian - a period of rapid subsidence in the western Cumberland Basin that ranks amongst the highest experienced in the Paleozoic Maritimes Basin. During deposition of the Joggins Formation, sediment supply from the adjacent highlands remained almost perfectly balanced with subsidence, thus preserving a remarkable thickness of alluvial strata deposited near relative base level. Joggins strata can be subdivided into open water, poorly drained, and well drained facies associations. These facies associations represent discrete depositional environments and are arranged in fourteen cycles of flooding and subsequent infilling.

As a prelude to later chapters, we provide an overview of the regional geology, summarize the sedimentology of the facies associations and place this information in a paleoecological context.

## 3.2 TECTONO-STRATIGRAPHIC FRAMEWORK FOR THE MARITIMES BASIN

The term "Maritimes Basin" has come into general use to represent the Upper Paleozoic rocks exposed onshore or concealed beneath the sea across Atlantic Canada

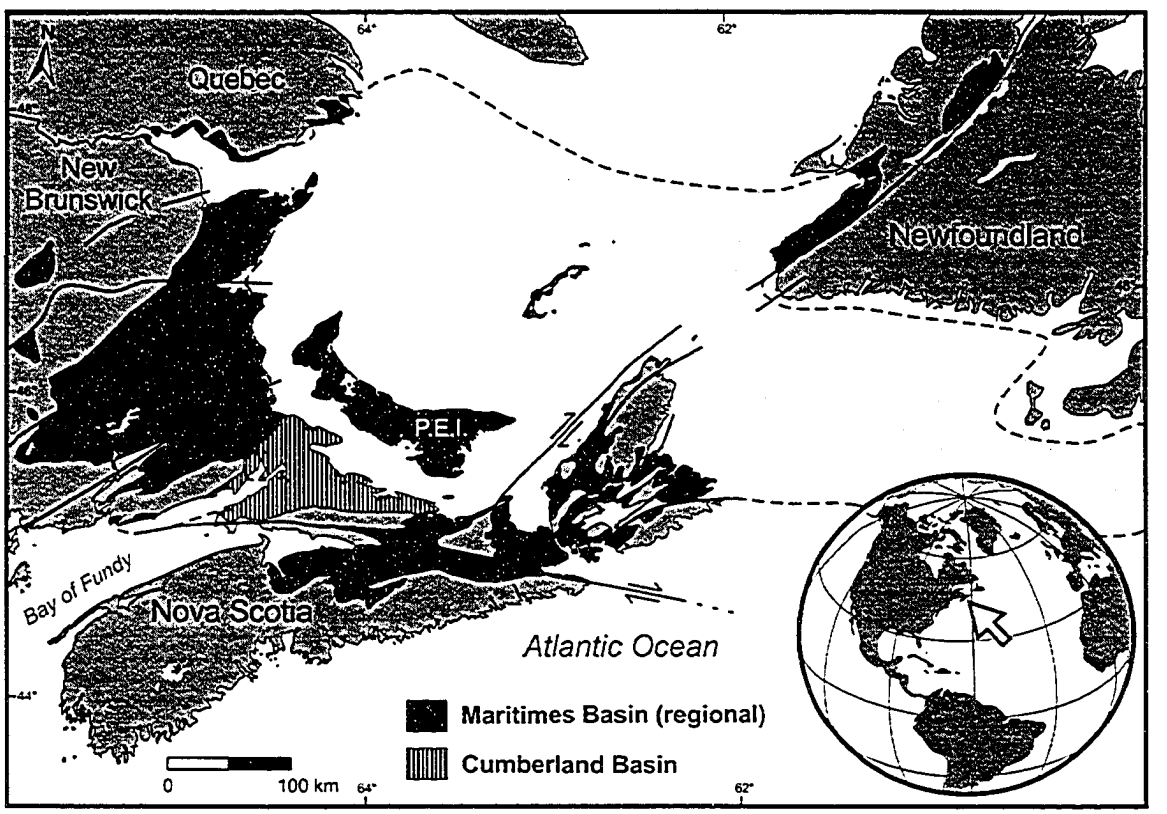



Figure 9: Map showing the extent of the Maritimes Basin (after Gibling *et al.*, 1992).

(Fig. 9). After closure of the Iapetus Ocean during the Acadian Orogeny, sedimentation in this area commenced in the mid-Devonian and continued through phases of the Alleghanian Orogeny into the Early Permian (Calder, 1998), when Laurasia and Gondwana finally amalgamated to create the supercontinent of Pangea (Fig. 10; Golonka and Ford, 2000; Trappe, 2000; Scotese, 2001). The basin fill rests upon basement rocks of ancestral North America (the Grenville Province), and several accreted microcontinents including the Avalon and Meguma Terranes (Schenk, 1981; Barr *et al.*, 1995). The huge landmass of Gondwana, once adjacent to eastern Canada, drifted away from North America during the Mesozoic and Cenozoic as continental sea-floor spreading created the Atlantic Ocean and destroyed the Pangean supercontinent (Wade *et al.*, 1996).

Strata of the Maritimes Basin are up to 10 km thick under the Gulf of St. Lawrence (Sanford and Grant, 1990), and extend from western New Brunswick east to the Grand Banks and from central Nova Scotia north to Newfoundland and Quebec (Fig. 9). The Maritimes Basin comprises a suite of formerly isolated to interconnected depocenters bounded by faults or uplifted basement blocks (Gibling, 1995). Where individual depocenters can be recognized, they have historically been termed "basins" in their own right: one of these is the Cumberland Basin, host to the Joggins Formation. The Maritimes Basin fill accumulated in successive phases of subsidence separated by episodes of inversion, and can be considered as a series of superimposed basins that record a "polycyclic" basin history (Fig. 11). Detailed accounts of the Maritimes Basin

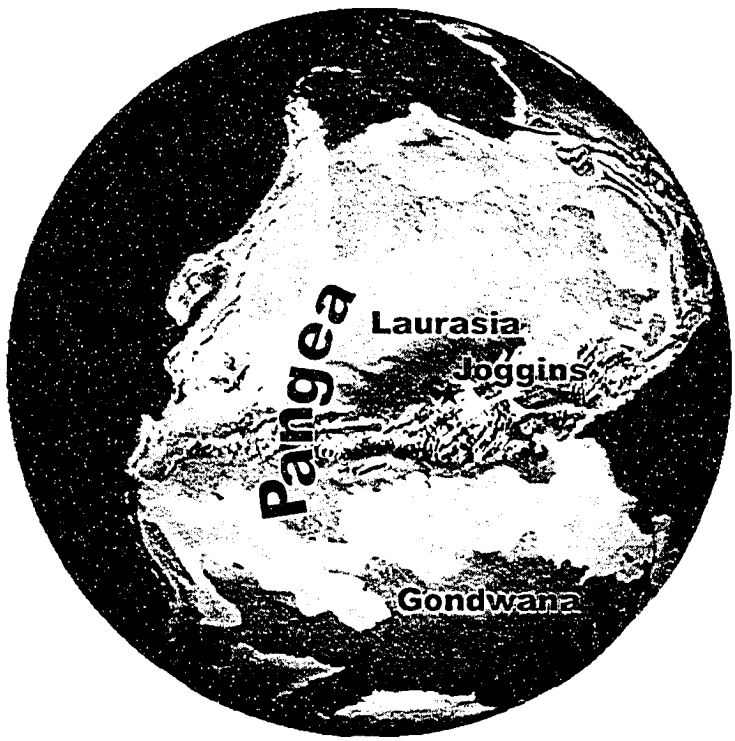



Figure 10: Pennsylvanian paleogeography (modified from paleographic maps at http://jan.ucc.nau.edu/~rcb7/globaltext2.html).

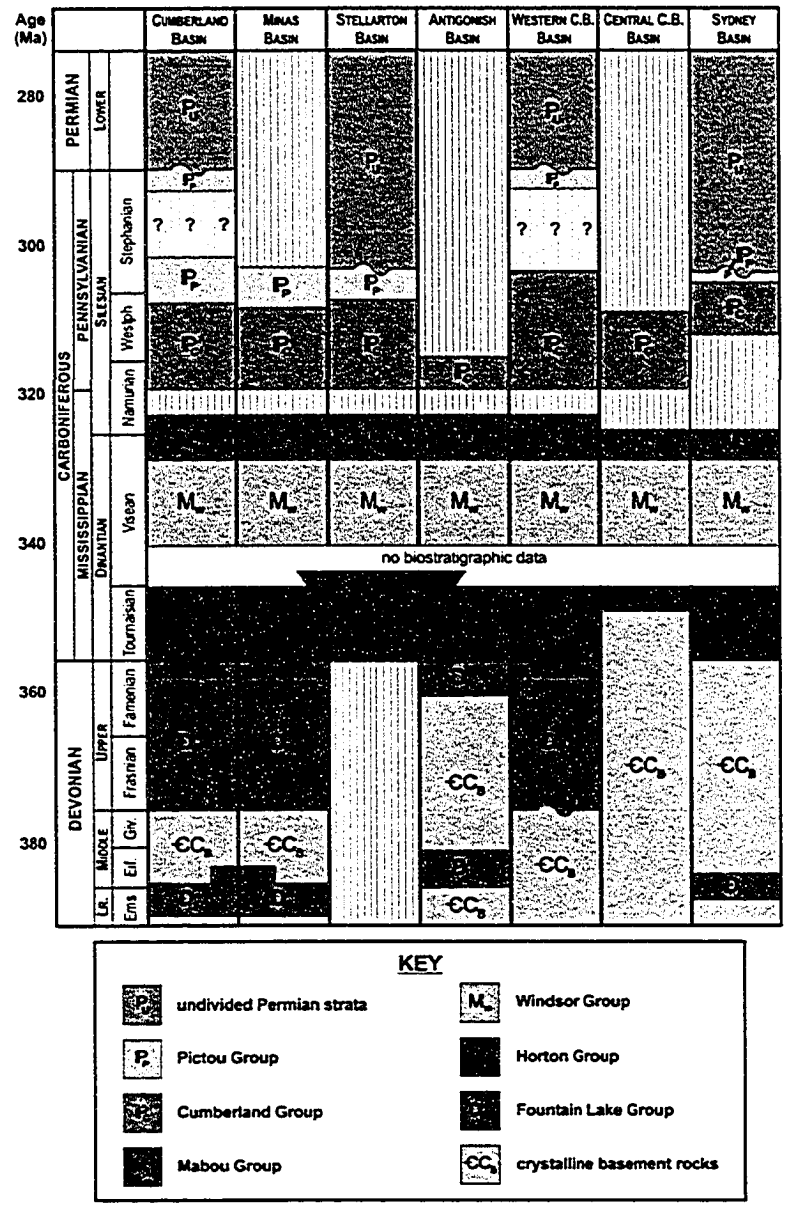



Figure 11: Stratigraphy of the Maritimes Basin (after Calder, 1998).

can be found in Bell and Howie (1990), Williams (1995), Calder (1998), and Pascucci et al. (2000).

### 3.2.1. Devonian through Mississippian

The early history of the Maritimes Basin was characterized by the development of half-grabens formed by extensional reactivation of Acadian faults (Marillier *et al.*, 1989) or collapse structures formed in response to the intrusion of Devonian-Carboniferous granites (Piper, 1994). This period of localized rifting and episodic basin inversion is recorded in the alluvial fan and lake deposits (including thick oil shales), bimodal volcanics, and restricted-marine strata of the Fountain Lake and Horton Groups (late Devonian to latest Tournaisian), each of which locally approach thicknesses of 3 kilometers (Hamblin and Rust, 1989).

This phase of dominantly clastic sedimentation ended in the middle Viséan, when the "Windsor Sea" rapidly invaded virtually all depocenters within the Maritimes Basin, forming a restricted, hypersaline gulf roughly the size of the Caspian Sea (Mamet, 1970; Howie, 1984; Schenk *et al.*, 1994). This transgression has counterparts across tropical Euramerica (Bless *et al.*, 1987; Rast, 1988) and coincided with declining subsidence rates and a transition to a phase of thermal sag in many extensional basins in the Atlantic region (Bradley, 1982). In the Maritimes, this marine incursion is recorded by the Windsor Group, a kilometer-thick unit of mid- to late Viséan evaporites (halite, gypsum, anhydrite, and minor potash salts), carbonates, and clastics. Cycles within the Windsor Group can be correlated regionally and probably record sea-level fluctuations associated with the glaciation of Gondwana (Giles, 1981), which lay over the South Pole at that time. The demise of the Windsor Sea in the latest Viséan probably resulted from some

combination of expanded Gondwanan ice accumulation (Veevers and Powell, 1987; Gibling, 1995) and the beginnings of Namurian tectonism in Atlantic Canada (Calder, 1998).

Locally, extension and reactivation of basement-cored faults triggered halokinesis of Windsor Group evaporites and development of synclinal Mabou 'minibasins' (Waldron and Rygel, Chapter 9). Mabou Group 'cementstone' carbonates and redbeds of fluvio-lacustrine origin attest to the persistence of semi-arid conditions following the retreat of the Windsor Sea.

### 3.2.2. The mid-Carboniferous event

Between 320 and 319 Ma, global sea level fell by as much as 130 m, probably in response to a major phase of Gondwanan ice accumulation (Saunders and Ramsbottom, 1986; Crowley and Baum, 1991; numerical ages of Menning *et al.*, 2000). This eustatic event exposed shelf areas around the globe, caused a wave of marine extinctions, and contributed to the generation of a widespread unconformity between the Mississippian (Lower Carboniferous) and Pennsylvanian (Upper Carboniferous) systems (Saunders and Ramsbottom, 1986; Gonzalez-Bonorino and Eyles, 1995). In Atlantic Canada, this mid-Namurian (Chokerian-Alportian) event broadly coincides with the oblique collision between Laurasia and Gondwana during the Alleghanian Orogeny and the accompanying transition from an extensional to a strongly transpressional-transtensional tectonic regime (Arthaud and Matte, 1977; Gibling, 1995). At this time, Atlantic Canada marked a change in curvature in the dextral transcurrent zone which extended from southern Europe to the Alleghanian fold-and-thrust belt in eastern North America. Prominent tectonic periods in this complex and prolonged deformational episode are generally

referred to as the Variscan Orogeny in Europe and the Alleghanian Orogeny in North America.

In the Cumberland Basin (which contains the Joggins Formation), reactivation of the Meguma/Avalon terrane boundary inverted the Cobequid and Caledonia massifs (Waldron *et al.*, 1989), initiated local deformation (Webb, 1969; Plint and van de Poll, 1984; Browne and Plint, 1994), and caused overthrusting and alluvial-fan deposition, especially at restraining bends along the Cobequid Fault (Nance, 1987; Plint and Browne, 1994).

The mid-Carboniferous boundary also coincides with major changes in paleoclimate and depositional environments across the Maritimes Basin. A dramatic floral changeover reflects the transition from relatively arid conditions in the Mississippian to relatively humid, seasonal conditions in the Pennsylvanian (Calder, 1998) - a pattern also noted in the Appalachian Basin several hundred kilometers to the south (Cecil *et al.*, 1985). North of the Cobequid Fault, the basal part of the Pennsylvanian Cumberland Group (see below) marks a remarkably widespread phase of fluvial sedimentation ushered in by increased rainfall and rejuvenation of the surrounding uplands (Plint and Browne, 1994).

### 3.2.3. Pennsylvanian through Permian

The early Pennsylvanian was a period of basinal subsidence unparalleled in the Maritimes (Calder, 1998). Most profoundly affected was the western Cumberland Basin, wherein salt withdrawal contributed to the accumulation of 4,500+ m of Cumberland Group strata (including the Joggins Formation) in as little as 5.5 million years (numerical dates of Menning *et al.*, 2000; Waldron and Rygel, Chapter 9). During the late

Pennsylvanian, subsidence rates diminished as rifting and then tectonic activity gave way to thermal sag, resulting in a "cratonic" style of basinal architecture across the amalgamated continental terranes (Pascucci *et al.*, 2000; Gibling *et al.*, 2004). In the Sydney Basin and Gulf of St. Lawrence this phase of thermal subsidence is represented by a widespread blanket of coal-bearing strata that is readily identified as a prominent reflector package in seismic reflection data. The ubiquitous passage through the 'coal window' (when conditions were suitable for peat accumulation and preservation), with a subsequent shift to red bed deposition, occurs diachronously between individual depocenters, ranging from the Langsettian in the Cumberland Basin to Autunian/early Stephanian in the Sydney Basin.

Across the Maritimes Basin, deposition of the redbed-dominated Pictou Group (later Pennsylvanian to Permian) marks a regional lowering of water tables and the end of significant peat accumulation. This increase in aridity, a phenomenon experienced across virtually all of Euramerica (Calder and Gibling, 1994), probably reflects both the development of rain-shadows associated with the assembly of Pangea (Besly, 1988) and the supercontinent's northward drift from an equatorial rainy belt into a tropical seasonal belt (Schutter and Heckel, 1985; Scotese, 2001). Although significant Permian sediment accumulations are preserved only in offshore areas, Prince Edward Island and the Magdalen Islands, the bituminous rank of Westphalian and Cantabrian coals (Hacquebard and Donaldson, 1970; Hacquebard and Cameron, 1989) and fission track studies (Hendriks *et al.*, 1993; Ryan and Zentilli, 1993) both suggest that much of the Maritimes Basin was formerly buried under a thick sedimentary cover. Subsidence in the Maritimes Basin probably terminated by the late Permian as thermal sag gave way to basin inversion

and unroofing associated with the breakup of Pangea, and renewed sea-floor spreading began to create the modern Atlantic Ocean (Wade *et al.*, 1996).

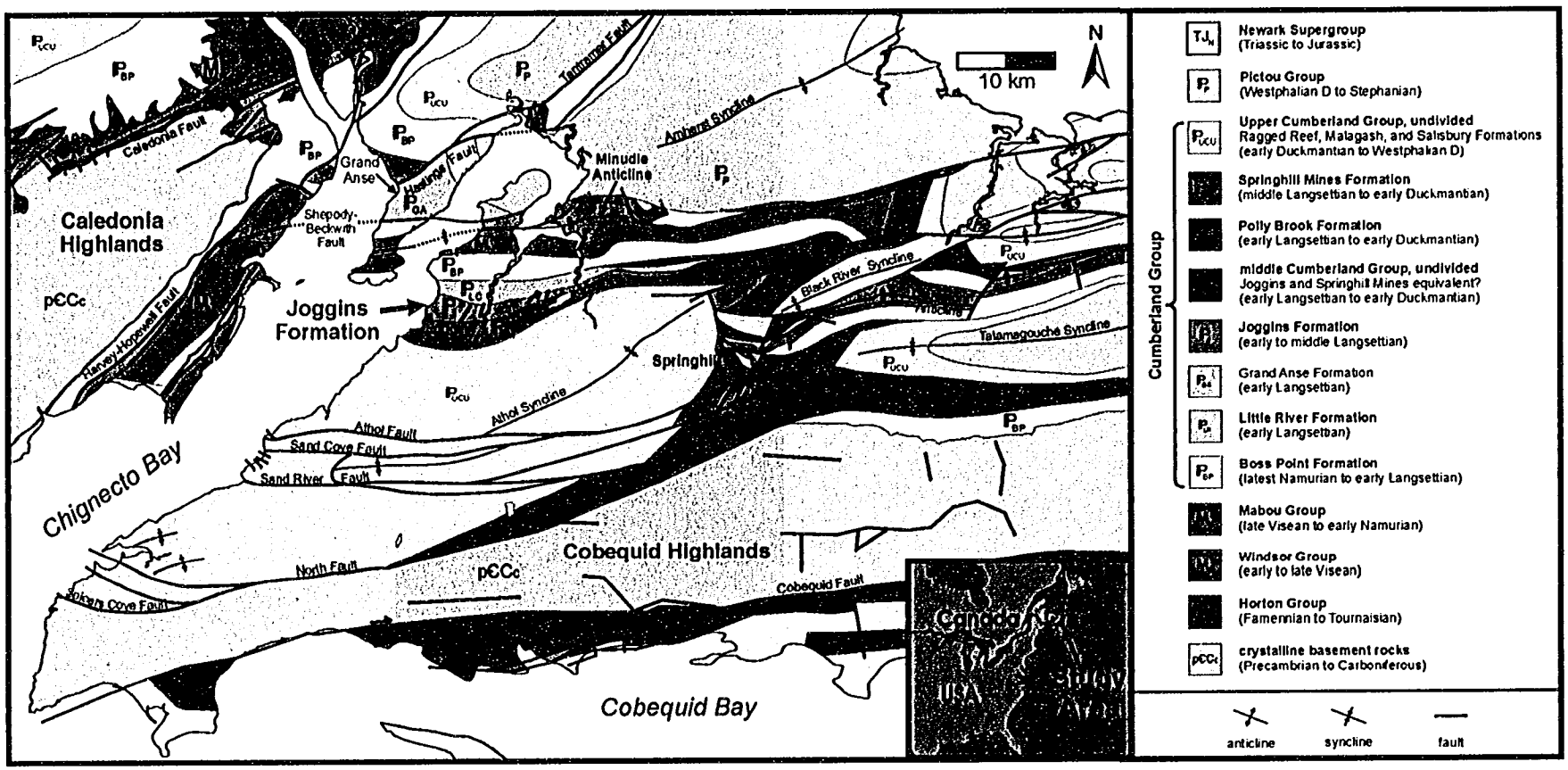
## 3.3. Geology of the Cumberland Basin

### 3.3.1. Tectonic setting

The fault-bounded Cumberland Basin is a 3,600 $km^2$ depocenter which covers much of northwestern Nova Scotia and parts of southern New Brunswick (Figs. 9 and 12; Ryan *et al.*, 1987). Situated between the Caledonia and Cobequid Highlands massifs, the margins of this fault-bounded depocenter are defined by the Harvey-Hopewell Fault to the west, the North Fault to the south, and the Caledonia-Dorchester Faults to the north (Browne and Plint, 1994). The northeastern margin below the Gulf of St. Lawrence is poorly constrained, but may in part be defined by a basement horst along the Hastings Fault (Martel, 1987). Although the exact timing of motion along these faults is poorly understood, the 8 km of Carboniferous (Viséan to Duckmantian) basin fill resting above the Avalonian basement attests to significant fault-induced subsidence during this time. The bounding Harvey-Hopewell Fault Zone and the Hastings Faults have a complex history which includes both dip-slip and strike-slip motion (Webb, 1963; Browne and Plint, 1994). Despite the complexities of reconstructing an individual fault's offset history, 200 km of dextral motion along the terrane-bounding Cobequid fault in the Pennsylvanian (Nance, 1987) caused some degree of dextral transpression on most faults in the region.

The Joggins section crops out along the northern limb of the Athol Syncline – the dominant structural feature of the Cumberland Basin (Fig. 12). This 25-km-wide by 75-km-long syncline formed between the salt-cored Minudie Anticline to the north, the

Figure 12: Geologic map of the western Cumberland Basin (Ryan *et al.*, 1990; Ryan *et al.*, 1990; Keppie, 2000; New Brunswick Department of Natural Resources and Energy, 2000; St. Peter, 2001).


Caledonia Highlands
Joggins Formation
Chignecto Bay
Cobequid Highlands
Cobequid Bay
Caledonia Fault
Harvey-Hopewell Fault
Shepody-Bedwrth Fault
Grand Anse
Minudie Anticline
Amherst Syncline
Black River Syncline
Tatamagouche Syncline
Athol Syncline
Athol Fault
Sand Cove Fault
Sand River Fault
North Fault
Cobequid Fault
Terminal Fault
10 km
N
Newark Supergroup (Triassic to Jurassic)
Pictou Group (Westphalian D to Stephanian)
Upper Cumberland Group, undivided Ragged Reef, Malagash, and Salisbury Formations (early Duckmantian to Westphalian D)
Springhill Mines Formation (middle Langsettian to early Duckmantian)
Polly Brook Formation (early Langsettian to early Duckmantian)
middle Cumberland Group, undivided Joggins and Springhill Mines equivalent? (early Langsettian to early Duckmantian)
Joggins Formation (early to middle Langsettian)
Grand Anse Formation (early Langsettian)
Little River Formation (early Langsettian)
Boss Point Formation (latest Namurian to early Langsettian)
Cumberland Group
Mabou Group (late Visean to early Namurian)
Windsor Group (early to late Visean)
Horton Group (Famennian to Tournaisian)
crystalline basement rocks (Precambrian to Carboniferous)
anticline
syncline
fault

Black River diapir to the east, and the Athol-Sand Cove Fault Zone to the south (Calder, 1994). Thinning of stratal units against diapiric structures indicates that halokinesis was syndepositional and contributed to the creation of accommodation in the basin, particularly in the Langsettian coal-bearing units (Waldron and Rygel, Chapter 9).

### 3.3.2. Stratigraphy

Along the southern shore of Chignecto Bay over 4,300 m of Carboniferous strata are continuously exposed in a gently dipping coastal section on the northern limb of the Athol Syncline (Figs. 12 and 13). The basal 1,100 m of the section consists of the Viséan through earliest Namurian-aged sediments of the Windsor and Mabou Groups. These strata comprise the evaporite-dominated cycles of the Windsor Group, the fluvio-lacustrine Shepody Formation, and the coarse-grained fluvial deposits of the Claremont Formation. Following initial rejuvenation of the adjacent highlands during the mid-Carboniferous event, earliest Pennsylvanian sediments comprise the alternating lacustrine-braidplain cycles of the Boss Point Formation (?latest Namurian to earliest Langsettian). The transition into the redbeds of the Little River Formation (Chapter 8) marks a basin-wide shift from sand-rich to sand-poor sedimentation which can be traced across the Maritimes (Rehill *et al.*, 1995). The overlying coal-bearing strata of the Joggins Formation (early Langsettian) pass laterally into the thick conglomerates of the Polly Brook Formation (Langsettian-Duckmantian) towards the southern basin margin along the Cobequid Highlands (Ryan *et al.*, 1991).

Continuing upsection along Chignecto Bay, the abundance of redbeds and absence of significant coals/limestones indicates that deposition of the Springhill Mines Formation (late Langsettian to early Duckmantian) was accompanied by regionally lowered water tables,

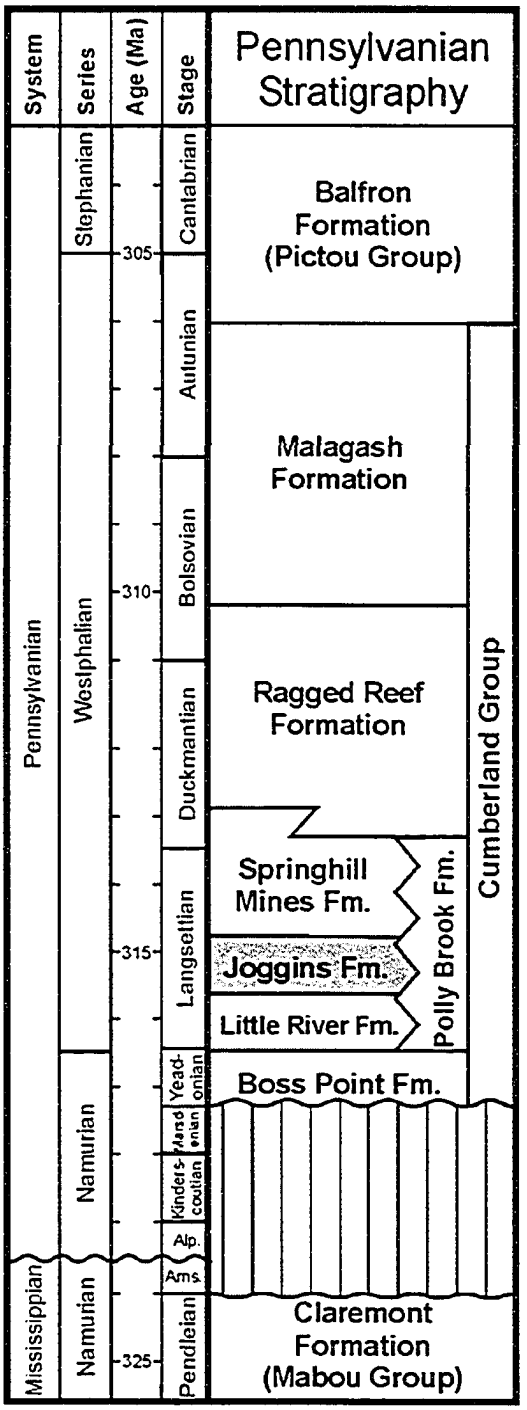



Figure 13: Details of Pennsylvanian stratigraphy in the Cumberland Basin (from Davies, *et al.*, submitted).

perhaps due to increased aridity and tectonic activity (Rust *et al.*, 1984). Inland, the presence of thick coals in the Springhill Mines Formation attests to the former presence of groundwater-fed mires near the toes of Polly Brook alluvial fans (Calder, 1994). As redbed deposition continued into the mid- to late Duckmantian, the fine-grained, anastomosed fluvial systems of the Springhill Mines Formation were replaced by the conglomeratic, braided fluvial systems of the Ragged Reef Formation (Rust *et al.*, 1984; Ryan *et al.*, 1991). Overlying outcrops of the Malagash Formation (Bolsovian to Autunian) in the center of the Athol Syncline are erosional remnants of the 1.5 to 4-km-thick, late Pennsylvanian-Permian sedimentary rocks that once covered the now exposed Pennsylvanian sections (Ryan and Zentilli, 1993).

## 3.4. The Joggins Formation

### 3.4.1. History of stratigraphic nomenclature

Despite the spectacular exposure along the shores of Chignecto Bay (Fig. 14), determining the exact stratigraphic relationships between strata of the Cumberland Group has proven to be exceptionally difficult. The problem arises because of difficulty in dating the ubiquitous redbeds, local variations in thickness and sedimentation style, and the absence of marine bands or other laterally continuous marker beds. Furthermore, the coastal exposure provides only a two-dimensional view of the basinal strata, and a full regional understanding is complicated by minimal exposure inland, the presence of Chignecto Bay, and complex facies relationships southward towards the Cobequid Highlands (Fig. 12), which were an active, fault-bounded upland during Joggins deposition. In proposing a stratigraphic framework, every researcher since Logan has

Figure 14: View of the lower 600 m of the Joggins Formation.

Figure 15: Comparative stratigraphic chart to show the evolution of nomenclature for the Joggins Formation and associated strata in the Cumberland Basin. Vertical axis is approximately scaled to the thickness of the units. Chart refers only to major stratigraphic revisions that directly affected the coastal section. Asterisks denote units that are partially shown on this diagram (from Davies *et al.*, submitted).

Logan (1845)
Dawson (1868)
Bell (1912)
Bell (1914)
Bell (1943)
Shaw (1951a, b)
Copeland (1959)
Bell (1964)
Kelley (1967)
Ryan et al. (1991)
this paper
Division 3
Division 4
Division 5
Middle Coal Formation*
Millstone-grit Series*
Division 3
Division 4
Division 5
Middle Grindstone Division
Upper division (grey)
Lower division (reddish)
Middle Coal Measures
Upper red measures
Millstone-grit Series*
Joggins Formation*
Cumberland Group*
Joggins mbr.*
Cumberland Group*
#10*
#10a
Cumberland Group*
Facies B* (lower fine, coal-bearing)
Facies A (lower coarse)
Coarse fluvial Facies*
Cumberlandian strata*
Cumberland Group*
Springhill Mines Fm.
Joggins Fm.
Cumberland Group
Springhill Mines Fm.
Joggins Fm.
Little River Fm.
top of Ist. in coal Group #1
sst. 5' 6" below coal 45
sst. 168' 2" above base of Div. 3
top of Ist. in Coal Group #1
base of Coal #45

been faced with this difficult background.

Ryan *et al.* (1991), Ryan and Boehner (1994) and Calder (1998) summarized the history of stratigraphic nomenclature for the Cumberland Basin, and Rygel and Shipley (Chapter 2) set out more fully the history of stratigraphic work as it pertains to the coastal section; aspects pertinent to the Joggins Formation are outlined in Figure 15. Logan (1845) divided the Chignecto Bay strata into eight divisions (numbered from the top downwards), placing the predominantly grey, coal-bearing strata of the Joggins cliffs in Division 4. He measured this interval as 2539' 1" (774 m) of grey and red mudstone, sandstone, limestone, coal, carbonaceous shale and minor conglomerate. Logan identified 45 Coal Groups (identified with numbers) in Division 4, and recorded an aggregate thickness of 37' 9.5" (11.5 m) of coal and 23'3" (7.1 m) of limestone in the division. Red, red-green and chocolate shale and sandstone constituted 264 m (34%) of his section, the remainder being grey. In contrast, he noted the absence of coal in the underlying Division 5, which he described as red mudstone and grey and red sandstone, with a few green shale and calcareous nodular horizons. This division, only partially exposed at Lower Cove, was measured at 2082' (635 m) down to the top of South Reef, a prominent and thick sandstone body within Division 6. Logan's Coal Group 45 lies slightly above the base of Division 4 at Lower Cove, and was described as comprising 10' 2" (3.1 m) of coal, carbonaceous shale and interbedded shale and sandstone, with a basal thin coal 3" (7.5 cm) thick. These strata are underlain by 5'6" (1.7 m) of underclay and red shale and sandstone, the base of which marks the base of Division 4. The top of Coal Group 1 marks the top of Division 4 near Joggins village, where a 4' (1.2 m) limestone rests upon a 1' (0.3 m) coal. The overlying Division 3 has a lower proportion of coal (22 seams with

only 5'5" or 1.7 m aggregate thickness), no limestone and a higher proportion of redbeds. Division 2 is mainly red sandstone and mudstone.

Subsequent workers used aspects of this classification. Dawson (1854; 1855) divided Division 4 into 27 Coal Divisions (designated with Roman numerals), and provided more detail for some of Logan's Coal Groups. Dawson (1868) adopted aspects of British terminology in identifying a Millstone Grit Series and a Middle Coal Formation, a system that was modified by Bell (1912). Bell (1914) subsequently proposed the name "Joggins Formation" for Divisions 5, 4, 3 and part of 2, an interval 6886' (2099 m) thick. The overlying strata (most of Division 2 and Division 1) were named the "Shulie Formation." Bell discussed the rationale for combining the Division 5 redbeds and the Division 4 grey, coal-bearing beds into one formation, implying that a regional disconformity underlies Division 5 within the Cumberland Basin (although it is not apparent in the coastal section). He subsequently retracted the formation names (Bell, 1943) on the grounds that the distinctive Joggins coals thin out inland, making the distinction of formations problematic, and combined the Joggins and Shulie Formations as the "Joggins member" of an undivided Cumberland Group. Shaw (1951) mapped coarser- and finer-grained rock units within the basin, and assigned the Joggins grey strata to his unit 10, noting that conglomeratic wedges near the Cobequid Highlands thin northward and complicate the basinal stratigraphy. Copeland (1959) followed this approach, and confirmed that coals thin inland within the Joggins-Chignecto coalfield. Belt (1964) referred strata at this level across the region to the "Coarse Clastic Facies," but Kelley (1967) retained the Cumberland Group for the lower part of this interval.

Ryan *et al.* (1991) reinstated the Joggins Formation and presented a formal description with the Joggins cliffs as the type section. Ryan and Boehner (1994) mapped the formation inland, and included Divisions 5, 4 and the basal strata of Division 3 within the reconstituted Joggins Formation, for a total thickness of 1,433 m. In both papers, boundaries were shown on a visual column derived from Logan's section (their Fig. 2-13), but were not elaborated on in the text. In the coastal section, the Division 5/6 boundary was taken to mark the formation base, and the top was placed at the base of a thick sandstone body that precedes a more sand-dominated interval within the newly described Springhill Mines Formation. This upper boundary places the basal 168' 2" (51 m) of Division 3 within the Joggins Formation. Ryan and Boehner (1994) designated three members of the Joggins Formation: the Little River Bridge Member (Division 5), the Coal Mine Point Member and the Bells Brook Member (Division 4 and basal strata of Division 3). These members were not formally defined or shown on the accompanying maps.

Pending manuscript acceptance, the Joggins Formation as defined by Ryan *et al.* (1991) will be subdivided into the Little River Formation (Calder *et al.*, submitted; Chapter 8) and the Joggins Formation (Davies *et al.*, submitted), in order to restrict the Joggins Formation to the 915.5 m of limestone- and coal-bearing strata originally within Logan's Division 4. The base of the newly redefined Joggins Formation will be the base of the lowermost coal exposed in the section, within Coal Group 45 and 1.7 m above the base of Division 4 as originally defined by Logan (1845). This approach essentially retains Logan's Division 5 as a unit distinct from both the underlying Boss Point Formation and the overlying Joggins Formation, and draws upon Bell's (1914) debate

about the legitimacy of including these redbeds with the overlying coal-bearing beds. The formation top is redefined at the top of a prominent coal and limestone unit (Coal Group 1) south of Bells Brook, in contrast to the channel-sandstone base at a higher level designated by Ryan *et al.* (1991).

### 3.4.2. Recent studies

In addition to the sedimentological studies mentioned in Section 1.3 and the stratigraphic studies described above, the Joggins Formation has experienced a surge of scientific interest over the past 15 years (Table 2). The sedimentology and paleobotany of the section have received particular attention, although recent discoveries of marginal marine ostracods and tetrapod remains and trackways are awaiting publication.

### 3.4.3. The measured section

Until recently, the only formal stratigraphic log available has been the detailed written descriptions of Logan (1845) and Dawson (1854). Later workers have re-measured shorter segments, and Ryan and Boehner (1994) recast Logan's log as a simplified graphic log.

The centimeter-scale measured section of the Joggins Formation is presented in Appendix 4; this section is tied to the labeled air-photograph presented in Figure 16 and is shown in simplified form in Figure 17. Prominent outcrops in the intertidal zone (known in the local vernacular as "reefs") show up well on the air-photograph and provide useful marker beds. The thicknesses of fine-grained beds, limestones, coals, and planar-based sandstones shown in the measured section are generally constant across the outcrop belt, but the numerous lensoid channel bodies exposed only on the foreshore are not represented in the detailed measured section itself. Red and drab intervals are

| Research Area | Author(s) |
|---|---|
| Topical accounts | Scott (2001); Falcon-Lang and Calder (Falcon-Lang and Calder, 2004); Falcon-Lang *et al.* (2004) |
| Sedimentology and stratigraphy | Smith (1991); Davies and Gibling (2003); Calder *et al.* (submitted); Davies *et al.* (submitted) |
| Basin analysis and salt tectonics | Waldron and Rygel (2005) |
| Fossil forests and their entombment | Rygel *et al.* (2004); Calder *et al.* (in press) |
| Flora | Falcon-Lang (1999; 2003; 2003; 2003; 2004); Falcon-Lang and Scott (2000); Falcon-Lang *et al.* (2004); |
| Fauna | Archer *et al.* (1995) ; Reisz (1997); Holmes *et al.* (1998); Hebert and Calder (2004); Falcon-Lang *et al.* (2004); Chamberlain (2004); Hunt *et al.* (2004); Tibert and Dewey (2005) |
| Age assessment | Dolby (1991; 2005); Utting (1995); Utting and Wagner (2005) |
| Coal and source rocks | Hower (2000); Calder *et al.* (in press) |
| History of geologic research at Joggins | Rygel and Shipley (in press); Falcon-Lang and Calder (submitted) |

Table 2: Significant contributions to understanding of the Joggins Formation over the past 15 years.

Figure 16: Labeled air-photograph showing the coastal exposure of the Joggins Formation at its type section; labels designate cycles and the stratigraphic position of prominent outcrops in the intertidal zone. The image is a mosaic created from air-photographs A18580-125 (1:15,840) and 85314-3 (1:10,000), available from the Nova Scotia Department of Housing and Municipal Affairs, Land Information Services Division.

LEGEND
11
Cycle number and approximate extent
Ⓐ
access
CB 597
"reef" type & stratigraphic position:
CB = channel body
SS = sheet sandstone
SBS = sharp-based sandstone
LS = limestone
*stratigraphic up is to the top of the page
N
200 m
Bell's Brook Ⓐ
Spicehill Mines Fm.
Joggins Fm.
14
LS 872
CB 849
13
12
11
SS 717
SS 691
SS 673
10
Coal Mine Point (CB 648)
SS 630
SBS 569
CB 591
9
8
CB 480
CB 494
7
6
CB 382
CB 307
5
SS 175
SBS 45
4
cliff face
3
SS 92
SBS 69
2
CB 30
1
Joggins Fm.
Little River Fm
tidal flat
low tide level
Chignecto Bay
(Bay of Fundy)

Figure 17: Simplified Joggins section based on the detailed version presented in Appendix 4. OW = Open Water facies association, PDF = Poorly Drained Floodplain facies association, WDF = Well Drained Floodplain facies association.

Key
Cycle base & number
Lithology abundance
SS #
LS #
CB #
250
200
150
100
50
0
500
450
400
350
300
250
750
700
650
600
550
500
915.5
900
850
800
750

recorded to the left of the column; these color designations are highly generalized, and drab intervals in particular show wide variation from dark to light grey and green. Most channel sandstones are grey-brown regardless of their association, and their color is typically shown on the log as similar to the strata above and below.

### 3.4.4. Age

Historically, the age of the Joggins Formation has been given as Duckmantian (Bell, 1943; Hacquebard and Donaldson, 1964; Davies *et al.*, submitted). More recently, the Joggins Formation has been dated on the basis of comprehensive palynological sampling as Langsettian (Dolby, 1991; approximately 315 million years old using the numerical ages of Menning *et al.*, 2000), however the Namurian-Westphalian boundary is extremely difficult to resolve in the Maritimes Basin in the absence of fully marine index fossils (Calder, 1998). Recent investigation and taxonomic revision of the megaflora supports an early Langsettian age (R.H. Wagner, personal communication).

The age of the underlying redbeds of the Little River Formation (Calder *et al.*, Chapter 8) is still more vexing due to the paucity of floral and palynological records. However, its position between the Boss Point and Joggins Formation brackets it as early Langsettian (Utting *et al.*, 2005). The persistence of late Namurian floral elements emphasizes the proximity to the Namurian-Westphalian boundary, and the absence of certain diagnostic spore groups suggests that certain plants, including the densospore-producing lycopsids, may have been ecologically excluded, further blurring the stage boundary (Calder, 1998).

## 3.5. CURRENT SEDIMENTOLOGICAL FRAMEWORK

The sedimentological and sequence stratigraphic framework discussed in this section provides an overview of Davies and Gibling (2003) and Davies *et al.* (submitted). In these studies, the Joggins Formation was described in detail, remeasured for the first time since 1845, and the lithofacies/cyclicity contained therein was described. The result is a three-fold subdivision into open-water (OW), poorly drained floodplain (PDF), and well drained floodplain (WDF) facies associations (Table 3) which are in turn organized into fourteen cycles (Fig. 17). Each cycle typically records a flooding event (OW) followed by progradation of coastal wetland deposits (PDF) and oxidized floodplain deposits (WDF) - a typical succession is shown in Figure 18. As a preface to later chapters, each of these distinct ecosystems as described by Davies and Gibling (2003) and Davies *et al.* (submitted), is briefly described in the following sections.

### 3.5.1. Open water facies association (OW)

Although the open water facies association comprises only about 9.3% of the stratal thickness of the Joggins Formation, it defines the cyclicity in this interval. This facies association comprises carbonaceous limestone, laminated mudrock, and sharp-based sandstone (Table 3, Fig. 19). Occurrences of the OW vary in thickness from 4 to 22 m; this association is thickest in cycle 9 near the middle of the succession.

The lower boundaries of OW occurrences are defined by the basal contact of carbonaceous limestone with the underlying strata. These 0.3 to 1.0 m thick limestones are sharp-based and commonly overlie coals. The absence of erosional ravinement surfaces indicates that flooding events rapidly but passively overwhelmed floodplain mires during major flooding events. The abundance of bivalves (predominantly

| | Well Drained Facies Association (WDF) | Poorly Drained Facies Association (PDF) | Open Water Facies Association (OW) |
|---|---|---|---|
| **Common Lithologies** | Red mudrock, channel bodies, sheet sandstone, thin limestone and carbonaceous shale (both rare) | Green and grey mudrock, channel bodies, sheet sandstone, coal (<1 m thick), thin limestone, carbonaceous shale | laminated grey to black mudrock, carbonaceous limestone, sharp-based sandstone |
| **Other Features** | Rare standing lycopsids up to 1 m tall, poorly developed paleosols | Standing lycopsids commonly 5-6 m tall, poorly developed paleosols | Some evidence of marine influence (Archer *et al.*, 1995; Tibert and Dewey, 2005) |
| **Formation-scale abundance** | 284.6 m = 31.1% | 516.4 m = 56.4% | 85.5 m = 9.3% |
| **% of cycle thickness** | 0 to 90% (20% mean) | 8 to 100% (40% mean) | 0 to 30% (9% mean ) |
| **Thickness of individual occurrences** | 2.2 to 57.8 m (16.7 m mean) | 1.8 to 93.2 m (17.1 m mean) | 0.6 to 22.0 m (7.8 m mean) |
| **Amount of sandstone within each occurrence** | 4 to 43% (25% mean) | 0 to 97% (24% mean) | 1 to 32% (16% mean) |
| **Total channel bodies** | 37 | 45 | 0 |
| **Channel bodies/ 100 m of section** | 13.0 | 8.7 | 0 |

Table 3: Summary of facies associations in the Joggins Formation. Note that the formation-scale abundance row only adds up to 96.8%; the remaining 3.2% is covered.

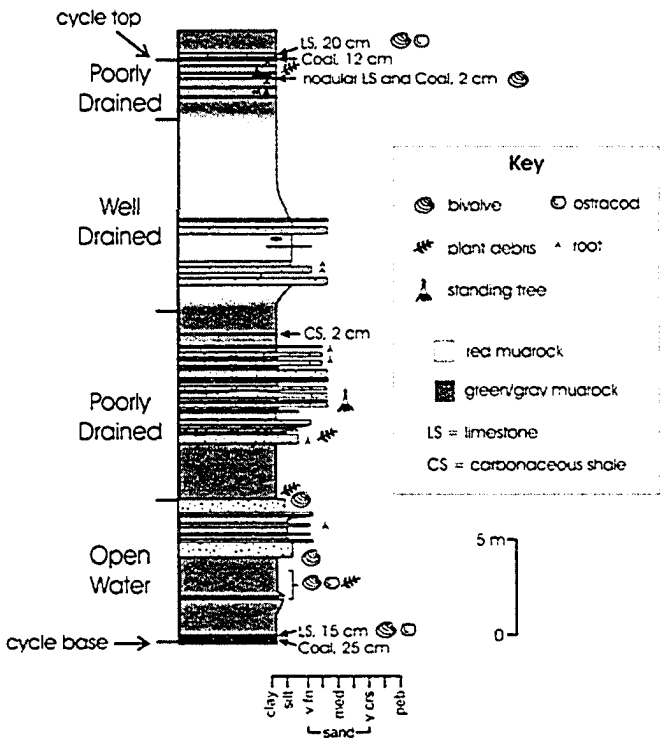
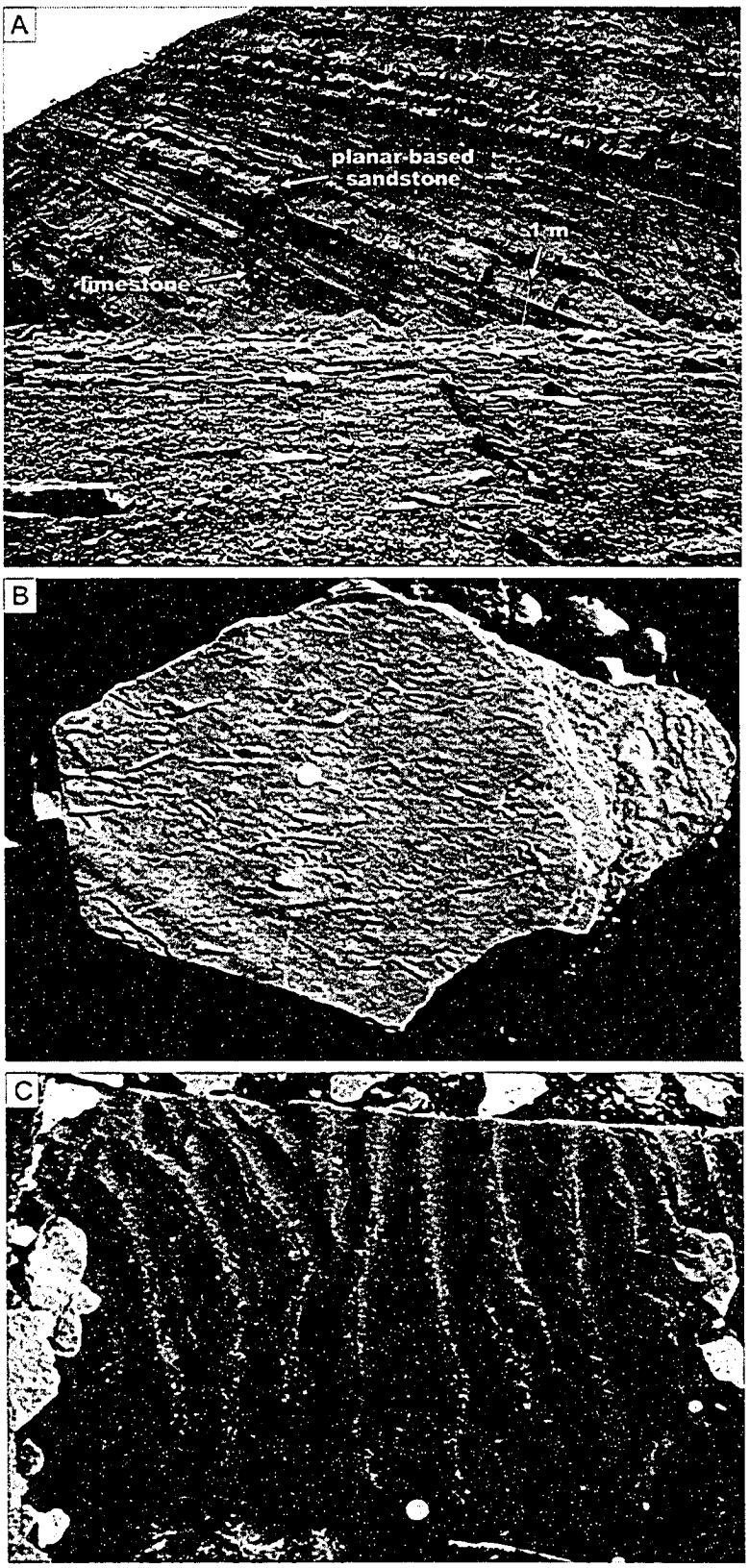



Figure 18: Facies succession and sedimentology of cycle 2, a "typical" Joggins cycle.

Figure 19: Views of the Open Water (OW) Facies Association. A) Open water strata at the base of cycle 4 of the Joggins Formation showing limestone overlain by laminated shale and planar-based sandstone. B) Tool marks on the base of a planar-based sandstone. C) Truncated wave ripple from the top of a planar-based sandstone. B and C from Davies and Gibling (2003), coin for scale (24 mm diameter).


A
planar-based
sandstone
1 m
limestone
B
C

*Curvirimula* and *Naiadites*), ostracods, spirorbids, gastropods, fish, insects, and arthropod remains in these limestones attests to the proliferation of aquatic life following drowning of the mires.

The return of clastic sediments is marked by a gradational to interbedded contact between limestones and overlying mudrocks. Mudrocks are typically beds of laminated, gray claystone to coarse siltstone organized into ~1-m-thick, coarsening-upward packages with siderite nodules scattered throughout. Transported plant debris is common, but the general absence of *in situ* roots and vegetation suggests that water depths were sufficient to inhibit plant growth. Siltstones also contain bivalve-rich laminae and rare agglutinated foraminifera have been recognized in cycle 9 (Archer *et al.*, 1995).

Near the top of open water intervals, laminated mudrocks are interbedded with distinctive sharp-based, fine-grained sandstones. These 0.3 to 1.0-m-thick beds are generally tabular in cross-section, but locally they may be organized into large-scale mounds (1-2 m high; 75-100 m wide) or cut by shallow channels (1.5-4.3 m thick; W/T 11-14). Internally, sandstones are dominated by unidirectional ripple cross-sets, primary current lineation, climbing ripple cross-lamination, and rare hummocky cross-stratification. Flute and groove casts are common at the base of beds and wave-rippled surfaces ubiquitously cap the sandstones. At several intervals in the section, sharp-based sandstones contain a variety of trace fossils including grazing and walking traces (Fig. 20: *Kouphichnium, Cochlichnus, Treptichnus*), paired vertical burrows (*Arenicolites*), and horseshoe crab resting traces (Archer *et al.*, 1995). Sharp-based sandstones are interpreted as distal delta lobes emplaced as sediment-laden floodwaters debouched into

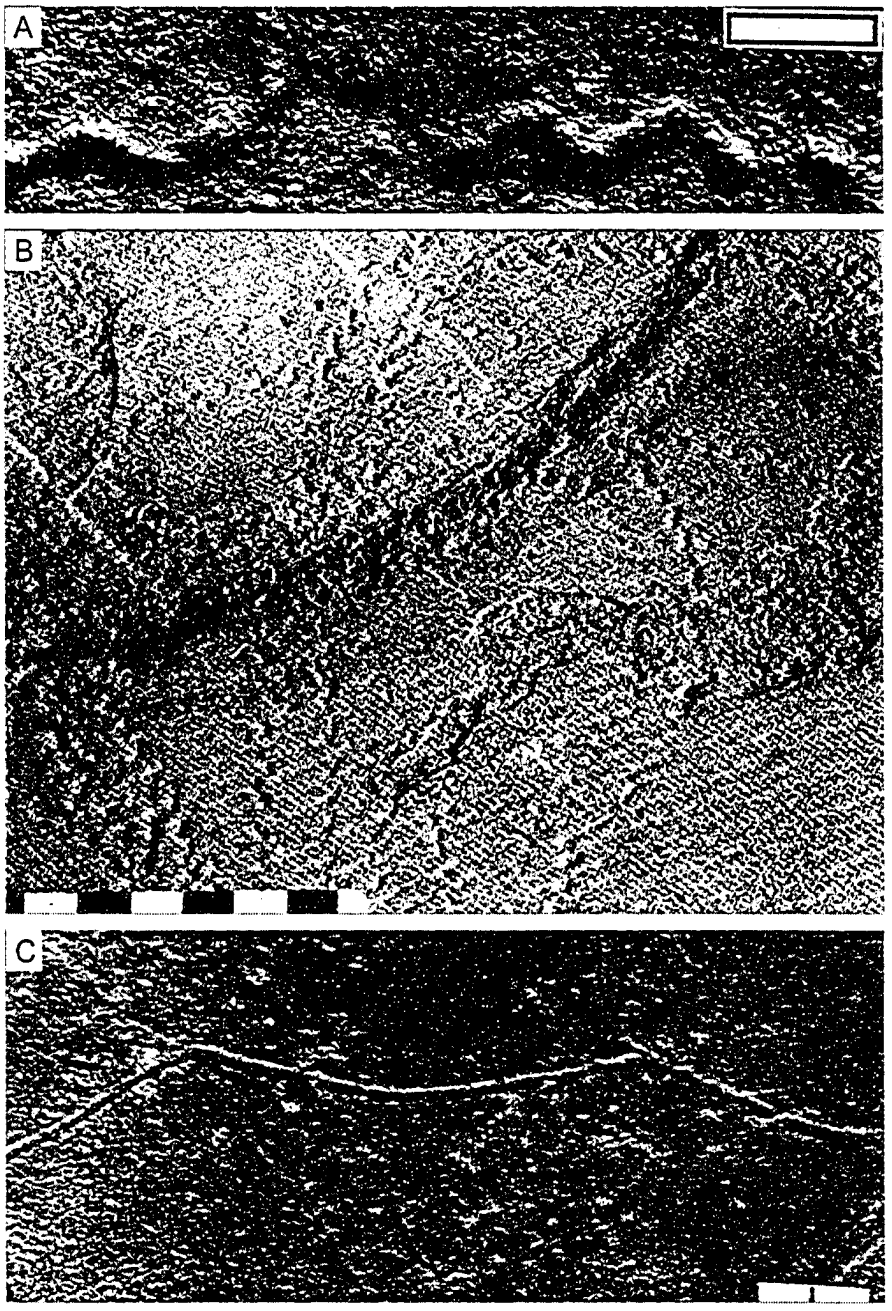



Figure 20: Invertebrate trace fossils from the open water facies above the Forty Brine Coal. A) *Cochlichnus*, B) *Kouphichnium*, and C) *Treptichnus* (scale gradations in cm; all from Archer *et al.*, 1995).

standing bodies of water. As flows waned, the newly emplaced sediment was subjected to wave reworking, plant growth, and eventually subaerial exposure.

There is a growing body of evidence suggesting that the open water facies was, at least sporadically, influenced by a marine connection. The debate first arose when Duff and Walton (1973) proposed that the presence of *Curvirimula* indicated a marine influence during limestone deposition. Archer *et al.* (1995) called upon brackish conditions to account for the presence of agglutinated foraminifera and the distinctive trace fossil assemblage described above the Forty Brine Seam. Fish bones within the limestones yield strontium isotope values consistent with brackish conditions (Calder, 1998). Most significantly, the recent identification of bairdiacean ostracods strongly suggests that these bodies of water had a near continuous marine connection (Tibert and Dewey, 2005).

### 3.5.2. Poorly drained floodplain facies association (PDF)

Perhaps the most well-known portion of the Joggins Formation, the poorly drained floodplain facies association (PDF), makes up 56.4% of the formation's thickness. This facies association can be subdivided into sand-poor intervals, sand-rich intervals, and coals. Although relative abundances vary between these subdivisions, common lithologies include green-gray siltstone, channel and sheet sandstones, limestone, carbonaceous shale, and coal. Occurrences of the PDF vary in thickness from <1 to 93 m. The top of cycle 5 marks the formation-scale shift to thick coals and a predominance of the sand-rich PDF (Fig. 17).

#### 3.5.2.1. Sand-poor intervals

This subdivision is predominantly composed of green-gray siltstone interbedded with carbonaceous shale, nodular siderite layers, and thin (25-45 cm) sheets of fine-

grained sandstone. Isolated small channel bodies (1-6 m thick; W:T 2-15), thin limestones, and lenticular sandstone are also present. Standing lycopsid trunks are preserved as faint coalified outlines within siltstone intervals. The ubiquitous presence of carbonized roots and siderite rhizoconcretions, combined with the paucity of bedding in many intervals suggests that root penetration was pervasive. Invertebrate faunas are limited to organic-rich rocks; limestones contain almost exclusively ostracods, and carbonaceous shales contain sparse ostracods and bivalves.

The sand-poor intervals record floodplain deposition in areas far from major channels where the supply of sand-sized sediment was relatively low. Silt was deposited as muddy floodwaters overwhelmed the vegetated floodplain. Sheet sandstones and small channel bodies represent occasional crevasse splay deposits, while pods of lenticular sandstone formed as scours around standing vegetation that were later infilled (Rygel *et al.*, Chapter 4). Limestones and carbonaceous shales were deposited in localized floodplain lakes and represent the temporary absence of clastics. Generally, water on the poorly drained floodplain was not deep enough to inhibit plant growth significantly.

3.5.2.2. Sand-rich intervals

This subdivision comprises sand-rich heterolithic packages of strata between 1 and 8 m thick. Internally these packages comprise 30 to 80-cm-thick beds of sandstone interbedded with thin beds of green-gray siltstone. Channel bodies representing both major meandering rivers and smaller crevasse splay or anastomosed channels form part of the sand-rich intervals. Although both channel-body types have sandy fill, meandering channel bodies are dominated by lateral accretion deposits and trough cross beds whereas

the smaller, fixed-channels contain dominantly ripple cross-lamination. Transported plant debris (finely macerated to greater than 1-m-long) is abundant throughout all the facies described above. Standing lycopsid trunks filled with sandstone are a common feature of sand-rich intervals (Fig. 21A; Calder *et al.*, in press).

The sand-rich assemblage was deposited in poorly drained portions of the floodplain near major rivers with a large supply of sandy sediment. Thus, sandy heterolithic packages of sediment were deposited as frequent flood events overwhelmed the adjacent forested floodplain and blanketed it with large amounts of sandy sediment. In a few cases, sandstone sheets with entombed trees can be traced across the wave-cut platform into channel bodies, thus linking the entombment events to channel overflow (Calder *et al.*, in press). Around many of the standing trees large erosional scours filled with sand (Fig. 21B) attest to the initial vigor of these flood events (Rygel *et al.*, Chapter 4).

3.5.2.3. Coals

Although adequate to support commercial mining for over 100 years, the coals of the Joggins Formation are thin (≤1 m) and have high concentrations of ash (generally between 10 and 40%), sulfur (≤13.7%), zinc (≤1.52%), arsenic (≤6%), and lead (≤6%) (element percentages are maximum values from Hower *et al.*, 2000). At the Fundy Seam and Logan's Coal 28, several thin seams separated by clastic partings form coal-bearing zones as much as 2 m thick. Through the basal 400 m of the formation there is an upward increase in coal thickness that culminates with a series of five thick coals in cycles 5-7. Coals in the section are bituminous in rank and generally have high vitrinite (humic material) content and contain numerous partings along fusain (fossil charcoal)

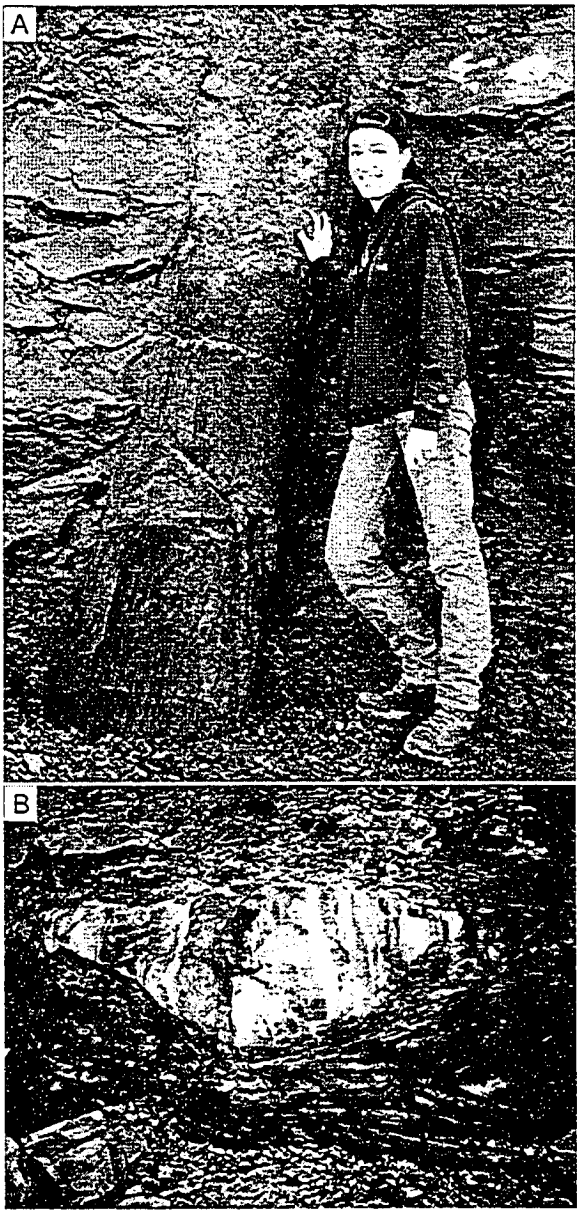



Figure 21: Features of the poorly drained floodplain facies association, A) standing lycopsid and B) centroclinal cross strata filling a scour developed around a standing lycopsid.

horizons. The floral assemblage is dominated by arborescent lycopsids (*Lepidodendron* and *Lepidophloios*) with minimal contribution from herbaceous plants in the understorey.

Overall, the Joggins coals represent periods of peat formation in rheotrophic (groundwater-fed) mires that formed in high pH environments where they could receive input from both meteoric and groundwater sources (Hower *et al.*, 2000). The abundance of charcoal and burnt standing trees (Falcon-Lang, 2000) indicates that these short-lived mires were able to withstand frequent forest fires only to be eventually overwhelmed by either rising base level or catastrophic burial during floods.

3.5.2.3. Paleoenvironmental Overview

The three subdivisions of the PDF record deposition within a coastal wetland or delta plain. This densely vegetated, waterlogged environment was criss-crossed by a network of meandering rivers and their anastomosed tributaries and distributaries (Chapter 6). Rivers frequently overflowed their banks, distributing large amounts of sandy sediment into the adjacent floodplain, sometimes entombing entire forest horizons in several meters of sediment. At this position in the basin, the majority of sandy sediment was deposited in wetlands; only a small amount of sand was transported to open water settings. Low-lying mires and shallow lakes abounded in parts of the floodplain far-removed from these rivers. Although drainage conditions were generally poor, the abundance of charcoal and burnt standing trees fossil charcoal in the PDF suggests some degree of wet-dry seasonality (Falcon-Lang, 1999). Environmental conditions on the poorly drained Joggins floodplain may have been analogous to those on the modern day Mississippi Delta (Tye and Coleman, 1989), upper Nile River (Rzoska, 1974), or Okavango fan (McCarthy *et al.*, 1992).

### 3.5.3. Well drained facies association (WDF)

3.5.3.1. Description

The well drained floodplain facies association (WDF) makes up 31.1% of the stratal thickness in the Joggins Formation. Well drained strata are present in eight of the fourteen cycles and particularly noteworthy in the abnormally thick fifth cycle, where ~90.5 m of well drained sediments make up 43% of the cycle thickness. The underlying 636-m-thick Lower Cove Formation is made entirely of this facies association. Common lithologies include red siltstone, heterolithic packages of interbedded red siltstone and sandstone, large multistorey channel bodies, and smaller u-shaped channel bodies (Chapter 6). WDF sediments are distinguished by their red coloration (Fig. 22A), scattered calcareous nodules, and the rarity of siderite nodules and coal, features indicating that the paleosols formed in an oxidizing environment. Some beds in the OW and within PDF channels are also red, but these beds lack paleosols and represent remobilized sediment derived from well drained alluvial plains and deposited as subaqueous beds. Minor flooding events, probably caused by a slight rise in the water table or by local ponding on the floodplain, are recorded within the well drained floodplain facies as thin (≤1 m thick), poorly drained zones with green-grey coloration, carbonized roots, and siderite nodules (Fig. 22B).

Redbeds, in the form of several meter-thick packages of red siltstone, are the dominant lithology in the WDF. These siltstone-dominated intervals may contain scattered thin sandstones and centimeter-scale, grey root-penetrated bands. Although

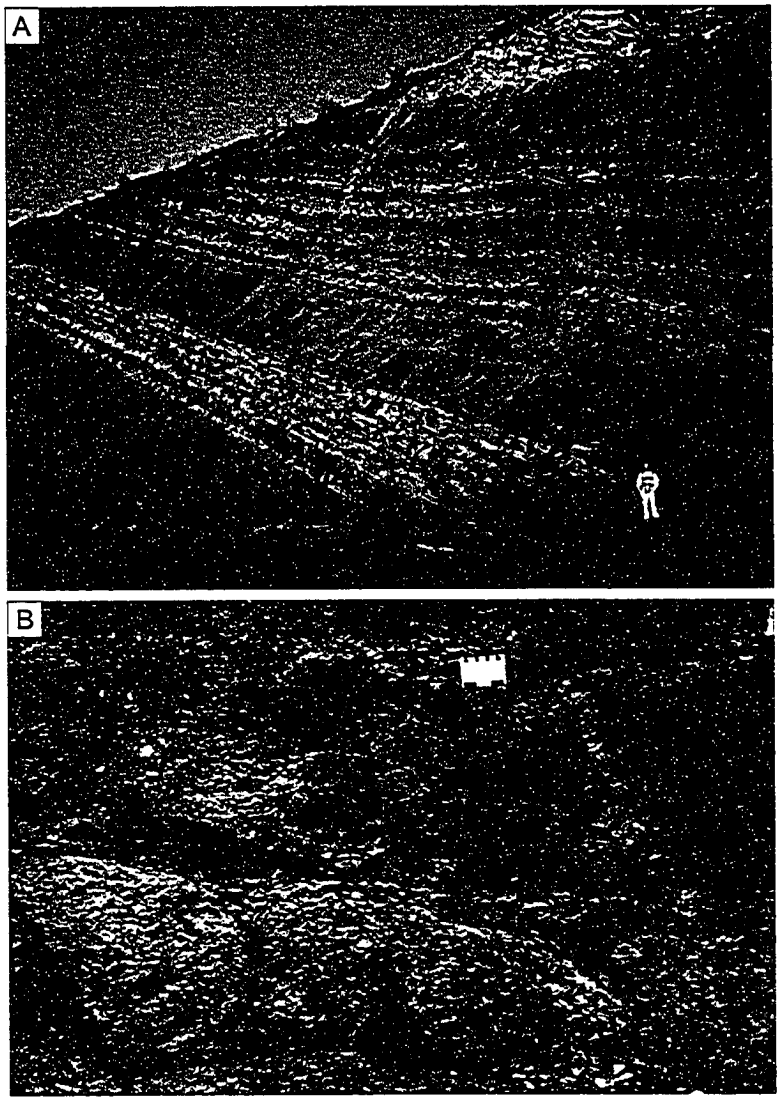



Figure 22: Features of the well drained floodplain, A) red mudrock with sheet sandstones and B) thin gleyed horizons recording localized wet conditions.

plant material is rare, standing lycopsid trunks are present as short (<50 cm tall) sandstone-filled casts, many of which are rooted in the thin, poorly drained intervals. Scattered calcareous nodules are found in association with poorly-developed paleosols within the redbeds, but in no place do they attain sufficient density to be considered petrocalcic horizons.

Heterolithic packages of red siltstone interbedded with thin sandstone sheets are also common in the well drained floodplain facies association. These intervals are dominantly sandstone (between 80 and 90%) and reach thicknesses of as much as 12 m. Because they are commonly laterally equivalent to channel bodies and thin dramatically away from them, many heterolithic packages probably formed as splay and levee deposits. Sandstones within heterolithic packages, particularly those near the middle of the fourth cycle, commonly bear tetrapod footprints and carbonized roots.

Large multistorey channel bodies of the WDF range between 5 and 9 meters thick; individual channel elements within these bodies are generally 2 to 4-m-thick and contain elements ascribed to bank-attached bars composed of trough cross-bedding, ripple cross-lamination, and planar laminae (Chapter 6). Scattered lenses of mudstone in the upper portions of some channel bodies represent abandonment fills. Within channel bodies, fragments of dryland flora (usually from the early gymnosperm *Cordaites*) are commonly preserved. These amalgamated channel bodies are interpreted as the deposits of 2 to 4-m-deep, sinuous channels which were either confined within small valleys (<9-m-deep) or were deposited at a time when accommodation (space available for sediment accumulation) was relatively low and fluvial deposits became amalgamated.

Smaller fixed-channel deposits (Chapter 6) are easily distinguished by their low W/T ratios, a trait which gives them their distinctive "u-shape". These channel bodies also have sandy fill organized into trough cross bedding, planar- and ripple cross-lamination. Although some of these channel bodies formed in association with crevasse splay deposits, many larger examples cannot be traced to any appreciable sandy overbank deposits. At several locations in the section, multiple channel bodies cut down from exactly the same stratigraphic level. Given the lack of thick, laterally equivalent crevasse splay deposits and the presence of multiple channels, many of the larger, stationary channels are interpreted as the deposits of anastomosed rivers the multiple channels of which were 1- to 6-m-deep. Several examples contain abundant plant and animal remains and probably served as important waterholes to the local flora and fauna on this otherwise dry floodplain (Falcon-Lang *et al.*, 2004).

3.5.3.2. Paleoenvironmental Overview

The WDF records deposition on an oxidizing floodplain drained by a network of meandering and anastomosing rivers which were largely sourced in uplands to the north. Although oxidizing conditions did not favor the preservation of organic material, abundant fossils within channel bodies attest to the abundance of life on the floodplain. High subsidence rates and abundant sediment precluded the development of mature paleosols, but the presence of scattered calcareous nodules and abundant red floodplain muds suggests some degree of wet-dry seasonality. However, the alternation of the red and green intervals within the predominantly red beds could have resulted from subtle changes in the subsidence rate, relative to the rate of sediment supply producing sustained changes in water table levels.

Insight into the Joggins floodplain was provided by Smith (1991), who studied Joggins paleosols and interpreted them as paleo-Alfisols formed under warm, dry, oxidizing conditions. Charcoal-based studies suggest that well drained areas were subject to seasonal conditions and frequent wildfires, which could have considerably increased the sediment supply to downstream locations (Falcon-Lang, 1999). Silicified cordaite wood lacks growth rings, suggesting that these plants were not subjected to water stress and may have grown in riparian settings where water was perennially available (Falcon-Lang, 1999; Falcon-Lang and Scott, 2000).

## 3.6. Formation-Scale Trends

### 3.6.1. Nature and proportion of overbank deposits

Overbank deposits in well drained and poorly drained floodplain successions contain nearly identical proportions of sandstone (25% and 24%, respectively) and have similar numbers of channel bodies per unit thickness (13.0 and 8.7 bodies per 100 m, respectively). Despite the marked decrease in the amount of sandstone cropping out in the tidal flat above 650 m in the measured section (Fig. 16), the measured section reveals that the amount of sandstone in floodplain sediments stays relatively constant above the 230 m level (Fig. 17). Comparison of the relative surface area of channel bodies and overbank deposits in the tidal flat shows that the change above the 650 m level is a result of a marked decrease in the abundance of channel sandstones from 4.3% in the first ten cycles, to 0.7% in the upper four cycles. Air-photo analysis of outcrop surface areas also revealed that channel bodies make up 3.5% of the Joggins Formation, a significantly lesser value than the 9.7% they represent in the line of the measured section (Fig. 17 and Appendix 4).

### 3.6.2. Cyclic patterns

The 14 cycles recognized in the 915.5 m of the Joggins Formation range in thickness from 16 to 212 m, averaging 65 m (Fig. 23). Facies distribution was used to construct a relative base-level curve for the formation (Fig. 24; Davies *et al.*, submitted). Unfortunately, the lack of firm biostratigraphic boundaries and absolute dates for the section preclude detailed regional correlation and the determination of cycle durations and precise accumulation rates.

Relatively predictable facies patterns are evident in Cycles 2 to 4 and in the basal part of Cycle 5. These intervals show a systematic upward succession from open water facies, which mark major transgressions, to poorly drained and well drained facies (regression). At some levels, thin occurrences of poorly drained facies below open-water intervals herald the base of the next cycle, denoting the onset of base-level rise. Limestones and platy siltstones are prominent, coals are thin and mainly underlie limestones, and the prominent planar-based sandstones that cap open-water deposits contain abundant trace fossils. Cycle 5 constitutes the most prolonged period of redbed accumulation, with alternate periods of poorly and well drained conditions and some thin coals in the upper 80 m.

The most marked and sustained lithological change within the formation is the relatively abrupt change from well drained to poorly drained floodplain deposits at the base of Cycle 6 (Fig. 17), with a suite of prominent coals; future mapping inland may provide justification for identification of a member boundary at this level. Cycles 6 to 8 are of moderate thickness, and usher in a period when the study area was dominated by coastal wetlands (poorly drained floodplain), with only thin intervals of open water

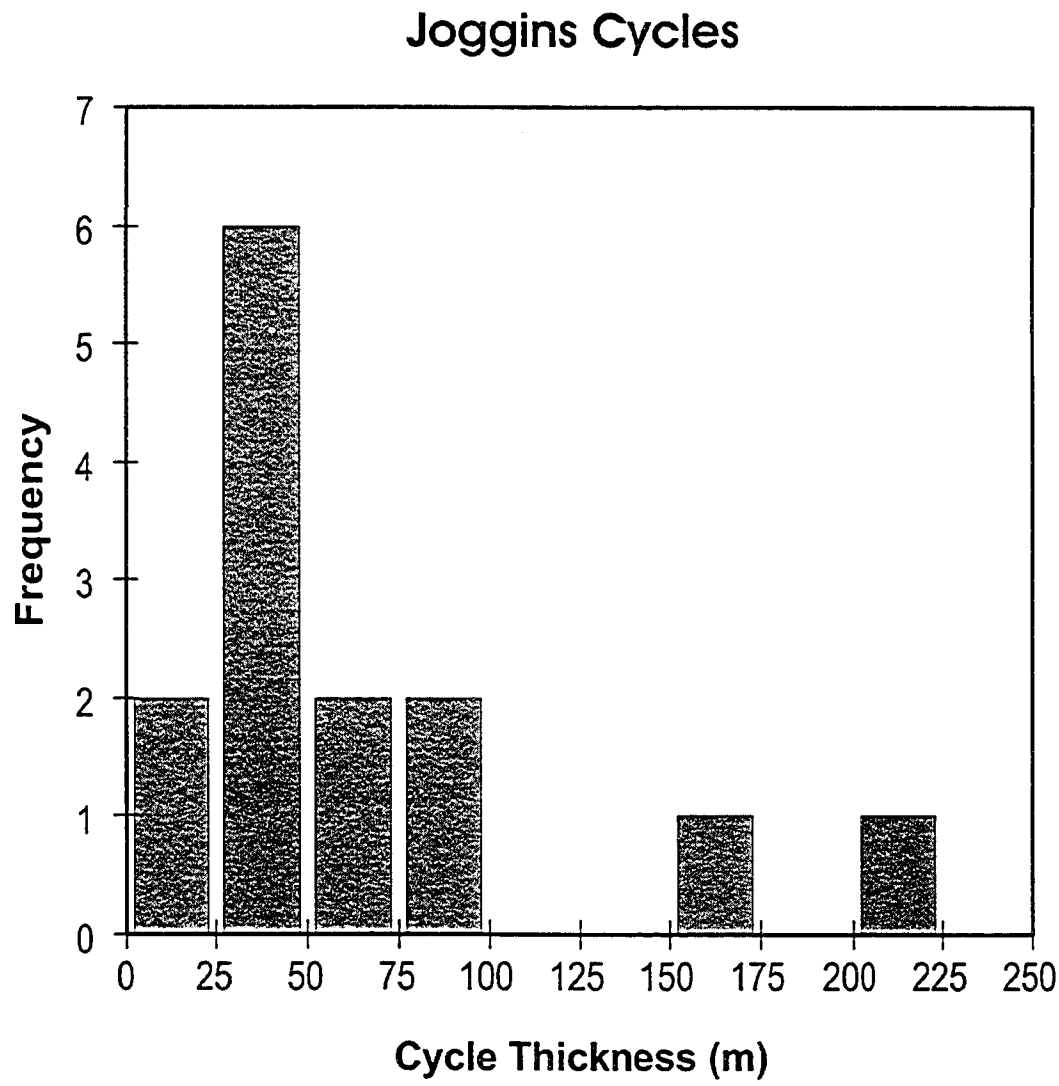
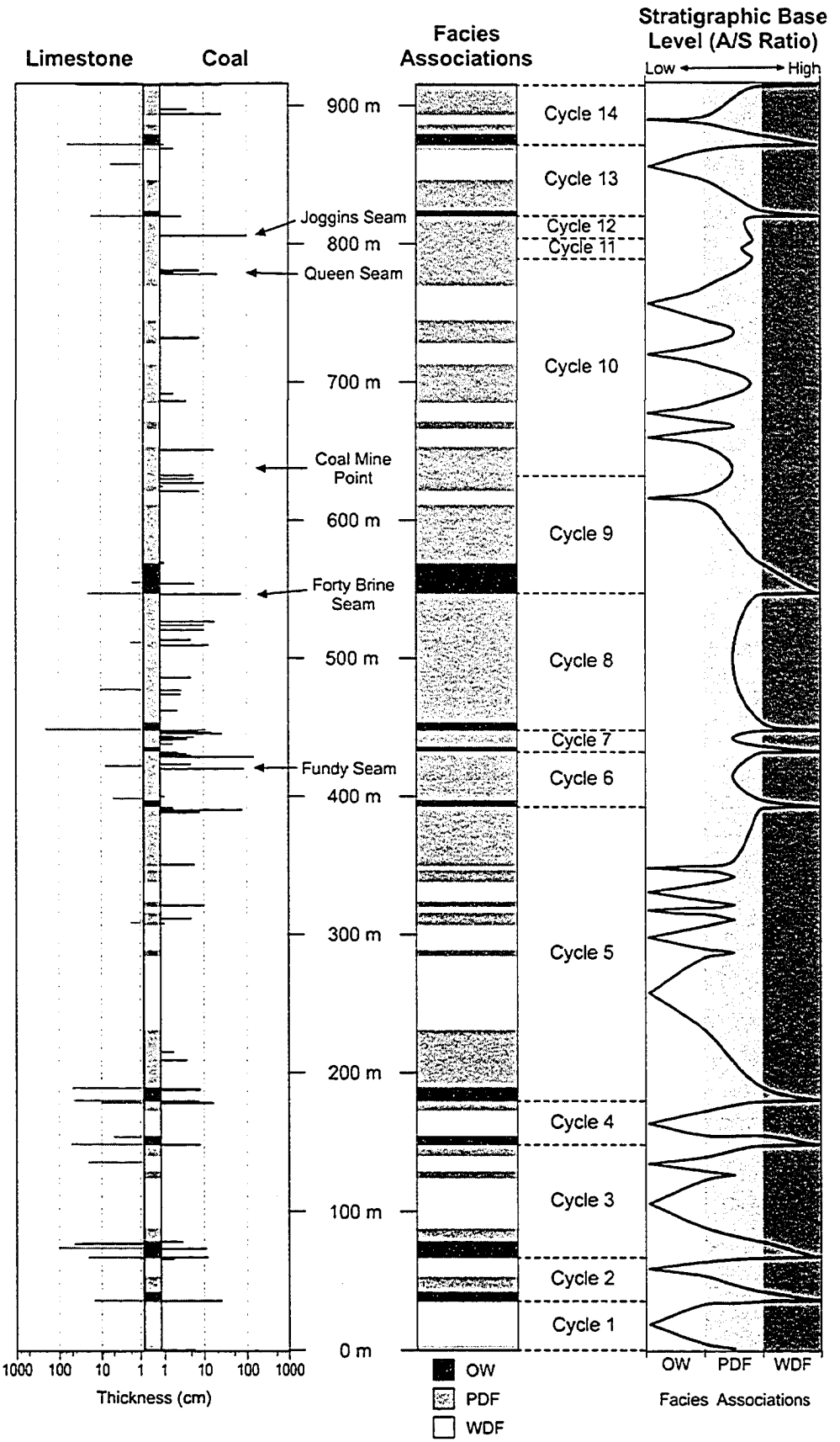



Figure 23: Histogram showing cycle thicknesses in the Joggins Formation

Figure 24: Limestone and coal thicknesses, facies distributions, and curve tracking the accommodation/sediment supply ratio for the Joggins Formation (from Davies *et al.*, submitted).


Limestone
Coal
Facies Associations
Stratigraphic Base Level (A/S Ratio)
Low
High
900 m
800 m
700 m
600 m
500 m
400 m
300 m
200 m
100 m
0 m
Joggins Seam
Queen Seam
Coal Mine Point
Forty Brine Seam
Fundy Seam
Cycle 14
Cycle 13
Cycle 12
Cycle 11
Cycle 10
Cycle 9
Cycle 8
Cycle 7
Cycle 6
Cycle 5
Cycle 4
Cycle 3
Cycle 2
Cycle 1
1000 100 10 1 1 10 100 1000
Thickness (cm)
OW
PDF
WDF
OW PDF WDF
Facies Associations

deposits. Coals are numerous and thick, and many of the most prominent fossil forests are found in this interval (Calder *et al.*, in press). Limestones are generally scarce, apart from a thick bed at the base of Cycle 8. Cycle 9 commences with a well developed open-water facies above the Forty Brine Seam (Skilliter, 2001), with limestones, mud drapes, diverse trace fossil suites (Archer *et al.*, 1995), and a large distributary channel body, passing upward into probable lacustrine deposits of stratified red and grey beds.

Cycle 10 (158 m thick) marks the start of a 200 m interval of alternating poorly drained and well drained deposits without open-water sections and limestones (Cycles 10-12). Prominent fossiliferous carbonaceous shales (Cycle 10) or thick coals (Queen and Joggins seams, Cycles 11 and 12) mark cycle bases, but several thin coals delineate minor transgressions within the numbered cycles. Limestones mark the base of Cycles 13 and 14 and the Joggins-Springhill Mines Formation contact.

Following the abrupt onset of wetland conditions at the formation base, the Joggins Formation records a punctuated set of advances and retreats of the coastal zone (Fig. 24). A long-term balance seems to have been maintained between accommodation creation and sediment supply, such that the study area remained close to the coastal zone during deposition of the Joggins Formation, with periods of more sustained open water, wetland or dryland conditions.

Thick limestones and thick coals tend to be mutually exclusive (Fig. 24): thin coals underlie many limestones, but thick coals rarely have limestone caps, the most notable exception being the Forty Brine Seam (Coal 20). This pattern probably reflects variations in the magnitude and rate of base-level rise. Large base-level rises would tend to flood much of the Cumberland Basin, resulting in reduced sediment flux to open-water

areas and the accumulation of fossil-concentrate limestone. Rapid base-level rise would tend to outpace the rate of peat accumulation, resulting in thin peats only. In contrast, thick peats (coals) probably accumulated where modest or slow base-level rise caused prolonged freshwater ponding inland of transgressive shorelines (Kosters and Suter, 1993). A rheotrophic (groundwater-influenced), planar character is the hallmark of the coals of the Joggins Formation (Hower *et al.*, 2000; Calder *et al.*, in press).

Thick heterolithic packages of sandstone accumulated preferentially in the poorly drained floodplain association, where coastal bays formed repositories for coarse detritus. In these areas, sand deposition was strongly focused into stacked sheets, scour fills and vegetation shadows where forested landscapes slowed overtopping flood waters (Rygel *et al.*, Chapter 4). In contrast, shoreface and delta-lobe sands of the open-water association are relatively thin, and dryland alluvial plains of the well drained association include numerous thin beds of sand occurring as levees, splays, and small channels.

### 3.7. Sequence Stratigraphy

Fourteen large-scale (15+ m thick) cycles within the Joggins Formation are ushered in by coal and carbonaceous limestones deposited during basin-wide(?) flooding events. Within these cycles, minor rises in base level are preserved as limestones and/or thin (<10 cm) coals. Stratal packages bounded by these minor flooding surfaces can be considered parasequences and record infilling of water bodies that ranged from relatively deep standing bays (OWF) to emergent floodplain (PDF). Within the well drained floodplain (WDF), parasequence identification is more problematic because many green intervals probably record localized waterlogging "events" on the floodplain rather than changes in relative base level. Large-scale cycles within the Joggins Formation comprise

one or more parasequence sets organized into progradational and aggradational patterns. Minor retrogradational intervals occur where cycle-bounding limestones are underlain by packages of poorly drained strata. The inland extent of these cycles is not known, although some thick coal/limestone packages (ex: Forty Brine seam) can be traced for tens of kilometers inland (Copeland, 1959) and hence represent relatively extensive flooding events. Conversely, the basal four cycles of the Joggins Formation cannot be recognized in boreholes located some 6 km inland near River Hebert.

The Joggins Formation lacks significant erosional surfaces and mature interfluve paleosols. Although multistorey channel bodies are present in the section, they appear to be integral parts of the floodplain and do not mark a basinward shift in facies. The one possible exception is the multistorey channel-body based at 572 m. This abnormally thick body is anomalous because it is bounded both above and below by PDF and has a more chaotic architecture than the well drained floodplain examples. Despite these differences, the evidence for base level fall is equivocal because the exposed margin of the channel-body terminates in poorly drained floodplain strata that lack both significant paleosols and erosion surfaces.

In light of these characteristics, strata of the Joggins Formation do not appear to have Exxon-style sequences marked by prominent sequence boundaries and containing distinct systems tracts. This stratal architecture probably resulted from rapid subsidence, enhanced by halokinesis (Waldron and Rygel, Chapter 8), within the Cumberland Basin which subdued drops in base level and enhanced flooding events. Cyclicity developed as this tectonic signature combined with the 100+ m eustatic fluctuations that have been interpreted for the Pennsylvanian (Soreghan and Giles, 1999). A similar architectural

style exists in the Cenozoic of Greece, where rapidly subsiding fault-bounded basins match or exceed fourth order eustatic falls (Gawthorpe *et al.*, 1994). Under such high subsidence conditions incisions are diminished, transgressions are enhanced, and progradational to aggradational sedimentation patterns dominate areas with high sediment supply (Gawthorpe *et al.*, 1994). Although climate change is likely recorded in the floral record (Falcon-Lang, 2003), its relative importance for stratal architecture is difficult to estimate due to the overwhelming tectonic signature.

### 3.8. Closing Remarks

Joggins is one of the world's best Carboniferous localities, a claim supported by the many scientists, university and school groups, and enthusiastic members of the public who visit the cliffs each year. Hopefully the detailed measured section (Appendix 4), labeled air-photograph (Figure 16), and new understanding of the depositional environments of the Joggins Formation will help to encourage interest in the rocks and fossils of the Joggins Formation. Given the huge and frequently overwhelming amount of rock on display, we hope that the log will serve as a simple guide to visitors with some knowledge of geology, as well as allowing specialists to mark precisely the locations of new fossil discoveries. As Lyell and his contemporaries realized more than 150 years ago, Joggins is all about ancient landscapes inhabited by remarkable plants and animals, for the fossils are at their most compelling when we can imagine them in the environments where they lived more than 300 million years ago.

# CHAPTER 4: VEGETATION-INDUCED SEDIMENTARY STRUCTURES FROM FOSSIL FORESTS IN THE PENNSYLVANIAN JOGGINS FORMATION, NOVA SCOTIA

*Michael C. Rygel, Martin R. Gibling, and John H. Calder*

## 4.1. ABSTRACT

Vegetation-induced sedimentary structures (VISS) are primary structures formed by the interaction of detrital sediment with in situ plants. VISS provide physical evidence of vegetation's fundamental role in mediating sediment accumulation and erosion in clastic depositional systems. Despite the abundance of modern VISS, descriptions from the ancient record are surprisingly rare. Analysis of fossil forests in floodplain strata of the Pennsylvanian Joggins Formation has identified seven types of VISS. Five hydrodynamic types comprise simple forms developed around a single plant (centroclinal cross-strata, scratch circles, upturned beds) and complex forms where structures have amalgamated between several plants (coalesced scour fills, scour-and-mound beds). Two types (mudstone-filled hollows, downturned beds) form by the decay of an entombed plant and represent filling of an empty hollow and/or soft-sediment deformation. Hydrodynamic types are present in both dryland and wetland settings, whereas decay-related types occur only in dryland settings where the water table was perennially or periodically low. VISS represent significant accumulations of sediment and are present in a high proportion of Joggins Formation strata. The paucity of descriptions from the ancient record suggests that these structures have been overlooked or possibly misinterpreted as strictly hydrodynamic. Recognition of VISS in early to middle Paleozoic strata may provide an important insight into the distribution of early land plants in oxidizing environments where organic material was not preserved.

## 4.2. INTRODUCTION

*"In a reddish shale above these beds there is a patch of grey sandstone interlaced with Stigmarian roots, as if the sand had been prevented from drifting away by a tree or stump."*

*J.W. Dawson (1868, p. 173)*

The evolution of vascular plants in the early Paleozoic changed terrestrial depositional systems forever. Although primitive vascular plants existed in swampy environments during the late Silurian (Wellman and Gray, 2001), it was not until the advent of the first trees in the middle Devonian (Chaloner and Sheerin, 1979; Mosbrugger, 1990) that vegetation colonized continental settings more fully. By the Pennsylvanian, peat-forming forest swamps covered most low-lying tropical areas of Pangaea. The record of these primeval forests is well preserved in the coal-bearing strata of the Euramerican Coal Province, an area that covers much of modern-day Europe, eastern North America and northern Asia (Calder and Gibling, 1994).

Land plants act as the physical embodiment of climate by influencing the hydrology, stability and erosion of the landscape. Specifically, vegetation exerts a profound influence on fluvial form and process (Smith, 1976; Cotter, 1978; Gregory and Gurnell, 1988; Thorne, 1990; Gradziski *et al.*, 2003), favors the production of finer grained sediment and reduces sediment yield through storage in hillslopes, valleys and alluvial plains (Schumm, 1968). Standing plants localize sediment accumulation by baffling sediment-laden flows in channels and overbank areas (Li and Shen, 1973; Petryk and Bosmajian, 1975; Graeme and Dunkerly, 1993; Jordanova and James, 2001; Zierholz *et al.*, 2001) and promote local erosion (Nakayama *et al.*, 2002).

Despite the fundamental role that vegetation plays in mediating sediment accumulation and erosion, direct evidence of plant-sediment interaction has been described only sporadically from the ancient record. This modicum of data is expanded upon here by providing detailed descriptions of seven types of "Vegetation-Induced Sedimentary Structures" from fossil forests in the Pennsylvanian Joggins Formation. Their volumetric significance in this stratal succession and their importance in documenting the earliest forests in the rock record are also examined.

## 4.3. Vegetation-Induced Sedimentary Structures (VISS)

### 4.3.1. Definition

Vegetation-induced sedimentary structures (VISS) are primary structures formed by the interaction of in situ plants with detrital sediment (cf. Noffke *et al.*, 2001). By definition, "primary" sedimentary structures "formed at the time of deposition or shortly thereafter and before the consolidation of the rock in which they are found" (Pettijohn and Potter, 1964, p. 3). Seven types of VISS are identified in the present study (Fig. 25). Five are the product of hydrodynamic processes (centroclinal cross-strata, scratch semicircles, upturned beds, coalesced scour fills, scour-and-mound beds), and two are the product of plant decay and represent infilling of an empty hollow and/or soft-sediment deformation (mudstone-filled hollows, downturned beds). Although hydrodynamic structures such as scratch circles, sediment shadows and obstacle marks form around many types of objects (see reviews in Allen, 1982; Nakayama *et al.*, 2002), the VISS designation applies only to structures formed in association with in situ plants.

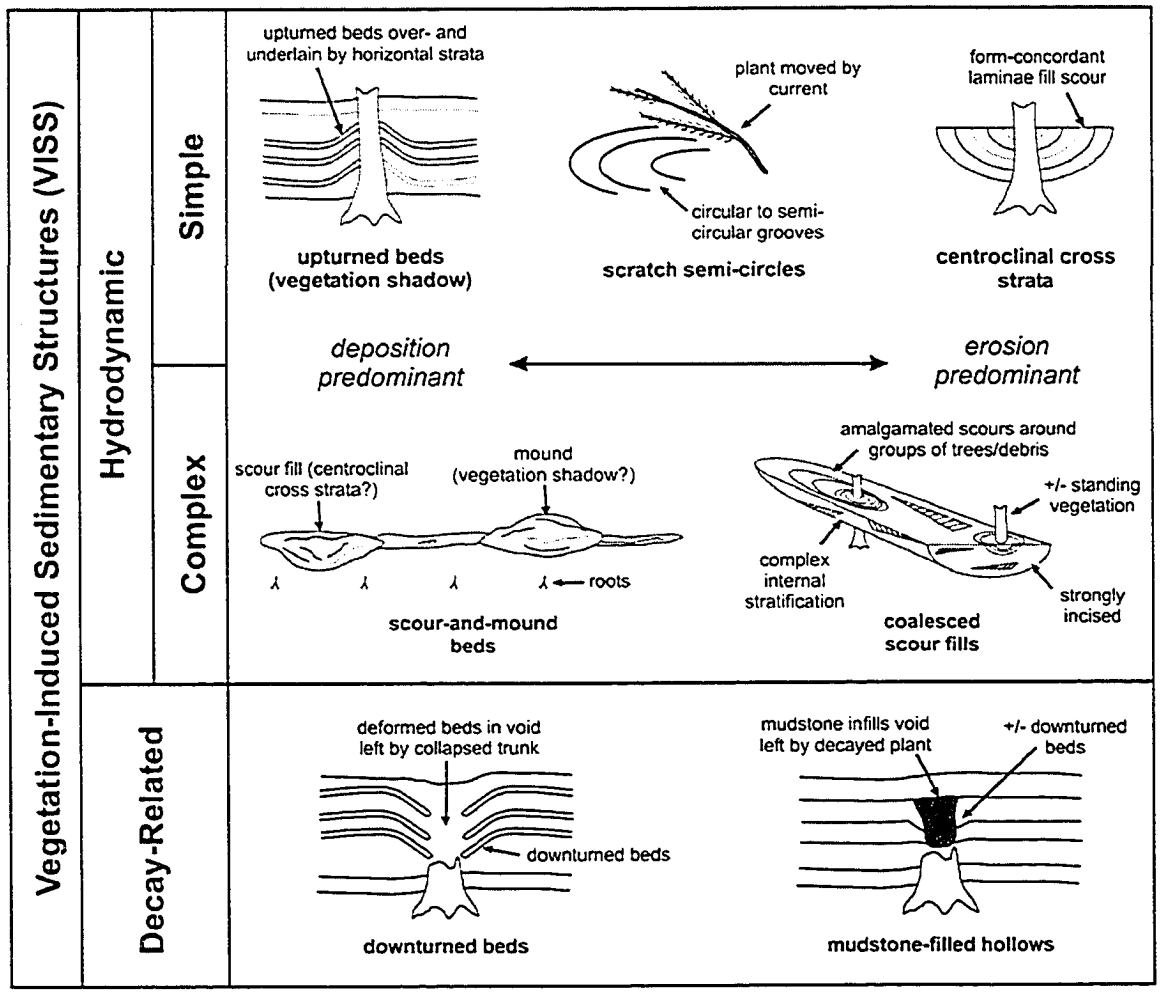



Figure 25: Summary of form diagram for the seven types of vegetation-induced sedimentary structures associated with *in situ* plants, as described in this study. Structures are classified as simple/complex hydrodynamic features formed under a range of aggradational to erosional flow conditions, and decay-related structures formed in association with the decay of a plant and collapse of adjacent sediment.

Preservation of plant material is not a diagnostic criterion for positive identification of VISS, although careful interpretation may be required to establish a link to vegetation. VISS are not considered to be biogenic structures because they are the product of hydrodynamic processes around a vegetative obstacle, passive contact with the substrate or a distinct style of soft-sediment deformation (sensu Metz, 1991).

### 4.3.2. Previous research

Sedimentary structures formed around vascular plants have been described from many modern areas (Table 4). Accretionary features include current shadows (also termed sediment tails, sediment shadows or obstacle shadows) that form around plants in alluvial and aeolian settings and are locally large enough to be considered fluvial barforms or aeolian dunes. In the tidally flooded swamps of the Orinoco Delta, forest litter and sediment accumulate as irregular hummocks around palm and mangrove roots (Scheihing and Pfefferkorn, 1984). Erosional flows produce circular scours filled by centroclinal cross-strata, as well as current crescents and obstacle marks. Scratch circles form where currents in water or wind bend a plant, causing it to inscribe concentric grooves in the adjacent sediment. Some structures form without the aid of a moving current. The most widespread are cradle knolls, which are depressions and mounds (treethrow mounds) formed by the root masses of toppled trees (windthrows). Downslope movement of sediment combined with in situ accumulation of organic material forms mounds or hillocks around grass tufts.

| | Type of Structure | Author |
|---|---|---|
| Accretionary Structures | Current shadows formed through wind and water | (Bagnold, 1941; Doeglas, 1962; Karcz, 1968; Froehlich *et al.*, 1972; Allen, 1982; Fielding and Alexander, 1996; Nakayama *et al.*, 2002) |
| | Current shadows at scale of fluvial bars | (Jackson, 1976; Woodyer *et al.*, 1979; Sneh, 1983; Witt, 1985; Fielding *et al.*, 1997; Gibling *et al.*, 1998) |
| | Current shadows at scale of eolian dunes | (Clemmensen, 1986; Pye and Tsoar, 1990; Thomas and Tsoar, 1990; Cooke *et al.*, 1993; Tengberg and Chen, 1998) |
| | Hummocks | (Scheihing and Pfefferkorn, 1984) |
| Erosional Structures (With Local Accretion) | Circular scours filled by centroclinal cross-strata | (Underwood and Lambert, 1974) |
| | Current crescents and obstacle marks | (Jahns, 1947; Axelsson, 1967; McKee *et al.*, 1967; Fielding and Alexander, 1996; Fielding *et al.*, 1997; Nakayama *et al.*, 2002) |
| | Scratch circles (from water and wind) | (Richter, 1926; Twenhofel, 1926; Langerfeldt, 1935; Barthel, 1966; Gerharz, 1966; Kukal and Al Naqash, 1970; Koerfer and Schwarzbach, 1971; Seppälä, 1972; Allen, 1982) |
| Structures formed without current activity | Cradle knolls | (Buol *et al.*, 1973; Johnson *et al.*, 1987; Retallack, 1990; extensive review in Small, 1997) |
| | Downslope accumulations | (Schlesinger *et al.*, 1990; Sanchez and Puigdefabregas, 1994; Barois *et al.*, 1998; Bochet *et al.*, 2000) |

Table 4: Literature examples of modern sedimentary structures associated with standing vegetation.

Descriptions of these features from the ancient record are surprisingly rare (Rygel and Gibling, 2001). To date, the only detailed sedimentological studies feature centroclinal cross-strata (Underwood and Lambert, 1974; Leeder *et al.*, 1984) and scratch circles (Allen, 1982; Metz, 1991, 1999). Other workers briefly mention centroclinal cross-strata (Calder *et al.*, 1996; Falcon-Lang, 1999; Falcon-Lang *et al.*, 2001; Fielding and Alexander, 2001; Davies and Gibling, 2003), cradle knolls (Retallack, 1976; Gibling and Rust, 1992), hummocks (Cantrill and Nichols, 1996) and scratch circles (Prentice, 1962).

### 4.3.3. Similar structures

VISS do not include plant fossils (compressions, sediment-filled casts, permineralizations), strictly organic growth features (e.g. the mire hummocks and hollows of van der Molen *et al.*, 1994; Moore, 1995; Pryor, 1996) or "basket podzols" and other features formed by chemical weathering beneath plants (Buol *et al.*, 1973; Retallack, 1990). Circular tool marks (Rigby, 1959), scours and sediment shadows (McGowen, 1969; Keller and Swanson, 1979; Nanson, 1981; Robison and Beschta, 1990; Montgomery *et al.*, 1996; Nakayama *et al.*, 2002) can form in association with large woody debris (Montgomery and Piégay, 2003), but these structures are not true VISS because the transported plant material acts no differently from other mobile debris. Additionally, structures formed around transported plant debris may be difficult to recognize because compaction of flat-lying organic debris can greatly disrupt the adjacent sediment (Rust and Gibling, 1990). Because standing and transported vegetation are commonly associated, detached plant materials can contribute to the formation of VISS.

## 4.4. GEOLOGICAL SETTING

### 4.4.1. Joggins Formation

The majority of present data comes from the Pennsylvanian Joggins Formation near the village of Joggins, Nova Scotia (Fig. 26). During the early Pennsylvanian, Nova Scotia lay within the equatorial humid belt, where extensive tropical mires formed the precursor peats of the Euramerican Coal Province under humid seasonal conditions (Calder and Gibling, 1994; Chandler, 1998; Falcon-Lang, 1999).

The Langsettian Joggins Formation is a 915.5 m thick interval of predominantly alluvial strata deposited in the Cumberland Basin, a fault-bounded depocenter within the regional Maritimes Basin (Ryan *et al.*, 1991; Calder, 1998). Home to numerous "fossil forests" (Lyell, 1843; Scott and Calder, 1994; Scott, 1998) and an abundant tetrapod fauna (Dawson, 1863; Carroll *et al.*, 1972; Milner, 1987), the Joggins section is commonly regarded as the world's finest exposure of coal-bearing Carboniferous strata (Lyell, 1871). In their study of part of the "classic" Joggins section (referred to in this chapter as the "measured section"), Davies and Gibling (2003) grouped these strata into open-water, poorly drained floodplain and well drained floodplain facies associations (Chapter 3). Together, these associations record repeated cycles of flooding and infilling and are considered retro- and progradational parasequence sets (Davies and Gibling, 2003). The VISS examined in this study occur within the poorly drained and well drained floodplain facies associations, each of which represents a discrete tropical ecosystem with a distinctive floral assemblage (Falcon-Lang, 2003). Because the new measured section of the Joggins Formation was not complete at the time that this phase of

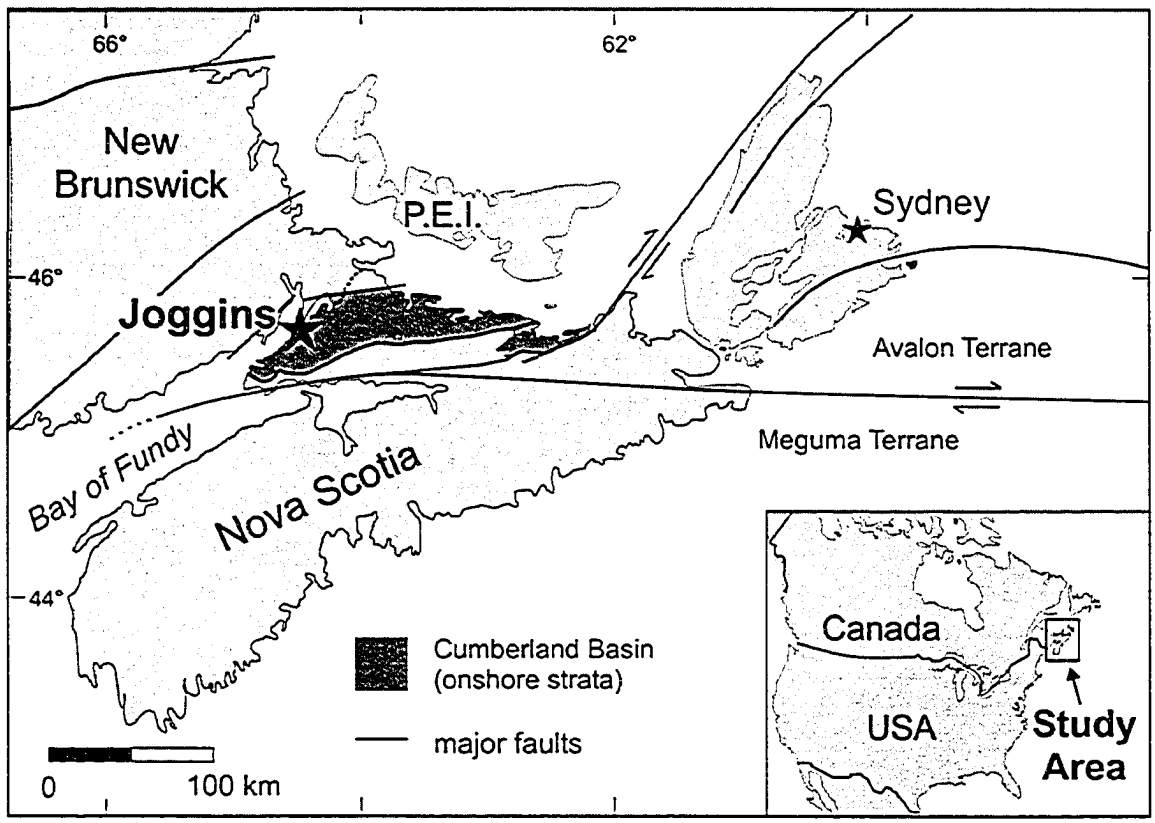



Figure 26: Map showing the location of Joggins and Sydney, Nova Scotia, onshore strata of the Cumberland Basin, and major faults within the regional Maritimes Basin.

my research was undertaken, the location of VISS described in this chapter are given relative to the measured section presented in Figure 27, which is modified after Davies and Gibling (2003).

The 20-m-high sea cliffs and a 400-m-wide wave-cut platform at Joggins provide excellent two-dimensional exposure. Although laterally extensive, the outcrop face is oriented perpendicular to tectonic dip (20°), and bedding plane exposures are restricted to small areas on the wave-cut platform. Consequently, there is limited opportunity to describe fully features best seen on bedding planes (treethrow mounds, scratch circles, vegetation shadows) and to observe the full three-dimensional form of many others. Given these limitations, it is likely that examination of VISS at other locations will add to the initial descriptions provided here and that new structures and variations of form will be identified.

Although standing plants in the Joggins Formation are present in floodplain, riparian and in-channel settings, the VISS described in this study were located in floodplain deposits at least several meters from the nearest channel. The literature on modern alluvial settings suggests that these structures can also form within channels and on adjacent banks. Two particularly well-exposed examples from coal-bearing strata of the Sydney Mines Formation (Pennsylvanian) near Sydney, Nova Scotia (Fig. 26), are also illustrated.

### 4.4.2. Poorly drained floodplain association

The poorly drained floodplain (PDF) association comprises channel and sheet sandstones, green and grey mudstone, carbonaceous shale and coal. These lithologies

Figure 27: Facies associations, cyclicity, and sedimentological log of a portion of the Joggins Formation showing occurrences of *in-situ* vegetation-induced sedimentary structures and horizons with standing plants in the 2000 and 2001 field seasons (modified from Davies and Gibling, 2003). Vertical lines drafted nest to the symbols for these structures are scaled to represent their true thickness, an aggregate value of 44.5 m in the 603-m-thick measured section. Where the location of VISS is given in meters in the text, the measurement refers to its position in this measured section. If no specific location is provided in the text, the VISS in question occurs in the Joggins Formation above the Davies and Gibling (2003) measured section.

Facies & Cycle Numbers
Measured Section
600 m
500
400
300
200
100
0
8
7
6
5
4
3
2
1
Forty Brine Coal
Fundy Coal
Facies Assemblages
well-drained floodplain
poorly-drained floodplain
open water
Vegetation
lycopsid(s)
calamite(s)
cordaite(s)
gymnosperm
VISS
centroclinal cross strata
coalesced scour fills
scour-and-mound structures
upturned beds

represent distributary and meandering channels, levees, stacked splays, gleyed paleosols (histosols) and floodplain fines deposited in a predominantly reducing environment (Davies and Gibling, 2003).

The PDF association represents wetland deposits in which forested mires (peatlands) flourished, and at times struggled in the face of repeated disturbance from fire and flood (Falcon-Lang, 1999; Hower *et al.*, 2000). Many of these forest swamp horizons with which the great standing lycopsid trees are associated were incipient mires, resembling the "clastic swamps" of Gastaldo (1986). The paleobotanical record of these mires is dominated by *Sigillaria* and *Lepidodendron* (*sensu latu*, including *Diaphorodendron*). Other floral elements, in particular seed-bearing medullosan pteridosperms and cordaitean gymnosperms, as well as possible progymnosperm elements, may have been better adapted to terra firma conditions external to the mires and are present both within PDF and WDF environments (described below). The disturbance-adapted calamites were highly successful and therefore ubiquitous, and a successional flora to the lycopsid forests as they became entombed.

The "fossil forests" of standing lycopsids in the Joggins Formation occur almost exclusively in the PDF association. Preservation of lycopsid forests began when floodwaters rapidly deposited large amounts of sediment, partially entombing the trees, which perished as their stigmarian roots smothered beneath this sediment blanket (sensu Gastaldo, 1986; Calder *et al.*, 1996). Although lycopsid decay rates are difficult to predict (Gastaldo, 1986), the tough outer periderm often remained standing long enough for the stump to become further entombed during subsequent floods - probably a period of several decades. Eventually sediment-laden floodwaters overtopped the hollow trunk and

filled it with clastic sediment. Lyell (1842) described standing lycopsids as much as 12.2-m-tall, but specimens exposed over the last several decades are generally less than 6-m-tall. Calamites were entombed by similar processes, but frequently survived burial by adventitious propagation (Gastaldo, 1992).

### 4.4.3. Well drained floodplain association

The well drained floodplain (WDF) association includes red mudstone, channel and sheet sandstone. These strata represent channels, levees, splays, poorly developed paleosols (entisols) and floodplain fines deposited in an alluvial environment where oxidizing conditions prevailed through much of the year (Davies and Gibling, 2003; Falcon-Lang, 2003).

The low preservation potential for plant material in tropical dryland settings has limited knowledge of Carboniferous floras in such environments (Mapes and Gastaldo, 1986; Lyons and Darrah, 1989; Falcon-Lang and Scott, 2000; DiMichele *et al.*, 2001). In a pioneering study of the Joggins Formation that drew on charcoal and quadrat analyses, Falcon-Lang (2003) showed that the WDF flora was dominated by cordaitean gymnosperms with subordinate pteridosperms, sphenopsids and rare lycopsids (*Sigillaria* and stigmarian roots). Standing vegetation is rarely preserved in the WDF association, and only a few short (< 1 m tall), decorticated lycopsid stumps were observed.

## 4.5. SIMPLE VISS

### 4.5.1. Centroclinal cross-strata

#### 4.5.1.1. Description

Underwood and Lambert (1974) described centroclinal cross-strata in recent flood deposits as bodies of very fine- to fine-grained sand that fill symmetrical, cone-shaped depressions centered on tree trunks. The sandy fill is typically organized into form-concordant, concentric laminae that dip towards the tree. Nineteen well-exposed examples of centroclinal cross-strata at Joggins were selected for study, 13 within the PDF association and six within the WDF association. Obstacle-forming vegetation is preserved within 10 PDF examples and comprises eight decorticated lycopsids (0.10-0.54 m diameter) and two calamites (0.05-0.09 m diameter). The six WDF specimens do not contain obstacle-forming vegetation, but stigmarian roots extend from the base of three examples.

The centroclinal cross-sets occur as discrete sandstone bodies with concave-up bases and flat tops (Fig. 28) that vary in diameter from 0.21 to 3.55 m and in thickness from 0.05 to 2.10 m (Fig. 29). The bodies comprise thinly to thickly laminated beds of very fine- to fine-grained sandstone organized into hemispherical, form-concordant laminae that dip towards the centre of the structure at 13° to 46°. As in the original description by Underwood and Lambert (1974), a noticeable flattening or reversal of lamina dip is common within a few centimeters of the obstacle-forming vegetation (Fig. 28A and B). Where obstacle-forming vegetation is not preserved, centroclinal cross-strata surround cylindrical zones of deformed or massive sandstone (Fig. 28C-F). In cross-section, the cross-stratified lenses range from nearly symmetrical to elongate and tapering

downflow (Fig. 29). Externally, these forms range from discrete cross-sets within sandstone to isolated sandstone pods incised into mudstone. Laterally, centroclinal cross-strata extend into sheets of massive or ripple cross-laminated sandstone (Fig. 30A) or pinch out (Fig. 30B).

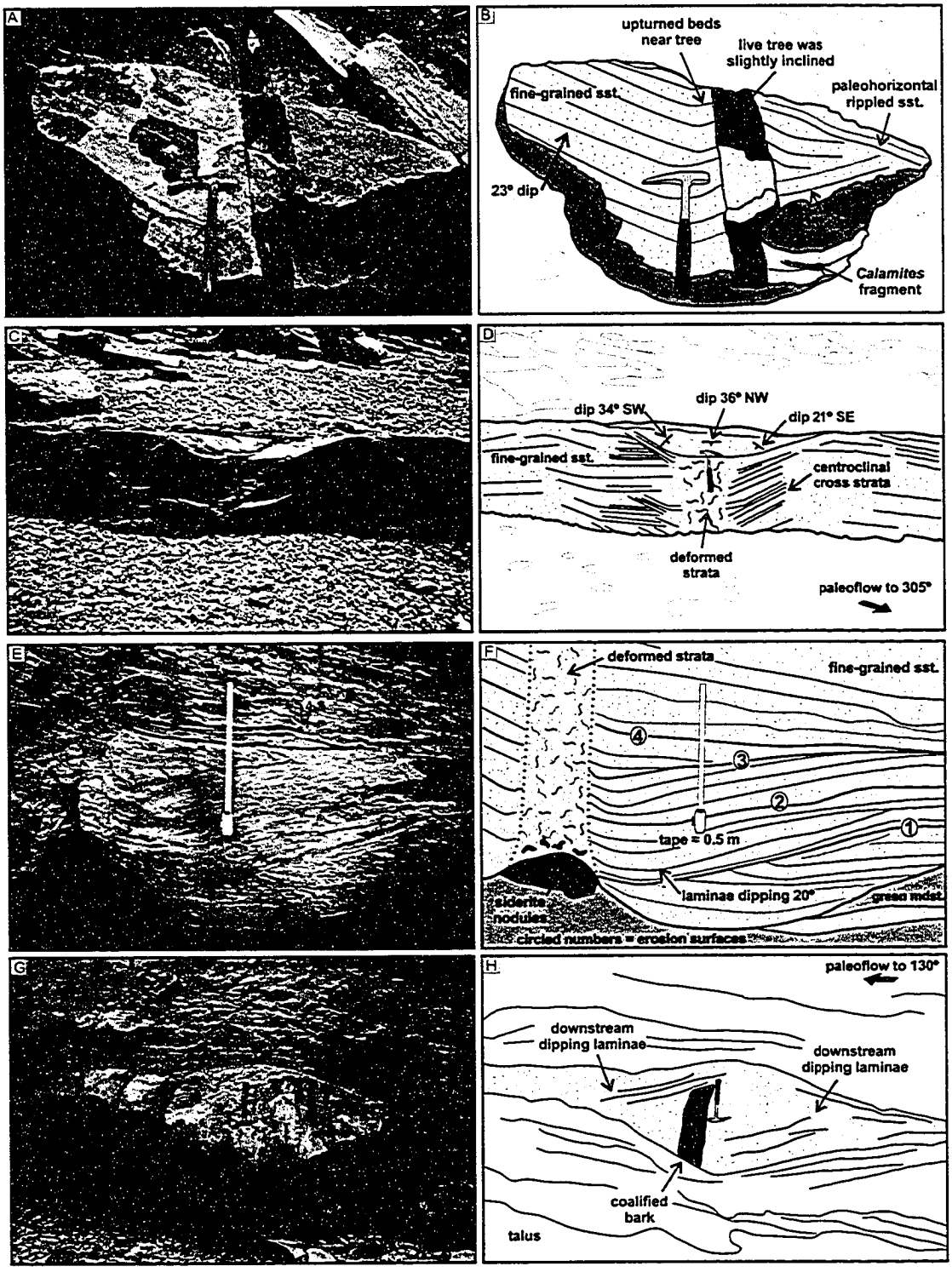
In some PDF examples, distinct erosion surfaces within the centroclinal fill separate packages of dipping laminae that concentrically drape or onlap the underlying erosion surface (Fig. 28E, F). Locally, several discrete, vertically stacked centroclinal cross-sets surround a single plant.

A lycopsid at 435 m in the measured section is surrounded by a 1.3 m deep scour filled with "uniclinal" cross-strata (Fig. 28G, H). This unique fill comprises a single cross-set that dips in the downflow direction on both the lee and stoss sides of the plant.

4.5.1.2. Interpretation

Underwood and Lambert (1974) attributed the formation of centroclinal cross-strata to the "infilling of scours created around trees by swirling flood water." Recent studies of scour around cylindrical bridge piers allow further insight into the scouring process (Fig. 31). In front of cylindrical obstructions (e.g. trees and piers), decelerating flow and friction with the bed material causes a downward pressure gradient (Allen, 1982, p. 175) that leads to erosive downflow. Downflow and accompanying horseshoe vortices generate a U-shaped scour around the front and sides of the obstruction (Melville and Coleman, 2000). Wake vortices shed from the obstruction remove additional sediment from the sides and rear, causing the scour to become increasingly circular in planform (Melville and Coleman, 2000). With impermeable obstructions, the circular planform can be enhanced by rotary or multidirectional flow (Fig. 32; Allen, 1982) and

Figure 28: Photographs and interpretive sketches of centroclinal cross-strata. Hammer is 0.32 m long and ruler is 0.5 m long. A, B) Large fallen block of centroclinal cross-strata in cross-section originally encased within PDF strata at ~430 m. C, D) Three-dimensional exposure of centroclinal cross-strata in WDF strata at 394 m. Note that bedding dips towards the center of the structure from all directions and that the nucleating plant is not preserved, instead structure is cored with deformed beds. E, F) Photograph and interpretive tracing of complex centroclinal cross-strata in PDF strata of the Sydney Mines Formation. Several distinct erosion surfaces are present within this example and portions of the nucleating plant have been partially replaced by siderite. Complete view of this structure is provided in Fig. 30B. G, H) Photograph of "uniclinal" cross-strata at 435 m. Note that laminae dip in a downflow direction (as indicated by bedforms in an adjoining splay) on both the lee and stoss sides of the tree.


A
B
upturned beds
near tree
live tree was
slightly inclined
paleohorizontal
rippled sst.
fine-grained sst.
23° dip
Calamites
fragment
C
D
dip 34° SW
dip 36° NW
dip 21° SE
fine-grained sst.
centroclinal
cross strata
deformed
strata
paleoflow to 305°
E
F
deformed strata
fine-grained sst.
4
3
2
1
tape = 0.5 m
laminae dipping 20°
siderite
nodules
green mdst.
circled numbers = erosion surfaces
G
H
paleoflow to 130°
downstream
dipping laminae
downstream
dipping laminae
coalified
bark
talus

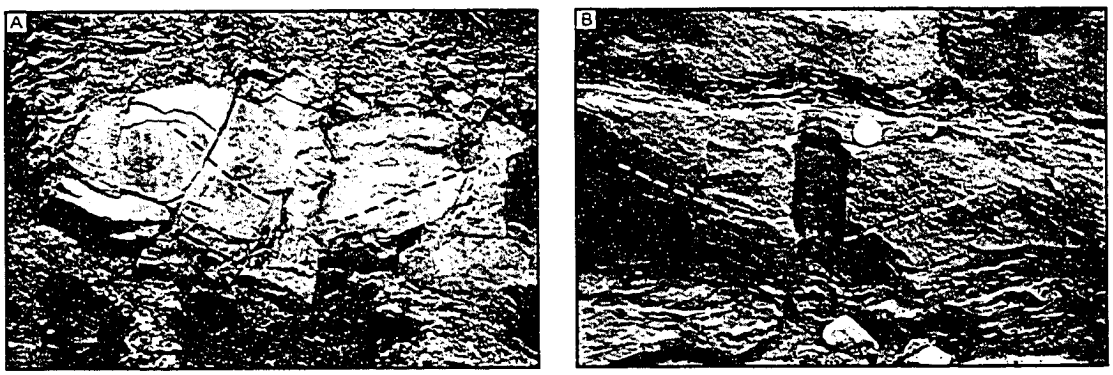



Figure 29: Centroclinal cross-sets range in size from A) 1.3 m thick and 3.5 m in diameter to B) 0.12 m thick and 0.36 m in diameter (at ~ 430 m). Dashed lines show orientation of bedding; hammer is 0.32 m long and coin 26 mm in diameter.

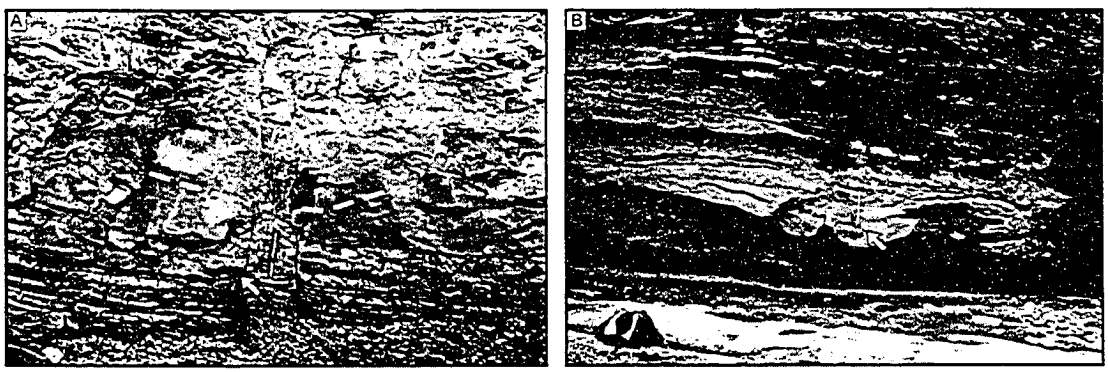



Figure 30: Variations in centroclinal cross-strata external form. A) Discrete centroclinal cross-sets within sandstone bed at ~ 430 m. Dashed line shows orientation of bedding, arrow marks the location of upturned beds, and hammer is 0.32 m long. B) Isolated pod of sandstone incised into mudstone in the Sydney Mines Formation; ruler above the arrow is 0.5 m long.

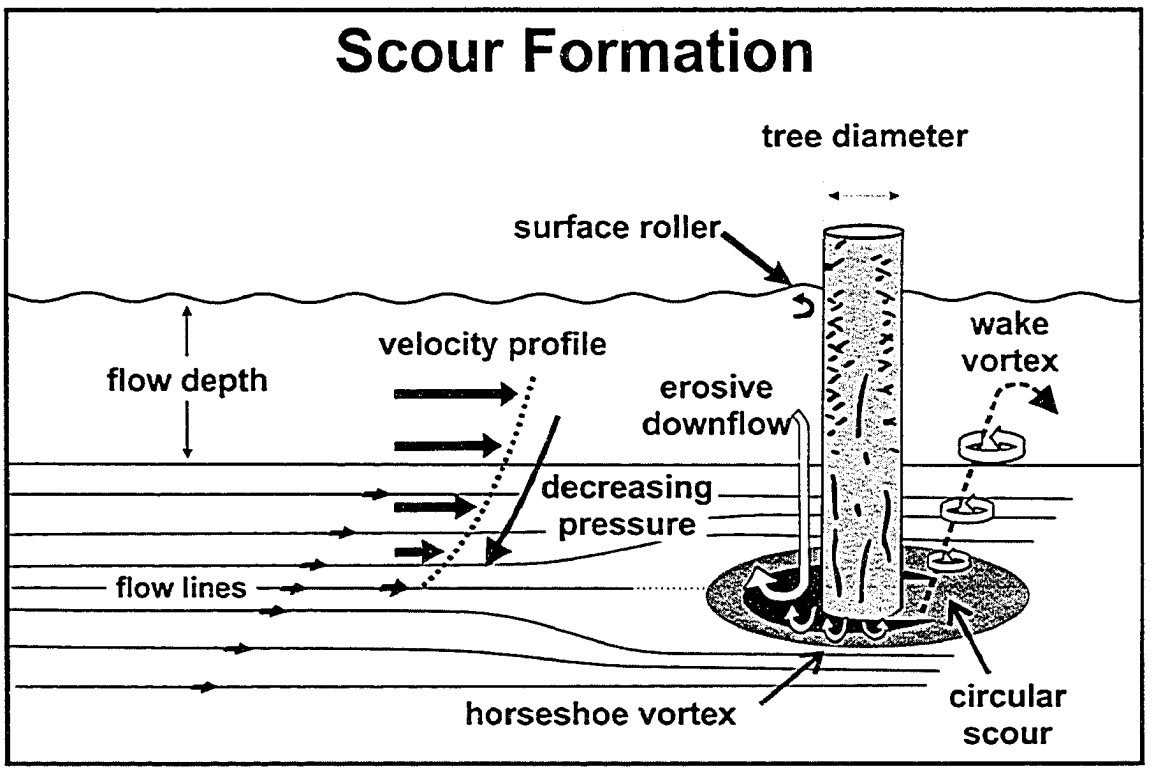



Figure 31: Illustration of the forces responsible for the formation of scours around standing trees (after Allen, 1982; Melville and Coleman, 2000).

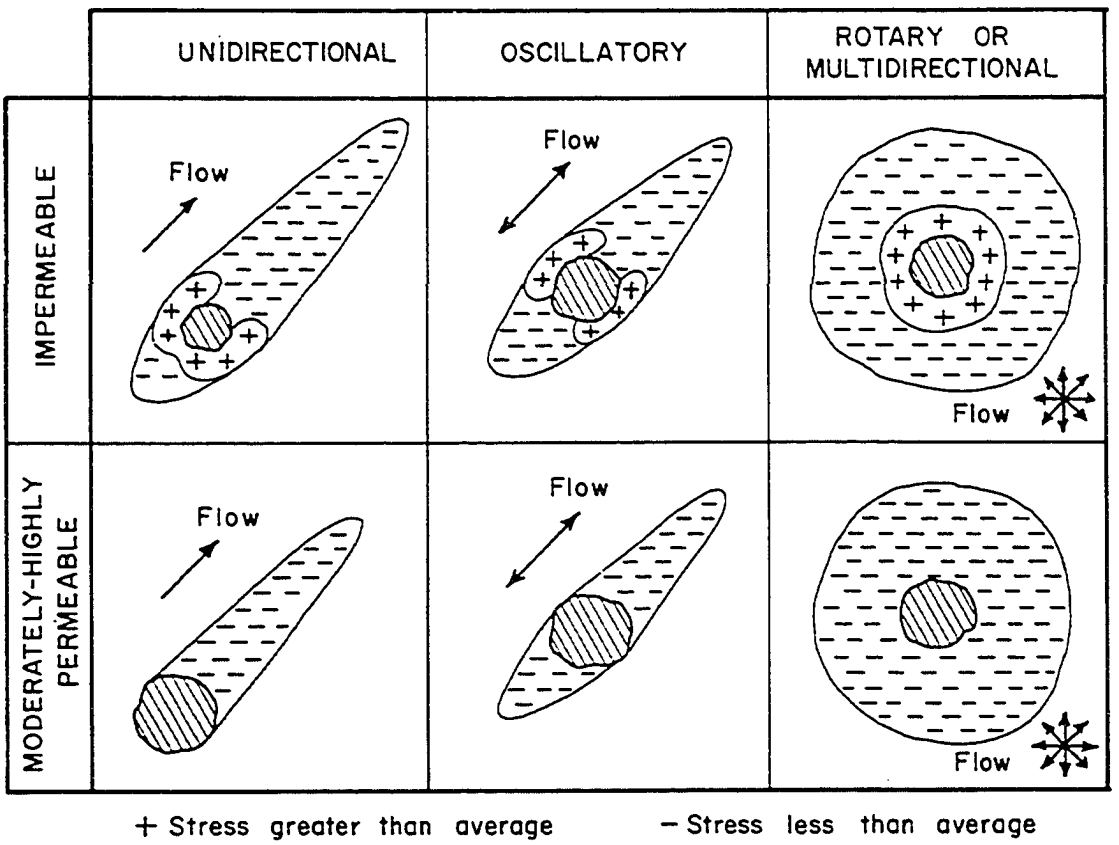



Figure 32: Effect of obstacles on bed shear stress in different types of flow (modified from Allen 1982).

floating debris rafts (Melville and Dongol, 1992). Although the flow dynamics depend on the properties of the fluid, obstacle and substrate, essentially the same processes form scours (and shadows) in air and water (cf. Hesp, 1981; Allen, 1982).

By comparison with studies of scour depth around cylindrical bridge piers, Underwood and Lambert (1974) suggested that scour depth is primarily a function of flow depth, obstruction diameter and flow velocity. Leeder *et al.* (1984) applied a predictive scour depth equation to an ancient centroclinal cross-set and solved for flow velocity using a combination of measured and assumed values. Although early studies of bridge scour emphasized the relationship between scour depth and flow velocity (Shen *et al.*, 1969), more recent engineering studies have downplayed the importance of velocity in controlling maximum scour depth (Jain, 1981; Melville and Sutherland, 1988; Melville and Coleman, 2000). Instead, they suggest that maximum scour depth is primarily a function of obstacle diameter and flow depth. Despite these advances in the understanding of scour hydrodynamics, applying these relationships to ancient centroclinal cross-strata is problematic because it requires a series of tenuous assumptions about flow conditions and substrate characteristics.

Filling of the scour commences during waning flow when sediment transport into the scour exceeds sediment loss. The sandy centroclinal laminae were probably deposited mainly from suspension and blanket the scour. "Uniclinal" fill may represent bedload-dominated filling and/or the downflow migration of a dune into the scour. Internal erosional surfaces developed through erosive flood pulses or by erosive truncation during subsequent episodes of scour and fill.

Although PDF and WDF centroclinal cross-strata formed in response to similar processes, they exhibit morphological differences. Obstacle-forming vegetation is commonly preserved in PDF examples (Fig. 28A and B) and absent in WDF examples (Fig. 28C and D). Additionally, most WDF examples lack significant internal erosion surfaces, suggesting that trunks in the WDF endured only one entombing flood event - probably as a consequence of shorter stump longevity or of a lower frequency of flood events. In some examples, trunk decay and collapse may have contributed to the deformation of beds in the centre of the cross-set and oversteepening of adjacent centroclinal laminae beyond the angle of repose.

### 4.5.2. Scratch semicircles

4.5.2.1. Description

Scratch circles are "sets of concentric grooves cut generally in sand or mud by the action of sharp objects anchored at the centre of curvature of the set, but otherwise free to swing or rotate horizontally about that centre" (features initially described by Richter, 1926; Allen, 1982). Two poorly preserved "scratch semicircles" (sensu Kukal and Al Naqash, 1970) are described from a talus block at 430 m in the measured section. They form moldss on the base of a block of very fine-grained sandstone (Fig. 33) where they comprise a series of < 1 mm high ridges that form arcs of 65° and ~40° (incomplete exposure) and have radii as much as 0.11 and 0.05 m respectively. Both semicircles occupy the same quadrant relative to the axis of rotation and show increased relief in a clockwise direction. The smaller semicircle terminates against a round depression that may represent the former resting place of a portion of the plant. The centre of the smaller

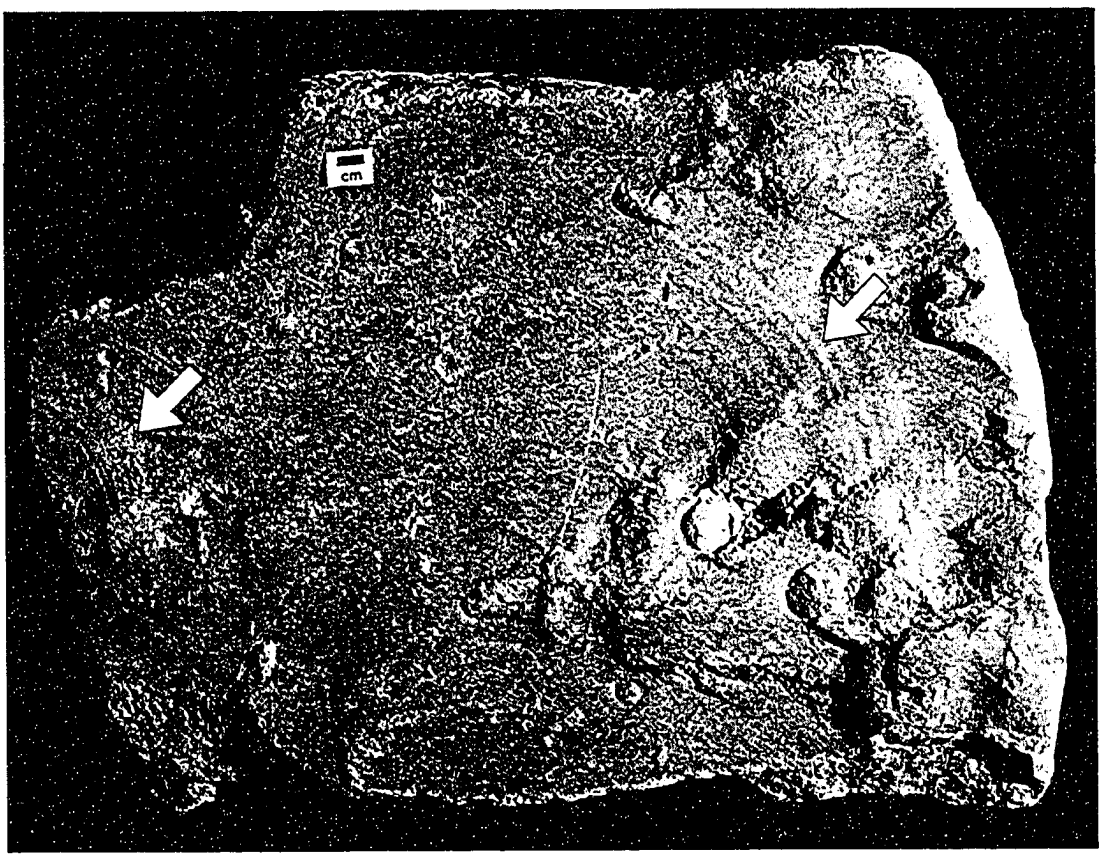



Figure 33: Molds of two scratch semi-circles on the base of a block of fine-grained sandstone from ~ 430 m.

semicircle lies off the slab, and no plant material is preserved at the centre of the larger semicircle.

4.5.2.2. Interpretation

The two scratch semicircles formed as two plants (or portions thereof) were bent by a current, causing them to scratch shallow concentric grooves into the adjacent substrate. The grooves were probably cut into a relatively cohesive (muddy?) substrate, which preserved them during deposition of the overlying sand. These scratch semicircles could record currents in wind or water (Twenhofel, 1926; Allen, 1982). Although Allen (1982) noted that circle shape is largely controlled by plant architecture and the torsional strength of the stem rather than by current direction, the limited circumference and similar orientation of these features suggests that they formed in response to a unidirectional current.

### 4.5.3. Upturned beds (vegetation shadows)

4.5.3.1. Description

Allen (1982) described current shadows as mounds of sediment deposited on the lee side of an obstruction. These modern accretionary features are generally described as mounds elongate in a downflow direction and containing form-concordant stratification (Karcz, 1968; Clemmensen, 1986). A "vegetation shadow" (a specific type of current shadow) is defined here as a sediment accumulation adjacent to a standing plant where a decrease in current velocity has caused the deposition of sediment. These structures may have the traditional downstream-tapering morphology in plan view, or may be represented by upturned beds deposited around much of the plant's periphery where seen in cross-section.

Five vegetation shadows are described from the PDF, three in association with standing lycopsids (0.25-0.51 m diameter), one with a calamite (0.09 m diameter) and one with a gymnosperm pith cast (0.03 m diameter). They appear in cross-section as intervals of upturned bedding adjacent to standing plants (Fig. 34), and details of planform are not available. Upturned beds are concave-up, dip away from the plant at 11-23° and appear to extend around at least 180° of the plant's perimeter in four examples (Fig. 34C and D). Upturned beds gently taper to horizontal over a distance of 0.07-1.60 m. Packages of upturned bedding are 0.06-0.45 m thick measured across dip, and inclined beds are elevated up to 0.06 m above the horizontal portion of the same bed. Upturned beds consist of non-micaceous, thinly laminated to thinly bedded siltstone to fine-grained sandstone with silty claystone interbeds.

4.5.3.2. Interpretation

The upturned beds formed where standing plants caused a decrease in bed shear, allowing sediment deposition near their base (Allen, 1982). This commonly occurs where helicoidal flow deposits sediment on the lee side of a plant (Hesp, 1981). Additionally, sediment accumulates along the front and sides of an obstruction when sedimentation rates are high, stems are closely spaced (centers closer than 12 times stem diameter), the obstruction is permeable (multiple stems acting as a single obstruction) or under multidirectional flow conditions (Fig. 32; Karcz, 1968; Castro, 1971; Froehlich *et al.*, 1972; Allen, 1982). Although bedding-plane exposures of these features are not available

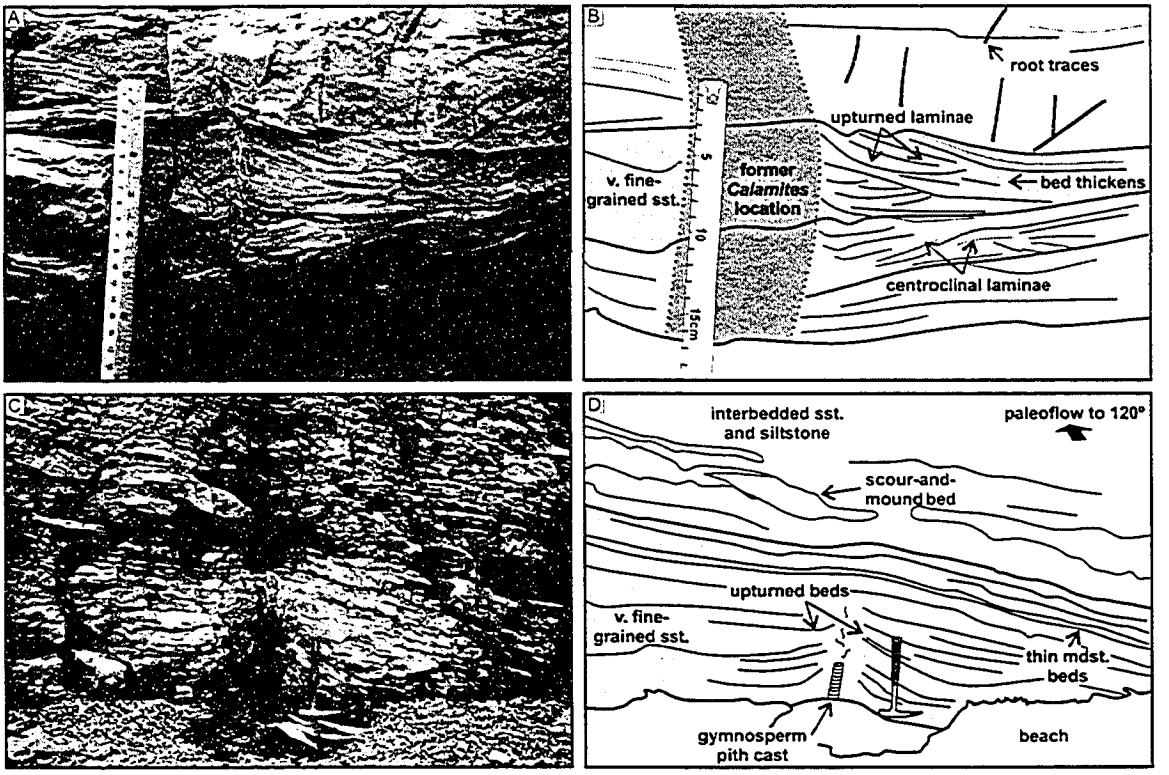



Figure 34: A, B) Photograph and interpretive tracing of upturned laminae adjacent to a calamite in wetland strata of the Sydney Mines Formation. Note that upturned beds occur atop centroclinal cross-laminae, recording a change from erosive to aggradational flow conditions. No reliable paleoflow indicators were observed in this bed. C, D) Upturned beds adjacent to the inner pith cast of a gymnosperm trunk at 435 m; hammer is 0.32 m long.

at Joggins, the presence of upturned beds in cross-section is consistent with the architecture of modern vegetation shadows (Karcz, 1968; Clemmensen, 1986). Upturned beds are interpreted as primary structures rather than the product of differential compaction because: (1) in most cases, the material within the trunk is similar to the surrounding sediment; (2) horizontal and centroclinal beds commonly occur above, below or adjacent to the upturned beds (Figs. 30A, B and 34A, B); and (3) upturned beds were described by Underwood and Lambert (1974) in modern, uncompacted sediments. The upturned beds might be interpreted as deformational structures caused by tree growth after entombment; however, there is no evidence of adventitious root growth adjacent to calamite-cored examples (sensu Stone and Vasey, 1968; Gastaldo, 1992) and, in addition, upturned beds adjacent to lycopsids occur more than 1 m above the stigmarian root system - sufficiently thick sediment to have caused the death of the tree (DiMichele and Phillips, 1994).

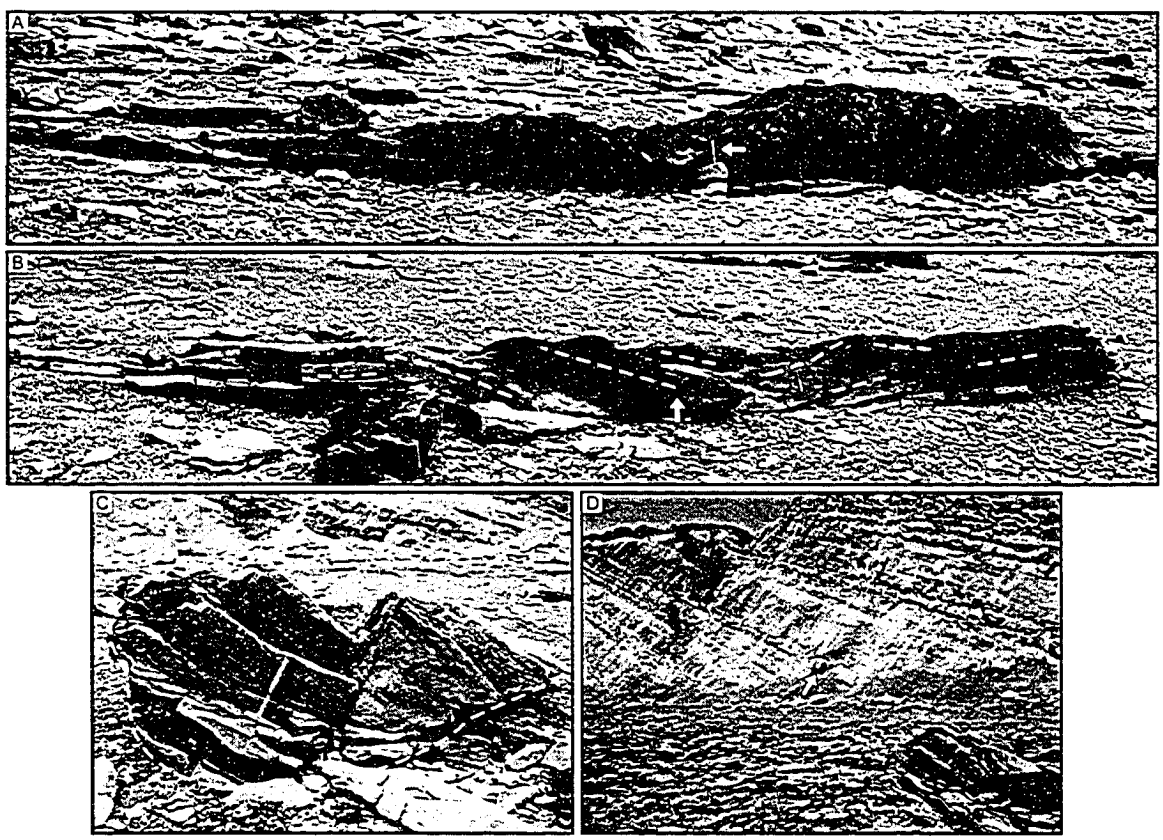
## 4.6. COMPLEX VISS

### 4.6.1. Coalesced scour fills

#### 4.6.1.1. Description

Coalesced scour fills are large, internally complex sandstone bodies in WDF strata, which superficially resemble small channel bodies (Fig. 35). These discrete, locally thickened accumulations are laterally equivalent to thin sheet (crevasse splay) sandstones and are strongly incised into red mudstone. Two examples contain groups of standing lycopsids (three to five individuals; 0.13-0.45 m in diameter); no plant material was apparent in the third. Exposed portions range from 0.75 to 1.20 m thick, 5 m wide

Figure 35: Coalesced scour fills in WDF strata of the Joggins Formation. Hammer is 0.32 m long. A) Cross sectional exposure of coalesced scour fill at 394 m. View is roughly perpendicular to the paleoflow direction (from right to left across the field of view). Arrow points to the location of a standing lycopsid trunk and hammer; two additional stumps (not visible from this angle) occur within this structure. Strata abruptly pinch out on the upstream side (right) and gradually taper in a downstream direction (left). B) Cross-sectional view of coalesced scour fill at 242 m. View is roughly perpendicular to paleoflow (right to left across the field of view). Bedding orientation is indicated by dashed white lines; location of the hammer indicated by the arrow. This example does not occur in association with standing vegetation, but it does contain intervals of centroclinal cross-strata. C) Downstream view of the coalesced scour shown in (B). Note the u-shaped cross-sectional form. D) Distant, downstream view of the coalesced scour fill shown in (C). A second coalesced scour fill (above the arrow) which is elongate in the same direction and contains three lycopsid trunks, occurs at the same horizon approximately 30 meters downflow.


A
B
C
D

(perpendicular to paleoflow) and 10-12 m long (along paleoflow). One particularly well-exposed example is U-shaped in cross-section (Fig. 35C; 1.2 m thick, 2.0 m wide), elongate parallel to paleoflow (Fig. 35B) and, assuming a semicylindrical shape, comprises 25 $m^3$ of sandstone. Fills comprise thinly laminated to thinly bedded strata that dip at 9-35°. Although their internal architecture initially appears chaotic, closer investigation reveals centroclinal cross-sets connected by poorly defined flat-laminated to gently inclined strata. The centroclinal cross-sets were not amenable to detailed measurement because they were incompletely exposed and had diffuse boundaries. Strike and dip within the fills show no systematic orientation relative to the paleoflow direction measured from ripples in the adjacent sheet sandstones.

4.6.1.2. Interpretation

Coalesced scour fills are strongly erosional structures formed where interconnected scours between trees are filled with sandy sediment during waning flow. Strong incision into underlying strata and downflow tapering suggests that the precursor scours formed in response to vigorous floods across the well drained floodplain, essentially unconstrained by channels and vegetation. The flows carried only enough sand to fill the scour and blanket the floodplain with a thin sand layer. The apparent absence of these strongly erosional structures in the PDF may reflect the inability of floodwaters to attain sufficiently high velocities in densely forested tracts, locally with standing water. Alternatively, their localization to the WDF may reflect lycopsid growth in linear, flow-parallel groves where upstream cohorts served to baffle vigorous floods (Fielding *et al.*, 1997; Fielding and Alexander, 2001; Nakayama *et al.*, 2002). The large and complex architecture of coalesced scour fills distinguishes them from simple

centroclinal cross-strata. Although internal sets of horizontal and inclined strata may not be directly attributable to the obstacle-forming vegetation, they probably represent amalgamated vegetation shadows and scour fills formed between trees, perhaps enhanced by rafts of plant debris.

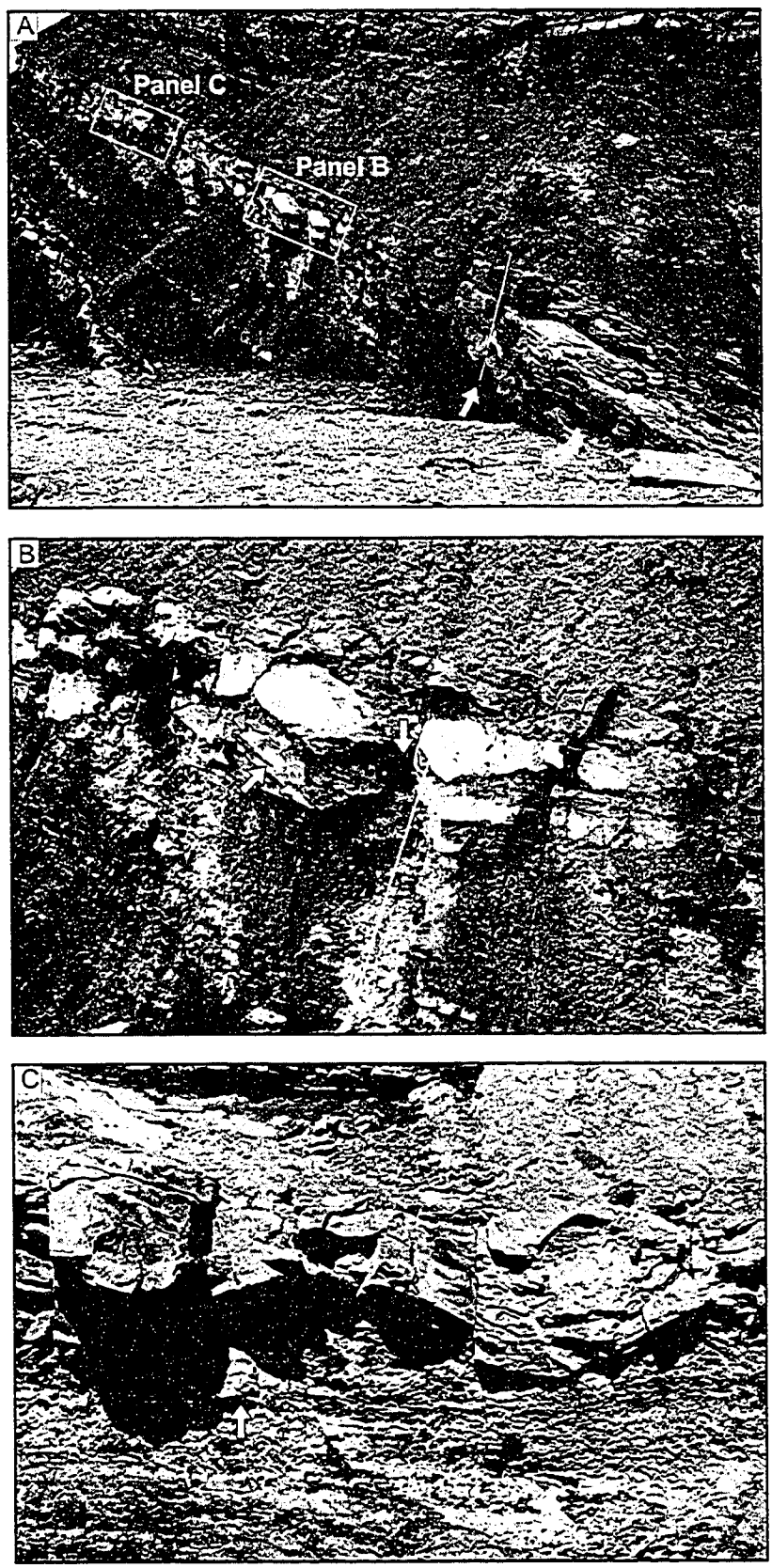
### 4.6.2. Scour-and-mound beds

#### 4.6.2.1. Description

Davies and Gibling (2003) described "scour-and-mound" structures as diffuse sandy lenses associated with standing vegetation at numerous horizons within the PDF association. Scour-and-mound beds typically occur above root-penetrated horizons (both stigmarian and unidentifiable types). Several examples contain standing lycopsids and calamites, but the exact relationship of individual scours and mounds to these plants is often unclear.

Scour-and-mound beds (Fig. 36) occur as isolated to interconnected lenses of very fine- to fine-grained sandstone connected by sheet sandstones. The beds commonly extend across the outcrop belt, a distance of several hundred meters. Where distinguishable, individual lenses range from 0.1 to 6.0 m wide and 0.02 to 2.00 m thick. Internal structure is rarely preserved, but those with discernible bedding contain horizontal, centroclinal and/or upturned laminae adjacent to visible trees (dips of 15-33°). Connecting sheet sandstones up to 1 m thick contain ripple cross-laminae. Cross-sectional shapes of individual lenses include elliptical forms with rounded bottom and top

Figure 36: Scour-and-mound beds in PDF strata at 200 m. A) View of cliff exposure of scour-and-mound bed. 2-m-thick "mound" near the base of the cliff thins to less than 0.5 m over a short distance and thickens again at the "scour" shown in (B). Scale near the base of the cliff is 2 m tall. B) Close-up of the "scour" shown in (A); ruler is 2.0 m tall. The arrow to the right points to a mudstone interval that probably represents the former location of a lycopsid trunk. This interpretation is supported by the presence of root traces immediately below the bed and by laminae which dip towards the mudstone interval (left arrow). The gross morphology of this feature and its probable association with a lycopsid suggests that it is a poorly preserved interval of centroclinal cross-strata. C) Detail of mounds shown in (A). Although closely associated with a standing lycopsid trunk (above the arrow), the exact relationship between the mounds and the tree is difficult to determine. Scour-and-mound beds are distinguished from coalesced scour fills because they are not strongly erosional and typically extend for several tens of meters.


A
Panel C
Panel B
B
C

surfaces, forms with concave-up bases and horizontal top surfaces and forms with horizontal bases and convex-up top surfaces.

4.6.2.2. Interpretation

Scour-and-mound beds represent poorly preserved intervals of centroclinal cross-strata and vegetation shadows connected by relatively thick sheet sandstones. Their setting within sand-rich and heterolithic PDF intervals suggests that they formed in forested areas with standing water ('deep swamps' of Gastaldo, 1986) where sand-charged flows rapidly decelerated and deposited large amounts of sediment with only minimal scour. Unlike the centroclinal cross-strata and upturned beds, scour-and-mound beds typically lack internal stratification and are difficult to attribute directly to the influence of standing vegetation unless trees are well preserved. The paucity of internal stratification probably reflects destruction of bedding by bioturbation, pedogenesis, dewatering and/or soft-sediment deformation.

## 4.7. DECAY-RELATED VISS

### 4.7.1. Mudstone-filled hollows and downturned beds

4.7.1.1. Description

Mudstone-filled hollows and downturned beds are sedimentary structures that appear to protrude into underlying strata. Well-exposed examples in the WDF association of the upper Joggins Formation (above the measured section) were described in detail at two locations, with several cryptic examples elsewhere. Although vegetation was not preserved within or closely adjacent to these structures, both occur several decimeters

above lycopsid material (trunks and stigmarian roots). The hollow fills and downturned beds are closely associated in most examples, although one type of feature may be more prominent.

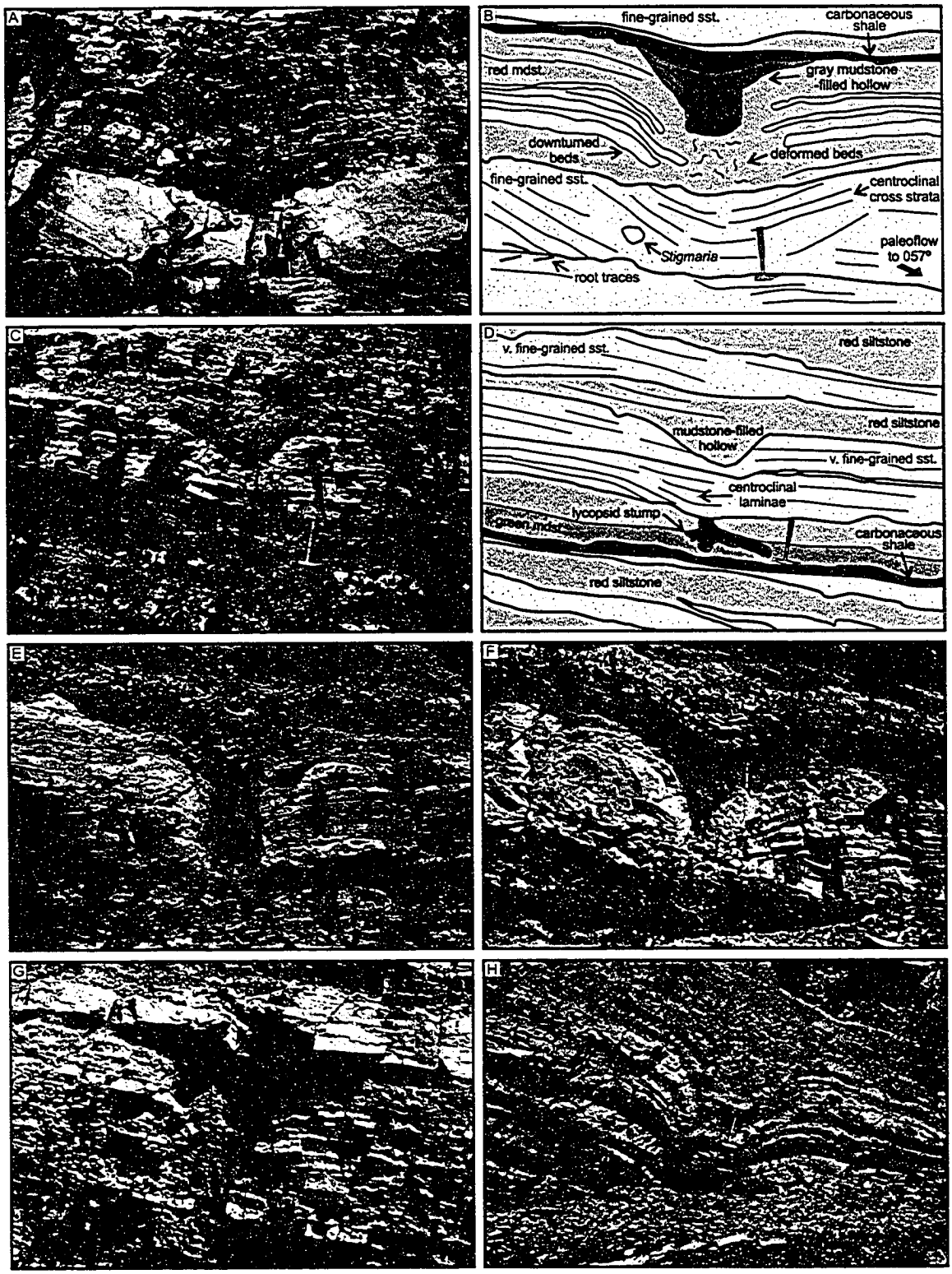
Mudstone-filled hollows are bodies of dark grey to red, massive mudstone against which beds of downturned strata commonly terminate (Fig. 37). The hollow fills range from 0.40 to 0.86 m thick, 0.28 to 0.39 m wide and commonly have a width-to-thickness ratio of unity or less. The example shown in Figures 37A and B are closely associated with downturned beds and centroclinal cross-strata. This presumably columnar body of grey mudstone rests atop 0.40 m of deformed bedding and a 0.54 m thick centroclinal cross-set (below which lies a stigmarian root). Laterally, flat-lying sheet sandstones begin to turn down 1.4 m from the hollow fill, dip at 20° and terminate against the fill. In cross-section, this example has steeply dipping margins, which suggests that the precursor depression had a pothole-like form.

Figures 37C and D show a shallow, asymmetric mudstone-filled hollow. Red siltstone 0.28 m thick fills the hollow, which is developed in very fine-grained sandstone. The sandstone entombs a small lycopsid and contains centroclinal laminae. Figures 37E-H show additional examples of mudstone-filled hollows and downturned beds; no preserved plant material was noted, but rooted horizons occur below the structures.

4.7.1.2. Interpretation

Mudstone-filled hollows and downturned beds are inferred to have formed through decay of an entombed plant. They reflect a prominent component of soft-

Figure 37: Decay-related sedimentary structures in WDF strata in the upper Joggins Formation; hammer is 0.32 m long. A, B) Gray mudstone-filled hollow and downturned bedding above centroclinal cross-strata and a stigmarian root. These decay-related structures probably formed as sediment infilled the void created by collapse and decay of the trunk. C, D) Asymmetric mudstone-filled hollow above centroclinal laminae and a lycopsid trunk. This structure is interpreted as the product of scour during unidirectional flow, followed by trunk decay and mud deposition. E-H) Mudstone-filled hollows and downturned beds. Although these features do not contain organic material, they both occur above rooted horizons and have a morphology which suggests that they formed in association with standing lycopsids. Exposed strata in (G) are approximately 2 m thick, see Gibling (1987) for preliminary discussion of (F).


A
B
fine-grained sst.
carbonaceous shale
red mdst.
gray mudstone -filled hollow
downturned beds
deformed beds
fine-grained sst.
centroclinal cross strata
Stigmaria
paleoflow to 057°
root traces
C
D
v. fine-grained sst.
red siltstone
mudstone-filled hollow
red siltstone
v. fine-grained sst.
centroclinal laminae
lycopsid stump
green mdst.
carbonaceous shale
red siltstone
E
F
G
H

sediment deformation in overlying and adjacent strata, but may also in part represent hydrodynamic activity around a plant that was not preserved. Mudstone-filled hollows differ from stump casts in the absence of preserved plant stems, and the mud was mainly deposited after the plant decayed. The fills only roughly approximate the shape of the plant, although the very low width:thickness ratio (< 1 in some cases) suggests that the decay cavity had preserved some of its original form. The symmetrical, presumably columnar, form of most mudstone-filled hollows distinguishes them from cradle knolls, which are strongly asymmetric hollows with mounds of sediment adjacent to the steepest side (Johnson *et al.*, 1987). Decay-related features may be restricted to the WDF because oxidizing conditions favored the rapid decomposition of the obstacle-forming plants and/or because sedimentation rates were lower than in the PDF wetlands. Formation of the hollow and downturned beds depicted in Figures 37A and B probably began when the stigmarian roots of a lycopsid were buried and smothered during one or more flood events. Decay of buried stigmarian roots and trunk may have caused localized subsidence and downwarping of adjacent beds. Eventually, grey mud filled the depression created by collapse of the trunk.

The hollow shown in Figures 37C and D formed by hydrodynamic processes but was affected by decay when the lycopsid decomposed before infilling. The lycopsid was partially entombed by red siltstone and two discrete sandstone packages. Centroclinal cross-strata in the lower package show that the tree influenced local flow and sedimentation. The asymmetric, mudstone-filled scour formed when unidirectional flow carved a more steeply dipping depression on the upflow side of the tree. The scour was not filled with sand because the flow did not transport coarse sediment or because flow

velocity decreased rapidly after scouring. The nucleating plant later decayed, and the hole was filled with mud during subsequent flood events. Unlike a cradle knoll, this asymmetric hollow developed around a standing tree.

Deciphering the origin of these features is relatively straightforward where portions of the obstacle-forming plant are still present, but disentangling the exact origin of other examples is more difficult. Although none of the examples in Figures 37E-H contain plant material, they closely resemble more obvious decay-related structures.

## 4.8. Discussion

### 4.8.1. Recognition of VISS

This study provides the first comprehensive sedimentological analysis of ancient sedimentary structures formed from the interaction of vascular plants and alluvial sediment. Since the advent and proliferation of terrestrial forests in the Devonian (Beerbower, 1985; DiMichele and Hook, 1992), vegetation has exerted a profound influence on clastic depositional systems by localizing erosion and actively trapping sediment. Despite their abundance in modern settings, descriptions of VISS in the rock record are surprisingly rare. As was discovered during field study, it is easy to misidentify VISS as purely hydrodynamic features. In the absence of the nucleating plant, the key to their recognition lies in their internal architecture, external form and relationships to nearby strata (Table 5).

The five types of VISS formed by hydrodynamic processes represent points in the continuum between erosive and aggradational flow conditions (Fig. 25). Decay-related structures add an additional level of complexity. Without particularly well-exposed

| Type of VISS | Distinctive Characteristics | Similar Structures |
|---|---|---|
| All VISS | closely associated with *in situ* plants (standing trunks and large roots); proximity to zones of intense penetration by small roots, concretions around roots and trunks, paleosols, or detached plant remains; internal stratification commonly disrupted by root action | many possibilities |
| centroclinal cross-strata | elliptical in planform, not linear like channel bodies; fill typically concentric and form-concordant; rarely uniclinal | small channel bodies; trough cross-sets; infilled scours formed by whirlpools or eddies (Dorr and Kauffman, 1963) |
| Scratch circles and semi-circles | grooves have variable dimensions, "fretting" caused by irregular motion of plant parts (Allen, 1982); grooves form disconnected arcs (Bromley, 1990); concentric traces within the circle; some have plant remains at the axis of rotation (Metz, 1991, 1999) | spiral burrows of *Paraonis fulgens*, *Spirorhaphe* and *Nereites* (Pemberton *et al.*, 1992); circular tool marks (Rigby, 1959) |
| upturned beds (vegetation shadows) | thin beds locally upturned adjacent to plants; not associated with soft-sediment deformation; mound adjacent to *in situ* plant (if bedding plane exposure) | soft-sediment deformation structures; sediment shadows formed behind other structures; foreset bars |
| coalesced scour fills | discrete centroclinal cross-sets; elongate and tapering in a downflow direction | small channel bodies |
| scour-and-mound beds | poorly stratified; laterally continuous for several tens of meters; some have discrete centroclinal cross-sets and upturned beds; in contrast, bedforms are commonly cross-stratified, plane-bedded with current lineation, or show internal truncations and associated wave-formed structures (hummocky cross-stratification) | foreset bars; bedforms associated with dune-plane bed transitions; hummocky cross-stratification |
| mudstone-filled hollows and downturned beds | deformation localized in narrow intervals because of decay of the plant; are not part of deformed sheets; commonly associated with other types of VISS; deformed material similar to or connected to the surrounding sediment; beds above and below are horizontal; mudstone-filled hollows are similar to casts, but no organic material is preserved and the hollow may only roughly approximate the shape of the stump; smaller than most abandoned channel fills; symmetrical, columnar (?) form and occasional association distinguishes them from cradle knolls | soft-sediment deformation structures (Obermeier *et al.*, 1990); poorly preserved stump casts (Mossa and Schumacher, 1993); abandoned channels; cradle knolls; loading fractures (Tipper *et al.*, 2003) |

Table 5: Distinctive characteristics of VISS from the Joggins Formation.

examples, unraveling the origin and relationship of these structures (particularly where the obstacle-forming plant was not preserved) would have been difficult. Continued study of ancient VISS will probably reveal many variations in the basic morphologies described here.

Centroclinal cross-strata, vegetation shadows and scratch circles have been documented in many modern areas (Table 4). Modern equivalents for the other ancient structures described here may be difficult to identify because of limited cross-sectional and three-dimensional exposure, absence of compactional and diagenetic enhancement and incomplete destruction of the obstacle-forming plant (important for decay-related structures). Coalesced scour fills could form along anastomosed channels in central Australia, where coalesced scours around dryland trees grow large enough to form new channels (Gibling *et al.*, 1998). They could also form within the sandy bed of the Burdekin River in Australia, where linear groves of trees cause both scours and sediment shadows (Fielding and Alexander, 1996; Fielding *et al.*, 1997; Nakayama *et al.*, 2002). Any forested floodplain, especially where extensive sandy layers were deposited under poorly drained conditions, could contain scour-and-mound beds, but these large structures would be difficult to recognize without cross-sectional exposure. Mudstone-filled hollows and downturned beds could form in oxidizing environments where standing trees are prone to rapid entombment and decay, such as Pliocene-Pleistocene *Pinus* (pine) forests in Louisiana (Mossa and Schumacher, 1993) or modern *Fraxinus* (ash) and *Sequoia* (redwood) forests near Washington, DC (Sigafoos, 1964) and California (Stone and Vasey, 1968), respectively.

### 4.8.2. Indicators of early forests

The spatial and temporal distribution of VISS in the geological record is controlled by the paleogeographic and paleoenvironmental distribution of land plants. Although vascular plants evolved in the Silurian (Wellman and Gray, 2001), the features described here are among the world's oldest known VISS. With a descriptive framework in place, it is likely that similar features will be identified in increasingly older strata. Preliminary reports indicate that VISS are present in Mississippian strata in Atlantic Canada (Gingras, 2002; Melrose and Gibling, 2003), but a search of literature on older plant occurrences has not revealed any detailed descriptions of pre-Pennsylvanian VISS. Although early vascular plants consisted of small, herbaceous forms until the Middle Devonian (Goldring, 1927; Gensel and Andrews, 1984), structures developed around individual calamite stems in the Joggins Formation suggest that stems only a few centimeters in diameter can interact with flow to generate VISS. Additionally, the development of modern vegetation shadows behind grass tufts shows that even small, delicate plants can interact with transported sediment in certain situations. Recognition of VISS in early Paleozoic strata could provide insight into the distribution of early land plants (both vascular plants and bryophytes), especially in oxidizing environments where organic material was not preserved (Figs. 28C and D, and 37).

All the VISS described in this study formed around floodplain plants at least several meters from the nearest channel. Despite their apparently restricted paleogeomorphic range, it is likely that similar structures occur in a wider range of settings, including disturbance-adapted riparian communities, upland areas and within channels (Fielding and Alexander, 2001). This wider distribution is increasingly likely in

strata younger than the Joggins Formation because late Paleozoic and Mesozoic evolutionary advances allowed plants to flourish in more difficult terrestrial niches (Behrensmeyer *et al.*, 1992).

### 4.8.3. Vegetation type

Although the diameter of the obstacle-forming plants ranged from 0.03 to 0.54 m, all the plant taxa described in this study generated broadly the same types of hydrodynamic structures (Fig. 29). Decay-related structures were described only in association with lycopsids, perhaps because collapse of smaller calamite stems did not create noticeable bedding anomalies as a result of their rapid and complete burial under the aggradational conditions to which they were tolerant. VISS formed by hydrodynamic processes were noted only where plants were at least partially entombed by sandy sediment, although plants may have been entombed entirely by muddy sediment in areas distal to channels. Decay-related structures occur in both sandstone- and mudstone-dominated sediments, but are most obvious where these lithologies are interbedded.

### 4.8.4. Abundance and volumetric significance

VISS represent significant localizations of sand within the Joggins Formation. Assuming that centroclinal cross-strata fill a hemispherical scour, individual lycopsid-nucleated fills at Joggins contain between 0.3 and 7.2 $m^3$ of sandstone. Coalesced scour fills also represent significant amounts of sand (up to 25 $m^3$).

Interaction between alluvial sediment and standing vegetation may be of profound importance in some depositional systems. VISS are one of the most conspicuous and abundant sedimentary structures in the Joggins Formation; if the 603 m measured section were remeasured to intersect horizons where VISS are at their maximum thickness, a

44.5 m aggregate thickness (7.4% of the total stratal thickness) is dominated by VISS (Fig. 27). Although these structures form in both well drained and poorly drained settings, they are most abundant in the PDF association where they constitute the most prominent suite of sedimentary structures. Rapid relative subsidence rates during Joggins Formation deposition probably contributed to the high preservation potential of VISS, but the occurrence of similar structures in the Sydney Mines Formation shows that preservation is also possible under much lower, cratonic subsidence rates (Gibling *et al.*, 2004). As with most sedimentary structures, the creation and preservation of VISS is a short-term ("geologically instantaneous") phenomenon.

## 4.9. CONCLUSIONS

This study identifies a group of distinctive sedimentary features in the geological record that represent the interaction of in situ vascular plants with the sedimentary environment. These "vegetation-induced sedimentary structures" record hydrodynamic (centroclinal cross-strata, scratch circles, upturned beds, coalesced scour fills, scour-and-mound beds) and decay-related (mudstone-filled hollows, downturned beds) processes. Although coastal exposures of the Pennsylvanian Joggins Formation provide excellent two-dimensional views of VISS, bedding-plane exposures are rare, and descriptions from other areas may provide a stronger understanding of the full three-dimensional form of these features, possibly leading to the identification of new types.

The paucity of descriptions of VISS in the rock record suggests that these features may have been overlooked or misinterpreted as purely hydrodynamic features such as small channels, fluvial bars, convex-up bedforms and "traditional" soft-sediment deformation structures. VISS are prominent in about 7.4% of the total strata of the lower

603 m of the Joggins Formation, and are ubiquitous in both poorly and well-drained floodplain sediments. Additionally, these structures represent significant localizations of sand (25 $m^3$) and can have cross-sectional areas (up to 2.1 m thick and 3.6 m wide) comparable to those of small channel bodies.

Identification of VISS in early Paleozoic strata could provide important insight into the impact and distribution of plants during the initial stages of terrestrial colonization, particularly in oxidizing environments where organic material was not preserved. Although many early vascular plants were relatively small, Joggins examples suggest that plant stems only a few centimeters in diameter can interact with flow to generate VISS. In modern environments, vegetation shadows behind grass tufts show that even small, delicate plants can interact with transported sediment. Recognition of VISS can increase understanding about early vegetative colonization of the terrestrial realm, an event that profoundly impacted landscape stabilization, channel planform, mud storage in floodplains, carbon sequestration and atmospheric composition (Algeo *et al.*, 1995).

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# CHAPTER 5: TOURNAISIAN FORESTED WETLANDS IN THE HORTON GROUP OF ATLANTIC CANADA

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## 5.1. ABSTRACT

The Horton Group (late Famennian to Tournaisian) of Atlantic Canada provides an unusually complete record of Early Mississippian wetland biota. Best known for its tetrapod fossils, this unit also contains numerous horizons with standing vegetation. The taphonomy and taxonomy of Horton Group fossil forests has remained enigmatic due to poor preservation, curious stump cast morphology, and failure to recognize the unusual sedimentary structures formed around standing plants.

Four forested horizons within the Horton Group are preserved as cryptic casts and vegetation-induced sedimentary structures formed by the interaction of detrital sediment with *in situ* plants. *Protostigmaria*, the lobed base of the arborescent lycopsid *Lepidodendropsis*, occur as sandstone-filled casts attached to dense root masses. Mudstone-filled hollows formed when a partially entombed plant decayed, leaving a void that was later infilled by muddy sediment. A scratch semi-circle formed where a current bent a small plant, causing it to inscribe concentric grooves into the adjacent muddy substrate. Obstacle marks developed where floodwaters excavated erosional scours into sandy sediment surrounding juvenile *Lepidodendropsis*. These cryptic lycopsid forests had considerably higher tree densities than their Pennsylvanian counterparts.

Vegetation-induced sedimentary structures are abundant in Horton Group strata and could easily be misidentified as purely hydrodynamic or soft-sediment deformation structures without careful analysis. Recognition of these structures in Early Paleozoic

strata has great potential to expand our knowledge about the distribution of early land plants.

## 5.2. INTRODUCTION

Home to dense lycopsid forests and diverse tetrapod communities, Tournaisian wetlands were the predecessors of the "coal swamp" ecosystem that dominated tropical Euramerica throughout the Pennsylvanian (Scheckler, 1985; Ahlberg and Milner, 1994). Following the demise of *Leptophloeum* and *Archaeopteris* forests in the latest Devonian, forested tracts continued to expand into wetland and dryland areas during the Early Mississippian (Scott *et al.*, 1984; Scheckler, 1986, 1986; Falcon-Lang, 2000). During this time, animals were rapidly diversifying to fill the multitude of available niches in the terrestrial realm. The paucity of Early Mississippian wetland deposits has limited our knowledge of terrestrial ecosystems during this formative stage (Raymond *et al.*, 1985), and is largely responsible for "Romer's Gap", a 20-million-year hiatus in the fossil record of early tetrapods (Coates and Clack, 1995; Carroll, 2002; Clack, 2002).

Evolution of the arborescent habit in the Middle Devonian resulted in the preservation of numerous Late Paleozoic "fossil forest" horizons (Scott and Calder, 1994). Although Tournaisian plant-bearing localities occur worldwide (Scott *et al.*, 1984; Scott and Rex, 1987; DiMichele and Hook, 1992), this paper provides one of the first detailed descriptions of *in situ* Tournaisian wetlands. Tetrapod footprints and vertebrate skeletons from the Horton Group of Atlantic Canada (late Famennian to Tournaisian) are well known (Carroll *et al.*, 1972; Sarjeant and Mossman, 1978, 1978), but *in situ* vegetation remains poorly described despite several decades of study (Bell, 1960; Carter and Pickerill, 1985; Martel and Gibling, 1991).

In the present paper we provide a review of the Horton Group biota and place this information in a modern paleoecological context. Our description of cryptic stump casts and sedimentary structures formed around standing plants provides valuable information about the paleoecology and dynamics of these wetland ecosystems.

## 5.3. Geological setting of the Horton Group

The Horton Group comprises 600 to 3,200 m of Late Devonian-Mississippian strata that were deposited across much of the Maritimes Basin of Atlantic Canada (van de Poll *et al.*, 1995). Late Paleozoic sedimentation in this area began when post-Acadian extension and granite intrusion initiated a period of half-graben development from New Brunswick to southern Newfoundland (Marillier *et al.*, 1989; Piper, 1994). The resulting depocenters are considered "basins" in their own right and together form the regional Maritimes Basin. The Devonian history of these basins is recorded in the organic-rich deposits of the Murphy Brook and McAdams Lake Formations and the continental rift facies of the Fountain Lake Group (Calder, 1998). Overlying clastics of the Horton Group (Late Devonian to Tournaisian) generally exhibit a tripartite stratigraphy of fine-grained "lacustrine" deposits over- and underlain by coarse-grained alluvial deposits (Hamblin and Rust, 1989).

The Tournaisian forests described in this paper lie within the Horton Bluff Formation of Nova Scotia and the Albert Formation of New Brunswick (Fig. 38). These formations represent the fine-grained portion of the Horton Group in the Windsor (Nova Scotia) and Moncton (New Brunswick) Basins, respectively. During deposition of

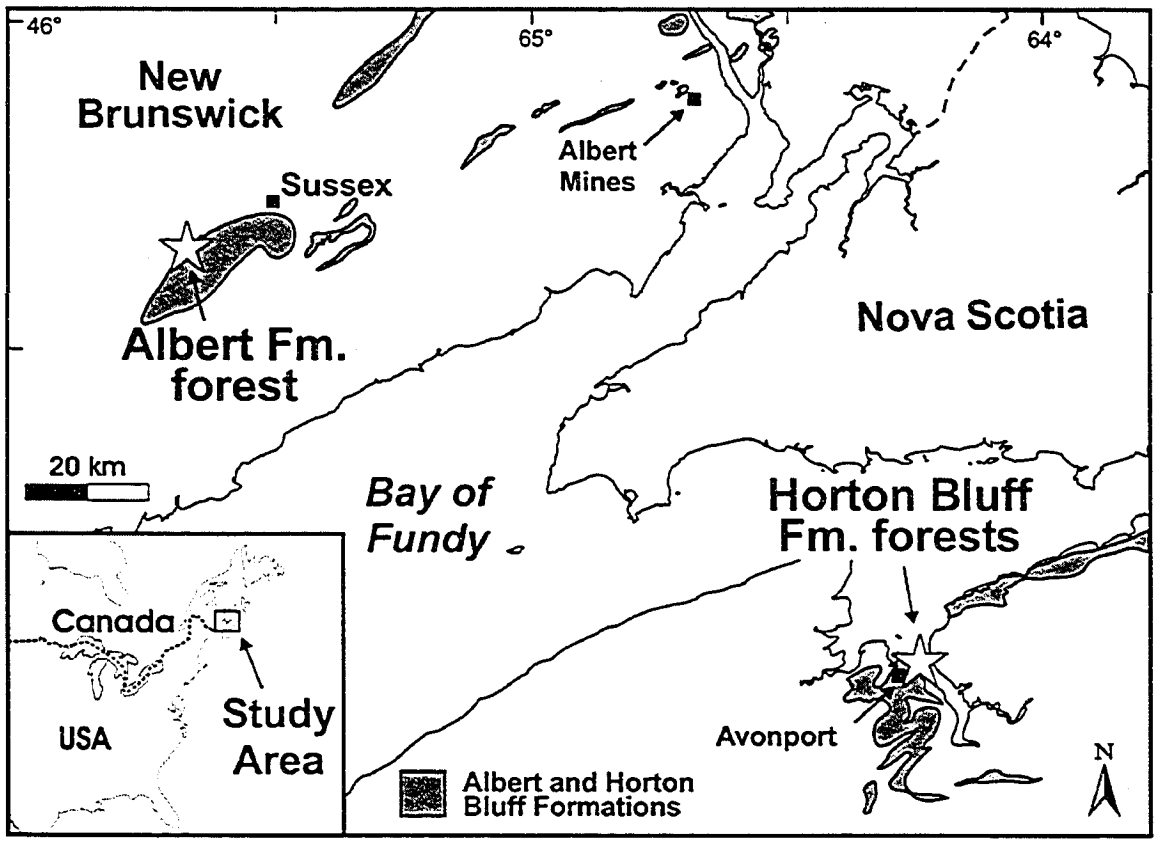



Figure 38: Location map showing the distribution of the Horton Bluff and Albert Formations (after Macauley and Ball, 1982; St. Peter *et al.*, 1997; Keppie, 2000). Stars denote study areas near Avonport, Nova Scotia and Sussex, New Brunswick.

the Horton Group, the Maritimes Basin was at ~12° South, in the heart of southern Euramerica's tropical dry belt (Van der Zwan, 1981).

### 5.3.1. Horton Bluff Formation

The late Famennian to late Tournaisian Horton Bluff Formation is subdivided into the Harding Brook, Curry Brook, Blue Beach, and Hurd Creek Members (Fig. 39). Three forested intervals within the Hurd Creek Member were studied at the Blue Beach North locality, near Avonport, Nova Scotia (Calder *et al.*, 1998). This youngest member of the Horton Bluff Formation contains spores of late Tournaisian (Ivorian) age (Utting *et al.*, 1989; Martel and Gibling, 1996).

Strata of the Hurd Creek and underlying Blue Beach members are organized into well developed, shallowing-upward cycles (Martel and Gibling, 1991). Cycle bases consist of laminated grey shale (low-energy, offshore deposits), that passes up into shale with interbedded hummocky and wave-rippled sandstone (wave-influenced nearshore deposits). The cycles are capped by green rooted mudstone with nodular and stratified dolomite ("marsh" deposits).

Cycle architecture, sedimentology, and fossil assemblages are similar in the two members, but the relative proportion of terrestrial ("marsh" and sandstone-dominated) facies increases in Hurd Creek cycles (Martel and Gibling, 1991). The gradational contact between these members is marked by an increase in sandstone proportion and decrease in ostracod abundance (Martel and Gibling, 1996).

Strata of the Horton Bluff Formation were interpreted as strictly freshwater (Martel and Gibling, 1991) until the discovery of brackish-marine ostracods and agglutinated foraminifera by Tibert and Scott (1999). Tibert and Scott (1999) concluded

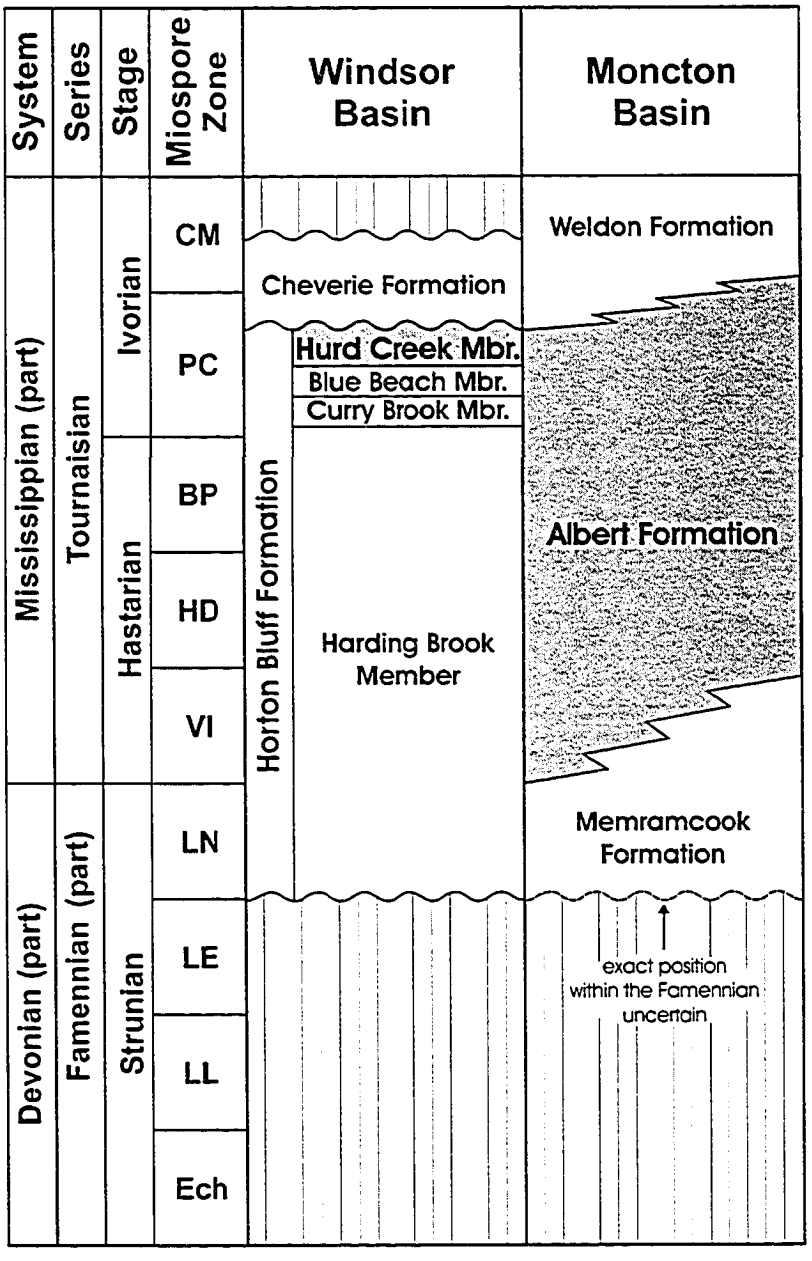



Figure 39: Stratigraphy of the Horton Group in the Windsor Basin of Nova Scotia and the Moncton Basin of New Brunswick (after Carr, 1968; Utting, 1987; Utting *et al.*, 1989; Martel *et al.*, 1993; St. Peter, 1993).

their study at cycle 20 of the Hurd Creek Member, which constitutes the top of the section in their study area (Blue Beach South). A detailed micropaleontological study would be necessary to verify the presence of marine indicators in every cycle at every location but, in general, terrestrial strata represent "wetlands" (see Section 5.5) bordering a body of water that was, at times, marine influenced.

### 5.3.2. Albert Formation

This study also considers a forested horizon in the Albert Formation in central New Brunswick (Fig. 38). This and other outcrops of the Albert Formation in the Sussex area are best viewed along Provincial Highway 1 between kilometer markers 168 and 180.

The Albert Formation constitutes the medial shale-dominated interval in the Horton Group of the Moncton Basin (Fig. 39; St. Peter, 1993; Keighley, 2000). It has been divided into three members in the type area near Albert Mines (Greiner, 1962; Carter and Pickerill, 1985), but this scheme is of limited utility because it oversimplifies the varied and intertonguing lithofacies that comprise the formation (St. Peter, 1993). Outcrops north of Albert Mines bear spores of late Hastarian to early Ivorian age (Utting, 1987), but samples from other locations in the basin suggest an early Hastarian to Ivorian age (St. Peter, 1993). Outcrops of the Albert Formation near Sussex exhibit paleontological and sedimentological similarities to those of the type area and are generally regarded as equivalent (Pickerill, 1992; Miller and McGovern, 1996).

Outcrop and core data from the Albert Formation typically indicate non-marine deposition (Pickerill, 1992). Strata of the Albert Formation were deposited within a fault-bounded valley and represent a collage of sedimentary environments including lakes, fan

deltas, alluvial fans, and fluvial systems (van de Poll, 1978; Keighley, 2000; Gingras, 2002).

## 5.4. Previous studies of biota

### 5.4.1. Floral record

The pioneering study of W.A. Bell (1960) remains the only comprehensive paleobotanical study of the Horton Group. Following Bell (1960), flora from all subdivisions of the Horton Group are discussed to give a complete overview (Table 6) of the plants that may have inhabited the Tournaisian forests described herein.

Compressions of the arborescent lycopsid *Lepidodendropsis* are by far the most abundant plant fossil in the Horton Group (Fig. 40A). These compressions exhibit false leaf scars arranged in pseudowhorls and may be found with the presumed cones (*Lepidostrobophyllum* sp.) and megaspores (*Triletes* sp.) of the plant (Bell, 1960). Bell (1960) noted the presence of a poorly preserved stem that he tentatively classified as *Lepidodendron*, but this is the only specimen (out of thousands) reported from the Horton Group and we therefore question its identification. The absence of lepidodendrids (lycopsids with stigmarian rhizomorphs) is supported by Bell's (1929) observation that, although slender roots resembling those connected to stigmarian rhizomorphs are abundant, the rootstocks themselves are completely absent - an observation repeatedly confirmed over the last seventy years.

Although seemingly paradoxical at the time, Bell's (1929) observations foreshadowed the discovery that *Lepidodendropsis* was a non-lepidodendrid lycopsid whose roots attached directly to *Protostigmaria*, the corm-like base of the trunk

| Class | Order | Genus and Species | Type of Fossil | Relevant Occurrences |
|---|---|---|---|---|
| **Lycopsida** | Isoetales (lycopsids with corm-like bases) | *Lepidodendropsis corrugatum* | bark | Albert and Horton Bluff Formations |
| | | *Lepidodendropsis* sp. | bark | Horton Bluff Formation |
| | | *Protostigmaria* sp. | trunk base | Horton Bluff Formation |
| | | *Lepidophyllum* (*Lepidostrobophyllum*) *fibriatum* | cone | Horton Bluff Formation |
| | | *Lepidostrobophyllum* sp. | cone | Albert Formation |
| | | *Triletes glaber* | large megaspore | Horton Bluff Formation |
| | | *Triletes cheveriensis* | small megaspore | Albert and Cheverie Formations |
| | Lepidodendrales (lycopsids with stigmarian rootstocks) | ?*Lepidodendron* sp. | bark | Horton Bluff Formation |
| **Sphenopsida** | Equisetales (horsetails and their relatives) | *Asterocalamites* (=*Archaeocalamites*) *scrobiculatus* | stem | Horton Bluff Formation |
| | | *Nematophyllum* sp. (*incertae sedis*) | stem | Kennebecasis Formation (Albert Formation equivalent) |
| **Filicopsida** | Filicales ("true ferns") | *Adiantites tenuifolius* | foliage | Cheverie Formation (overlies the Horton Bluff Formation) |
| **Gymnospermopsida** | Pteridospermales (seed ferns) | *Aneimites acadica* | foliage | Albert and Horton Bluff Formations |
| | | *Sphenopteridium macconochiei*? | foliage | Albert Formation |
| | | *Sphenopteridium* sp. | foliage | Cheverie Formation |
| | | *Sphenopteris strigosa* | foliage | Cheverie Formation |
| | | *Triphyllopteris minor* | foliage | Cheverie Formation |
| | | *Triphyllopteris virginiana* | foliage | Horton Group (undifferentiated) |
| | | *Diplotmema patentissimum* | foliage | Albert and Horton Bluff Formations |
| | | *indeterminate* | stem | Horton Bluff Formation |
| | *Incertae sedis* | *Carpolithus tenellus* | seed | Horton Bluff and Albert Formations |

Table 6: Fossil flora of the Horton Group, Atlantic Canada (modified from Calder, 1998).

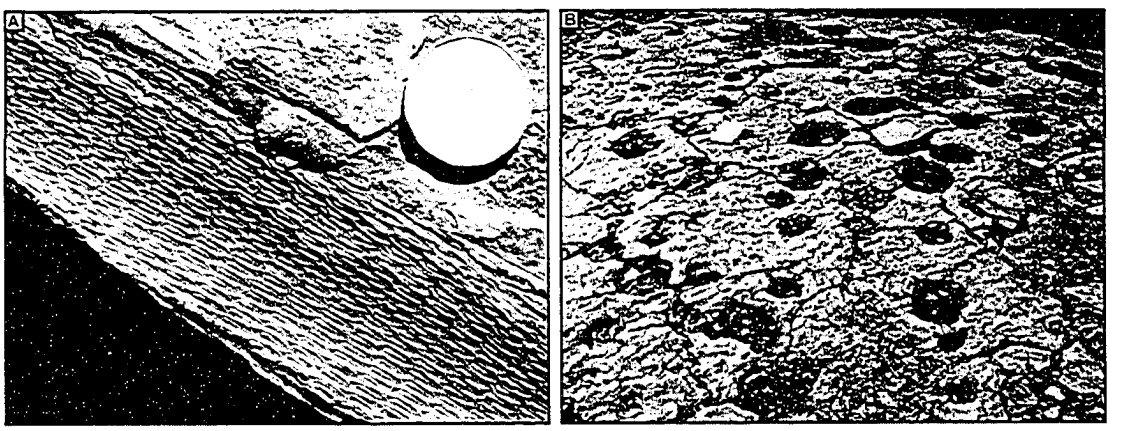



Figure 40: Common floral occurrences in the Horton Bluff Formation. A) Well-preserved compression of *Lepidodendropsis*. Coin for scale, 26 mm. B) Poorly preserved molds of *in situ* trees. Although no identifiable plant material is preserved in direct association with the molds, their size and nearby adpressions suggests that they are after *Lepidodendropsis*. Similar molds observed by Bell (1960) and Martel and Gibling (1996, their Fig. 9) were attributed to *Lepidodendropsis* and possibly *Archaeocalamites*. Book for scale, 19 cm long.

(Jennings *et al.*, 1983; Pigg, 2001; Gensel and Pigg, 2002; a corm is a short, thicknened underground stem). Following Stewart (1947) and Stewart and Rothwell (1993), we use the term "root" in reference to the hair-like, water-absorbing "true" roots of lycopsids and the term "rhizomorph" for the lobed or dichotomously branching organ to which they attach. Additionally, the absence of *Stigmaria* supports the Read and Mamay's (1964) and Scheckler's (1986) observation that although lepidodendrids appear in the middle Tournaisian in Europe, they may not have reached Appalachia until the Viséan.

*In situ* vegetation has been reported at many locations in the Horton Group, but poor preservation has limited our knowledge about the taxonomic affinity and paleoecology of these intervals (Fig. 40B). Bell (1929) noted that paleosols could be identified by their "not uncommon association with upright tree stems" and that at one horizon "120 feet by 15 feet, ninety-six such stems were counted in the basal 1 foot of a 6-foot soil bed". These stems, which reached a diameter of 30 cm, lacked stigmarian rhizomorphs and were tentatively classified as pteridosperms (Bell, 1929, p. 34). In a later memoir, Bell (1960) provided a more detailed description, changed his opinion about the affinity of the trunks, and provided insightful commentary on the probable root structure of *Lepidodendropsis*:

> Several siltstone soil zones with erect stems were noted by the writer towards the top of the middle [Blue Beach] member, but in the overlying upper [Hurd Creek] member these become numerous and highly characteristic. Commonly they stand out prominently to the eye on account of their "hackly" weathering and peculiar yellowish green coloration. ...erect stems occurring in the rootlet-bearing zones rarely

> exceed a foot in diameter, and 4 to 8 inches is most common. Generally, too, they are not more than a foot or so high. A few are marked by an external thin layer of coal, but most are arenaceous casts with no coal or surface markings. Stems were seen in some instances to have traces of rootlets directly attached to them and organisms resembling *Stigmaria* were extremely rare among the drifted plant remains. If the small stems belong to *Lepidodendropsis*, as seems probable, rather than to a pteridosperm, that genus seemingly lacked stigmarian rhizomes. (Bell, 1960)

Bell (1960) observed that one 216 $ft^2$ bedding plane had 58 stems (2.9 stems/ $m^2$) and a second 45 $ft^2$ surface had 19 stems (4.5 stems/ $m^2$). Standing vegetation figures prominently in the sedimentary model of the Horton Bluff Formation depicted by Martel and Gibling (Martel and Gibling, 1991, their Fig. 10), but they mention only that beds of green mudstone may "show moulds of roots and tree trunks with diameters up to 40 cm," and attribute the molds to *Lepidodendropsis* and/or *Archaeocalamites*. Preliminary reports of the forests documented below were presented by Gingras (2002) and Melrose and Gibling (2003). While this paper was in review, Falcon-Lang (2004) carried out and published a study of additional fossil forests in the Albert Formation near Sussex, New Brunswick.

Given the seasonally arid Tournaisian climate of the Euramerican paleotropics (Van der Zwan, 1981; Falcon-Lang, 1999), including the Maritimes Basin (Calder, 1998), low-lying, groundwater-fed (coastal?) areas may have been one of the few environments capable of supporting dense vegetation. Martel and Gibling (1991) attributed calm

conditions along the shore to wave attenuation by dense stands of *Archaeocalamites* growing in the shallow water of the nearshore (their facies 2c), which were in turn surrounded by *Lepidodendropsis* "marshes". Evidence for these wetland communities comes from the abundance of their detritus and brief descriptions of *in situ* vegetation. Accessory gymnosperm material was probably transported from somewhat drier areas where these floras thrived (Scheckler, 1985; Falcon-Lang and Scott, 2000).

### 5.4.2. Faunal record

#### 5.4.2.1. Invertebrates

From a paleoecological perspective, one of the most important discoveries within the Horton Group was the documentation of brackish/marine ostracods (*Copelandella*, *Shemonaella*, *Camishaella*, *Carbonita*, *Bairdia*, *Geisina*, and *Youngiella*) and agglutinated foraminifera (*Trochammina*) within the Blue Beach and Hurd Creek Members of the Horton Bluff Formation (Tibert and Scott, 1999). Tibert and Scott (1999) interpreted strata with paraparchitacean ostracods, glaucony grains, palaeoniscid fish, and serpulid worms as distal lagoon, low energy bay, and restricted nearshore deposits. Assemblages with carbonitacean ostracods, palaeoniscid fish, and serpulid worms were attributed to coastal ponds, and lycopsid-bearing strata with agglutinated foraminifera to "salt marshes."

The discovery of a trilobite pygidium (Order Proetida) in talus from Horton Bluff Formation provides convincing evidence of a marine connection (Weir, 2002). Although the exact stratigraphic position of the block is uncertain, it yielded Tournaisian spores (Dolby, 2003) and appears to be from a nearshore sandstone in the upper Horton Bluff Formation.

Invertebrate activity in the Horton Group is commonly recorded by the *Isopodichnus*, *Palaeophycus*, *Planolites*, *Rusophycus*, *Cruziana*, and *Lockeia* ichnogenera (Martel and Gibling, 1991; Pickerill, 1992; Wood, 1999; Weir, 2002). The wide range of depositional environments preserved within the group is mirrored by the diversity of trace fossil assemblages; previous paleoenvironmental interpretations range from fluvio-lacustrine (Pickerill, 1992) to open marine (Wood, 1999).

The most common ichnogenera of the Horton Bluff Formation (*Isopodichnus*, *Palaeophycus*, and *Planolites* (Martel and Gibling, 1991) represent various trophic-generalist behaviors. Such general and mixed ethological strategies are strongly linked to the exploitation of adverse depositional environments. This, and low trace fossil diversities coupled with high population densities, have been consistently associated with brackish-water deposits (Pemberton *et al.*, 1982). This assemblage is also similar to those described by Buatois *et al.* (2002) from Pennsylvanian strata in Kansas where a low-diversity, opportunistic, impoverished ichnofaunal assemblage comprised a mixed, depauperate *Cruziana* and *Skolithos* ichnofacies.

5.4.2.2. Fish

Scales, bones, and teeth of bony fish are ubiquitous in the Horton Bluff and Albert Formations. Scales from the palaeoniscid (ray-finned) genera *Rhadinichthys*, *Elonichthys*, and *Canobius* are particularly abundant in the Albert Formation (Lambe, 1910; Miller and McGovern, 1996). Spines from acanthodians (*Gyracanthus* and *Acanthodes)* are also present (Carroll *et al.*, 1972; Cameron *et al.*, 1992). Lobe-finned fish are represented by *Glyptolepis* scales (Martel and Gibling, 1991) as well as bones of rhizodontid crossopterygians (*Rhizodus hardingi*) and lungfish (?*Ctenodus*) (Carroll *et*

*al.*, 1972). Cartilaginous fish are represented by the elasmobranch shark *Stethacanthus* (Bell, 1929). If the preliminary report of a single dorsal plate holds to be that of an antiarch fish (Cameron *et al.*, 1992), it would represent the only known Mississippian survivor of the heavily armored placoderms.

In addition to a wide variety of sole structures (Martel and Gibling, 1994) and clastic dykes (Martel and Gibling, 1993), fish trace fossils are commonly preserved as casts on the base of nearshore sandstones. Common forms include sinusoidal trails left by fins and tails of swimming fish (ichnogenus *Undichna*) and isolated marks of fins and spines (Wood and Cameron, 1998).

5.4.2.3. Tetrapods

Until recently, amphibian bones and footprints from the Horton Bluff Formation were the only known tetrapod fossils from the Tournaisian (Milner *et al.*, 1986; Clack, 2002). Osteological remains of Devonian tetrapods are now known from the U.S., Greenland, Scotland, Latvia, Russia, and Australia (Daeschler *et al.*, 1994), but these early amphibians were predominantly aquatic forms with stout limbs and many fish-like characteristics (Milner *et al.*, 1986; DiMichele and Hook, 1992; Coates and Clack, 1995). In contrast, the Horton Bluff material suggests the presence of fully terrestrial tetrapods, including seymouriamorph anthracosaurs (Carroll *et al.*, 1972; Cameron *et al.*, 1992). Anthracosaurs are close relatives of early reptiles and their terrestrial lifestyle was underpinned by a femur structure fully adapted to dryland locomotion (Carroll *et al.*, 1972).

The Horton Bluff trackway record is exceeded in age by Devonian sites in Australia (Warren and Wakefield, 1972) and Brazil (Leonardi, 1983), but the Horton

Bluff type area is singular in its abundance of Tournaisian amphibian footprints. The most impressive and enigmatic trackway is impressed in a wave-rippled sandstone bed in the cycle underlying the lowest fossil forest in the Blue Beach North section. Provisionally ascribed by Sarjeant and Mossman (1978) to the ichnogenus *Baropezia* and inferred to be that of a large temnospondyl amphibian, the trackway runs for over 60 m and comprises footprints 10-12 cm in length. The trackway record is richer than the literature suggests and includes footprints impressed on desiccation-cracked substrates (Mansky and Wood, pers. comm.), as well as others that may have been made by swimming tetrapods (Carroll *et al.*, 1972). Included in the record are the first known Paleozoic footprints, collected in 1841 by Sir William Logan, assigned to the ichnogenus *Hylopus*, and the similar lacertoide prints *Peratodactylus bishopi* (Sarjeant and Mossman, 1978, b).

### 5.5. APPLICATION OF WETLAND TERMINOLOGY

Confusion and contradiction can arise in the use of wetland terms due to the use of similar terms in classification schemes based either on hydrologic or vegetative parameters (see Gore, 1983 for discussion). Although the term "marsh" as employed by Martel and Gibling (1991) is consistent with a non-peat forming wetland in the sense of Moore (1987), the prevalent usage of the term marsh to reflect herbaceous vegetation has the potential to be misconstrued. The term "swamp" offers less clarity still. The Horton Group forests are consistent with the vernacular usage of the term swamp in the USA, where it is commonly employed to describe a forested wetland irrespective of peat formation (e.g. the cypress swamps of the Mississippi). Gastaldo (1987) recognized this fact by differentiating "clastic swamps" from those that are peat forming. In the

hydrologically-based nomenclature advocated by Moore (1987), however, swamp refers to a rheotrophic wetland that is peat-forming (a mire). Whereas the Horton Group forests described herein are not rooted in a coaly (peat) substrate, they are not mires *per se*, and are best described as "non-peat forming, forested wetlands".

### 5.6. Evidence of forested wetlands in the Horton Group

The forested levels described here comprise cryptic stump casts less than 47 cm high that yield limited taxonomic information, giving an initial impression that vegetation provided only a modest contribution to the landscape. However, a fuller analysis showed that vegetation-induced sedimentary structures are widespread in the strata, both in association with stump casts and where little original vegetation is preserved. These primary sedimentary structures formed by the interaction of *in situ* plants with detrital sediment (Rygel *et al.*, Chapter 4). Based on analysis of features in the Pennsylvanian Joggins Formation, vegetation-induced sedimentary structures reflect three main types of process: 1) hydrodynamic processes around a plant (centroclinal cross-strata, vegetation shadows, coalesced scour fills, scour-and-mound beds, and obstacle marks); 2) passive contact between the plant and the substrate (scratch circles and semi-circles); and 3) sedimentation associated with a decaying plant (mudstone-filled hollows and downturned beds). *In situ* plants need not be preserved to positively identify vegetation-induced sedimentary structures, but a firm link to vegetation must be established to distinguish them from similar structures developed around mobile or nonvegetative obstacles. Identification of all three process types of vegetation-induced sedimentary structures in the Horton Group has greatly expanded our understanding of the nature and extent of these cryptic forested horizons.

We examined four horizons with suspected *in situ* vegetation in the Horton Group and described them using detailed sedimentological analysis (sensu Driese *et al.*, 1997). Particular attention was dedicated to description of vegetation-induced sedimentary structures (Rygel *et al.*, Chapter 4) and rooting systems (using the classification scheme of Pfefferkorn and Fuchs, 1991). Cliff exposures of the Horton Bluff Formation were described at the centimeter scale and the locations of standing vegetation were recorded on a photomosaic calibrated to a measured traverse. The Horton Bluff Formation forests described in this study are representative of the numerous other levels with poorly preserved stump casts. The forested bedding plane in the Albert Formation was divided into 1 meter grids, photographed, and the exact position of each stem and sedimentary structure was noted on a photomosaic calibrated to a measured traverse.

### 5.6.1. Stump/root casts

5.6.1.1. Description.

Twenty one stump casts were described along a 110 meter traverse in cycle 36 of the Horton Bluff Formation (Hurd Creek Member) at Blue Beach North. The *in situ* stump casts are entombed within the uppermost of three coarsening upwards packages in a 40-cm-thick mudstone (Figs. 41 and 42). This unit marks the initial phase of terrestrial deposition and overlies a *Lepidodendropsis*-bearing, nearshore sandstone (Fig. 43; Bed #8).

Preserved cast height ranges from 6 to 28 cm depending on the preservation of casting material and the relative abundance of sandstone and mudstone within (Fig. 44).

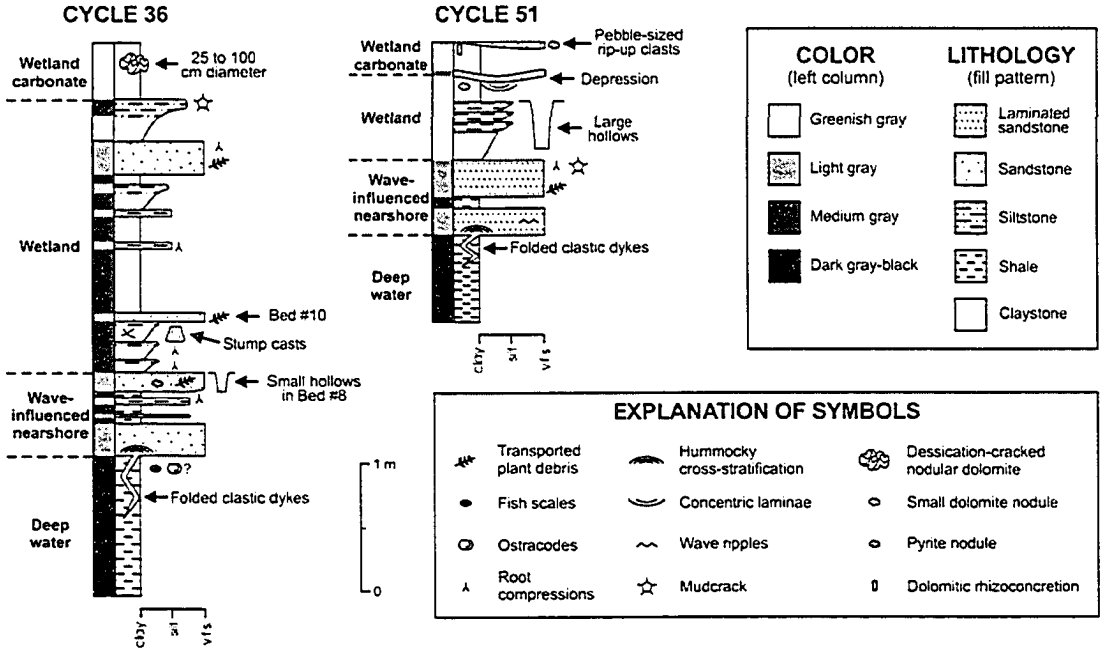



Figure 41: Sedimentological logs of cycles 36 and 51 of the Horton Bluff Formation (Hurd Creek Member) showing the location of the casts and vegetation-induced sedimentary structures. A full account of the sedimentology of the Horton Bluff Formation is given by Martel and Gibling (1996).

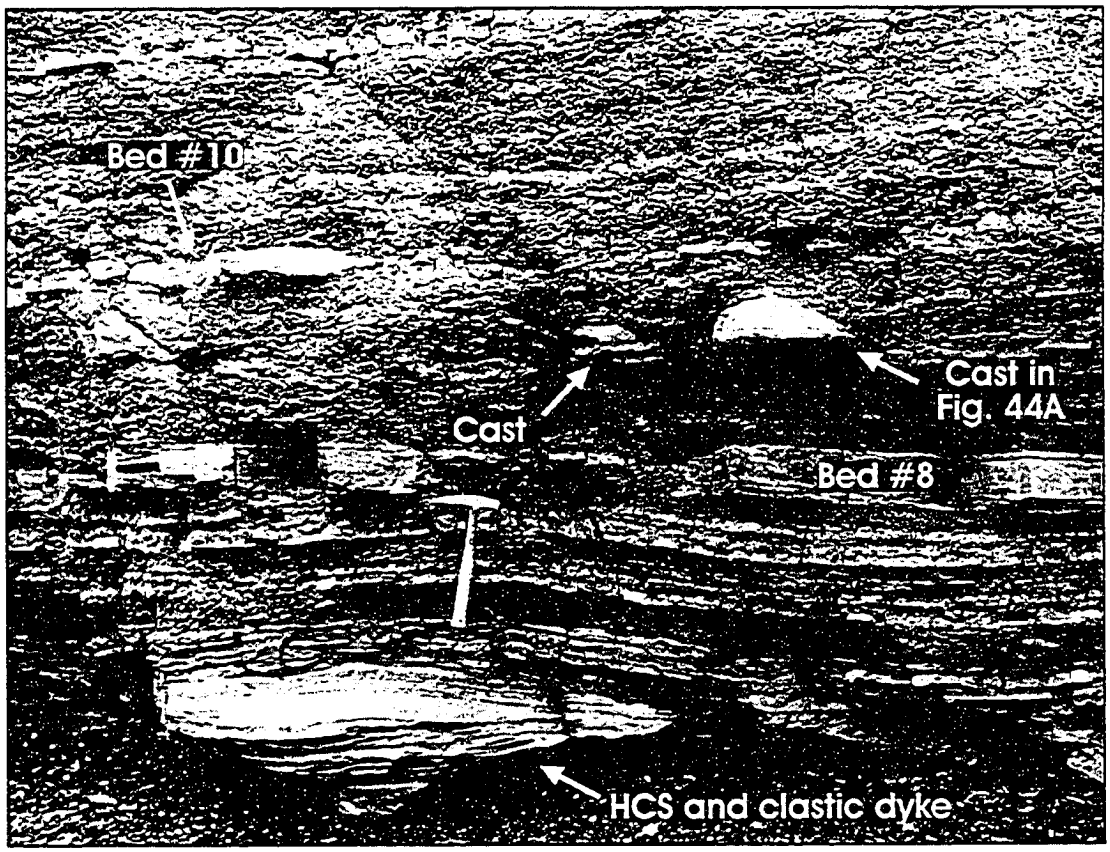



Figure 42: Photograph of nearshore and basal wetland strata in cycle 36 of the Horton Bluff Formation (Hurd Creek Member), Blue Beach North. Photograph accompanies the log in Figure 41; HCS = hummocky cross-strata. Hammer for scale, 32 cm.

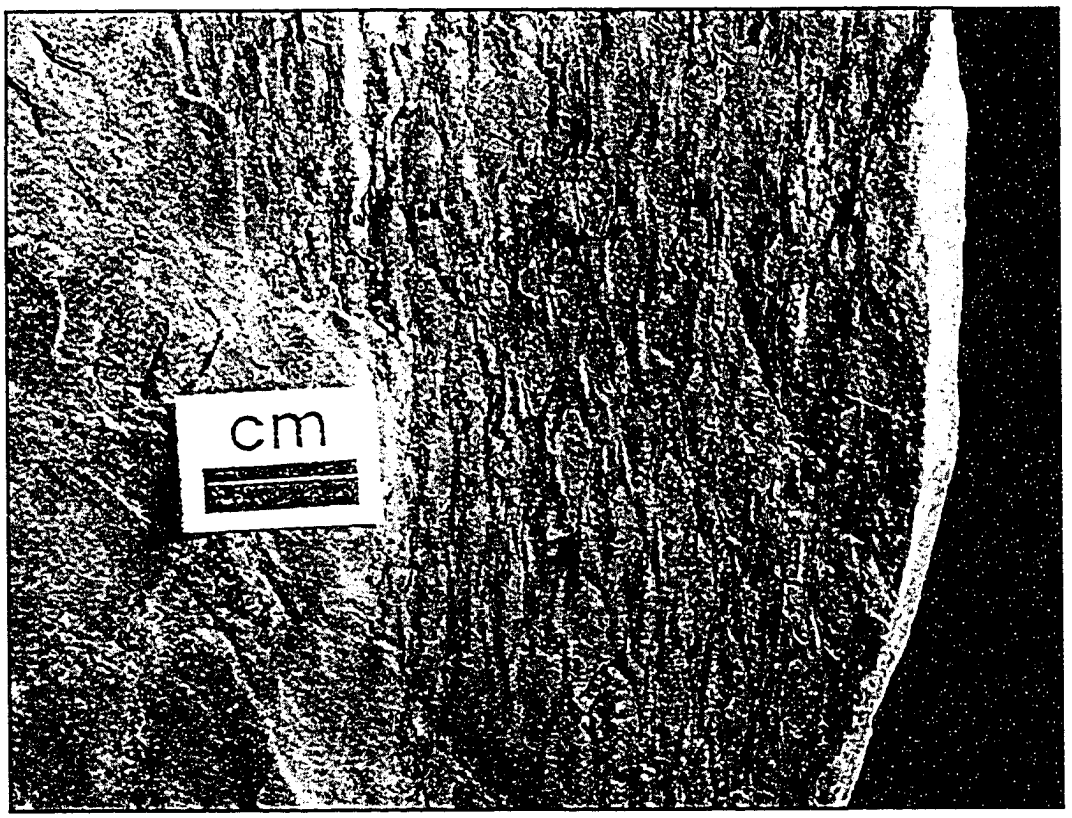



Figure 43: Poorly preserved compression of *Lepidodendropsis*? from bed 8 in cycle 36.

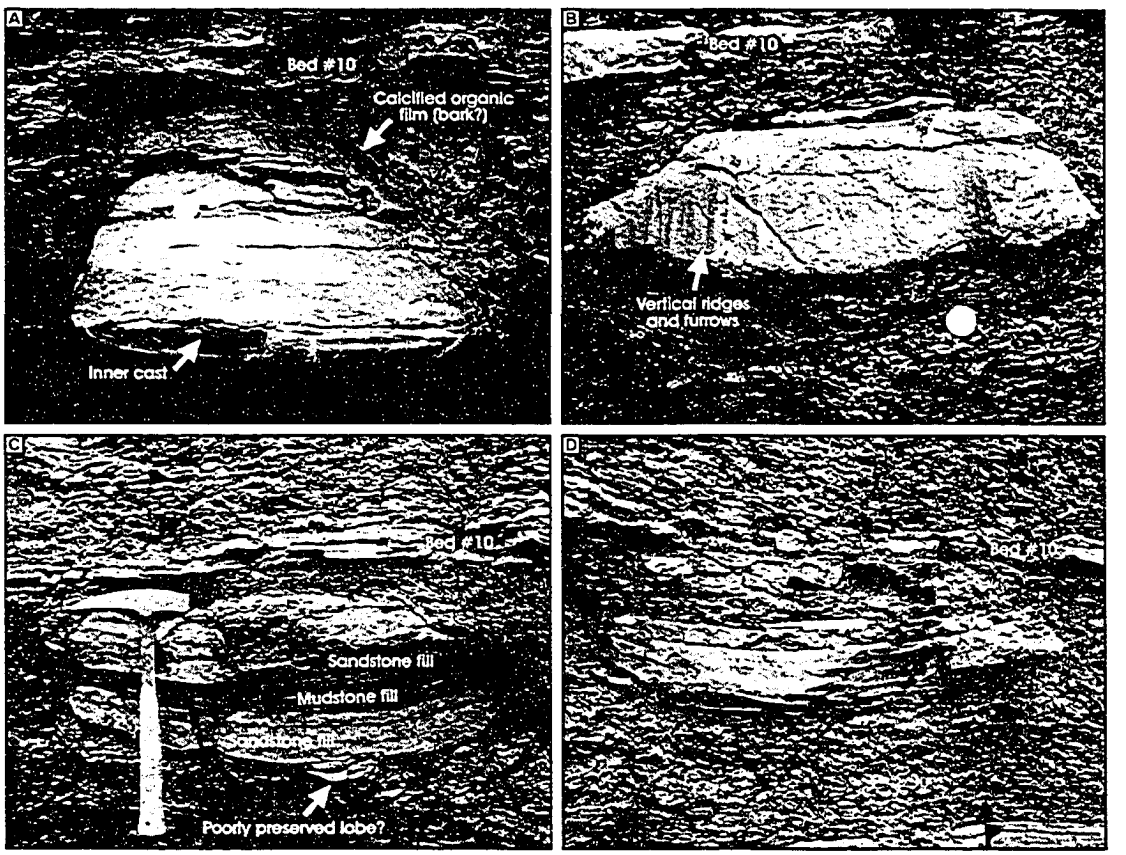



Figure 44: Variable quality casts of *Protostigmaria*, the lobed base of *Lepidodendropsis*. All casts are *in situ* and seen in cross section. A) Well-preserved cast showing how the outer surface weathers away to expose the laminated inner cast. Coin for scale, 18 mm. B) Poorly preserved cast with vertical ridges and furrows in sandstone fill. Coin for scale, 18 mm. C, D) Partially eroded casts, which crop out as cryptic, 2D forms. Hammer for scale in C, 32 cm; pen for scale in D, 14 cm.

Casts extend no higher than the overlying sandstone bed 16 to 28 cm above (Bed #10; bed thicknesses vary along the outcrop). Partial removal of the entombing mudstone reveals that casts have a columnar shape and a flared, convex-down base (Fig. 44A). The maximum (basal) cast diameter of the twenty measurable casts ranges from 16 to 109 cm, with a mean value of 50 cm. The bottom of the casts (< 5 cm) commonly flares at ~60° creating small (< 7 cm wide) "toes" in the adjacent sediment (Fig. 45). In all cases, these structures terminate within a few centimeters of the trunk and do not continue into stigmarian rhizomorphs. Many casts are too short (<28 cm) to accurately assess trunk diameter above the basal flare, but the tops of particularly well preserved specimens taper to between 53 to 89% (74% mean) of the basal width.

A partially calcified organic film coats newly exposed specimens (Fig. 44A). Subtle vertical ridges and furrows with less than 1 mm relief ornament the film and the adjacent sandstone (Fig. 44B). The mudstone encasing one specimen exhibits similar vertical features and had small pits approximately 20 cm above the base of the trunk suggestive of leaf scars. Shortly after exposure, the organic film weathers away to expose the cast fill. Internally, casts generally comprise a basal layer of very fine-grained sandstone (> 5 cm thick) overlain by varying proportions of interbedded very fine-grained sandstone and mudstone (Fig. 44C). Sandy casting material is thinly laminated, and gently onlaps or is truncated against the margin. Unless laminae in the casting mudstone are well preserved, the fill is indistinguishable from the entombing mudstone, which is invariably structureless. Laminae within the casting material are horizontal or convex down and form-concordant with the base. Casts quickly weather to form two-

Figure 45: A) Cross sectional view of *Protostigmaria* with "toe" extending into adjacent sediment. Pen for scale, 14 cm. B) Detail of "toe" showing the surrounding organic film, underlying organic-rich mudstone, and attached roots extending into the underlying sediment. Coin for scale, 19 mm.

A
Bed 10
Mudstone
Sandstone
Panel B
B
Sandstone
Organic film
Toe
Organic-rich mudstone
Roof
Compression

dimensional bodies that would be difficult to interpret without comparison with fresh examples (Figs. 44C and D).

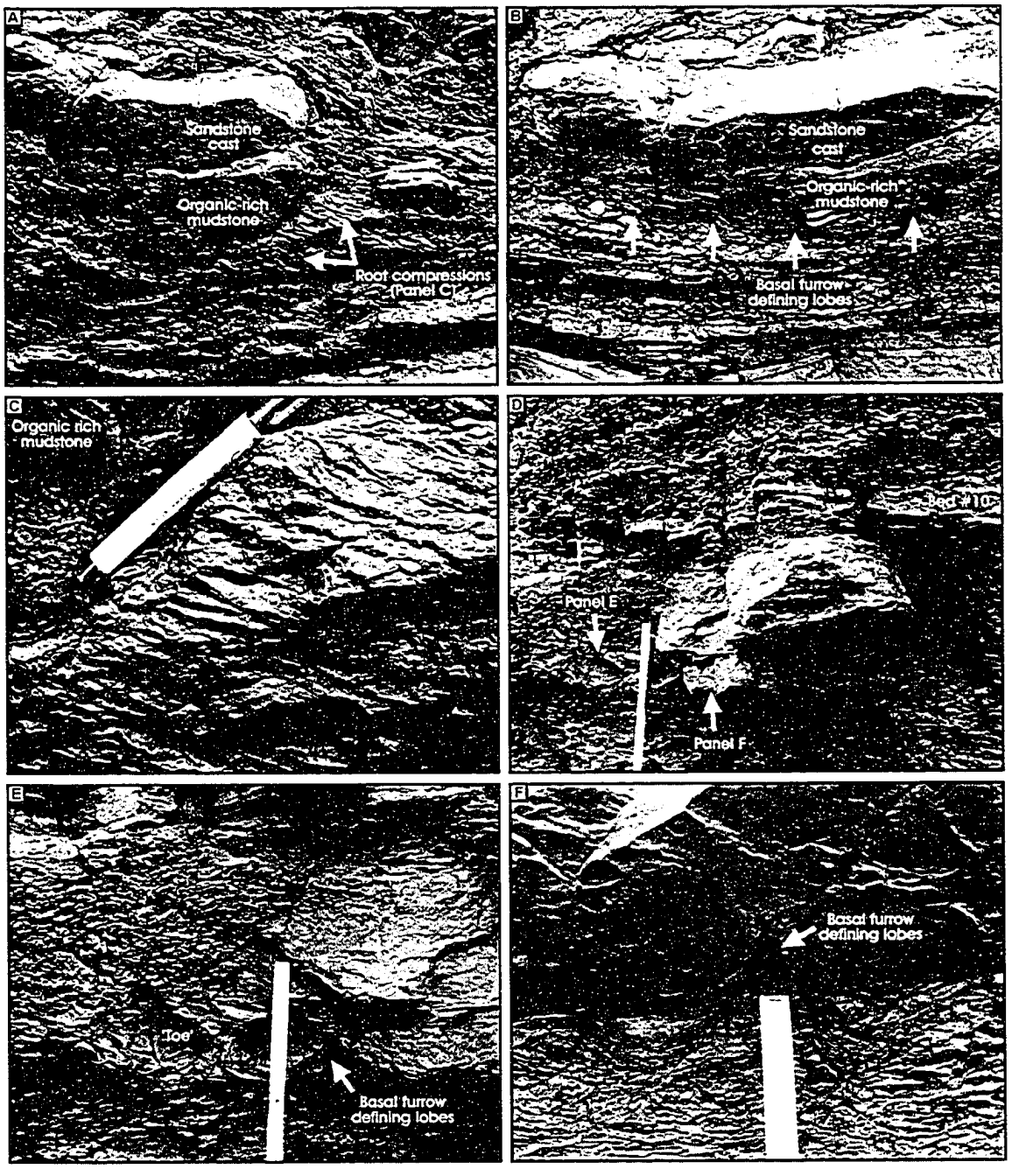
Casts and "toes" are underlain by 1 to 4 cm of organic rich mudstone which is not present in the adjacent strata (Fig. 46). Dense concentrations of slender, fibrous roots extend away from the carbonaceous shale beneath the "toes" (Figs. 46B and C). These roots exhibit a radial arrangement, penetrate downwards 20 to 40 cm into the subjacent strata, and are oriented 5° to 20° from horizontal (Type E-I/II-b rooting system). Scattered vertical roots are present to a depth of 20 cm directly below the casts. Individual roots are preserved as 3 to 8-mm-wide unbranched carbonized compressions (Fig. 46C) that occur almost exclusively in association with the casts.

Two particularly well-preserved stump casts exposed in cross section have <5 cm deep furrows which divide the basal surface of the sandstone fill and associated carbonaceous film into discrete lobes (Figs. 46B, D-F). The smaller of the two (45 cm diameter) has at least five lobes and the larger, partially eroded specimen (75 cm diameter) has at least three lobes. Poor preservation and the fissile nature of the casts/organic layer prevented fuller description of the lobed base of other specimens.

5.6.1.2. Interpretation.

Although several types of plants inhabited this area during Horton time, these casts are interpreted as the lobed protostigmarian bases of *Lepidodendropsis* because of their size (larger than *Archaeocalamites*), root and rhizomorph morphology, the ubiquity of *Lepidodendropsis* compressions throughout the over- and underlying beds, and because pteridosperms and filicopsids are infrequently preserved in this fashion (Gastaldo *et al.*, 1989). The well-known reconstruction of the original, three- to four-lobed

Figure 46: Lobed rhizomes and roots of *Protostigmaria*. A) Oblique view of the underside of *Protostigmaria* showing the relationship of the sandstone fill to the organic-rich mudstone and roots. Pen for scale in A and C, 14 cm. B) Side-view of the cast in A showing probable furrows and lobes in the organic-rich mudstone. Coin for scale, 19 mm. C) Detail of root compressions shown in A. D) Large, partially eroded *Protostigmaria* with well-developed toe and basal furrows. The furrow shown in F is not visible from this angle, but its position is shown. Ruler for scale in D-F, 15 mm wide. E) Detail of toe and adjacent basal furrow. F) Detail of a second well developed furrow, view is nearly perpendicular to that in D.


A
Sandstone cast
Organic-rich mudstone
Root compressions (Panel G)
B
Sandstone cast
Organic-rich mudstone
Basal furrow defining lobes
C
Organic rich mudstone
D
Bed #10
Panel E
Panel F
E
Toe
Basal furrow defining lobes
F
Basal furrow defining lobes

specimens of *Protostigmaria* depict a plant with a distinctive corm-like base (Jennings, 1975), but larger specimens are poorly preserved and difficult to interpret (Fig. 47; G. Rothwell, pers. comm.). Excluding differences in size, the casts described in this study are nearly identical to the multilobed *Protostigmaria eggertiana* described by Jennings *et al.* (1983) from the Price Formation of Virginia. Their largest (10-lobed) specimen had a basal diameter of 32 cm, whereas the Nova Scotian examples can be two to three times larger.

The 26% (mean) decrease in trunk width within the basal 22 cm of the Horton Bluff *Protostigmaria* is comparable to the flaring seen in the Price specimens. A particularly well-preserved specimen from Pulaski, Virginia has a 28 cm base that tapers to 17.5 cm (37.5 % decrease) in the first 39 cm; above this level the taper is very gradual (Jennings *et al.*, 1983).

### 5.6.2. Small mudstone-filled hollows

5.6.2.1. Description.

Fifteen small mudstone-filled hollows were described in cycle 36 of the Horton Bluff Formation (Hurd Creek Member) at Blue Beach North. The hollow fills occur within a 5 to 13-cm-thick, planar-bedded sandstone (#8) along the 110 meter traverse (Figs. 41 and 42). This *Lepidodendropsis*-bearing unit (Fig. 43) caps the heterolithic nearshore deposits and is overlain by the cast-bearing unit described above.

Hollow fills are discrete, mudstone bodies within an otherwise continuous, very fine-grained sandstone (Fig. 48). Mean hollow width is 21.5 cm and ranges from 7 to 43 cm, and fill thickness (5-13 cm) equals that of the surrounding sandstone. The mudstone fill is generally structureless, but some specimens contain 2 to 4 cm pyrite nodules. The

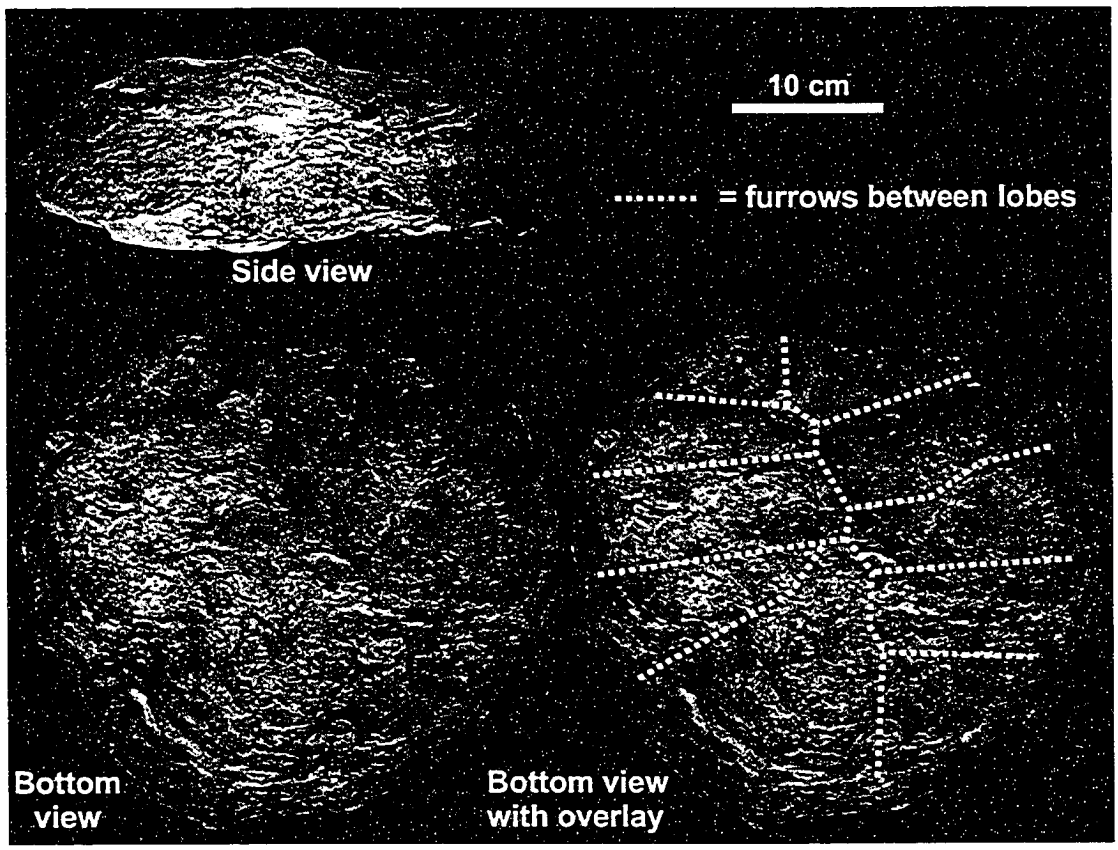



Figure 47: Photos of a ten-lobed *Protostigmaria* from the Price Formation showing cryptic furrows and lobes in a large specimen. Images courtesy G. Rothwell; see Jennings *et al.* (1983; their Figs. 9 and 10) for original description. Ohio University Paleobotanical Herbarium specimen #8113.

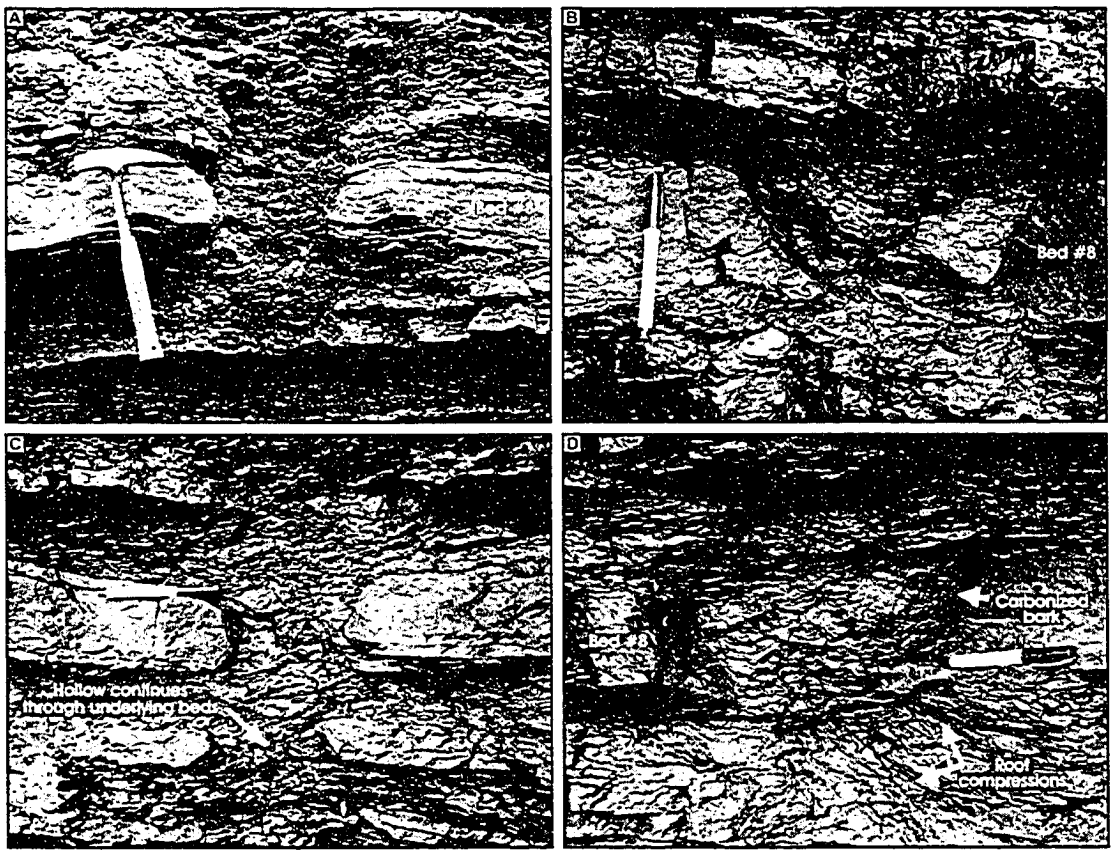



Figure 48: Small mudstone-filled hollows in bed #8, cycle 36. A) Hollow partially exposed in 3D, further excavation revealed that this feature has a columnar shape. Hammer for scale, 32 cm. B) Strongly tapered mudstone-filled hollow. Pen for scale in B-D, 14 cm. C) Hollow extending through 16 cm of underlying strata. D) Mudstone-filled hollow with root compressions and bark. Continued weathering would destroy the organic material, leaving only the mudstone fill.

surrounding sandstone layer has a sharp contact with the hollow fill and locally thins towards or gently onlaps the hollow fill, although layer thickness is typically unaffected by the presence of the fill. Partial erosion of one example revealed that the original hollow had a columnar form. Four specimens tapered strongly downwards with a basal diameter that is only 20 to 80% of that at the top (Figs. 48B and D). The fifteen hollows occurred only in a single sandstone bed, and one extended untapered through 16 cm of underlying sediment (Fig. 48C).

In twelve examples, vertical carbonaceous streaks are present in strata below the fills, where bedding was commonly disturbed or destroyed. These features only occur below hollow fills and are inferred to represent poorly preserved roots (Type D-II-b).

In five examples, a thin organic film lined the contact with the adjacent sandstone (Fig. 48D). Removal of the surrounding sandstone in one example revealed a poorly preserved, carbonized bark impression with vertical ridges and furrows with possible rounded leaf or root scars (~3 mm diameter). The underlying sediment was disturbed and had organic streaks that may represent poorly preserved roots (Type D-II-b). Adjacent, weathered mudstone within the hollow was massive and lacked a carbonaceous film.

5.6.2.2. Interpretation.

Although a few hollow fills may be poorly preserved stump casts (including the example with a bordering bark impression), most hollows have no features diagnostic of plants (cf. Gastaldo *et al.*, 1989) and can be identified only by their apparently columnar shape and the contrast between mudstone fills and adjacent sandstone. However, roots and disturbed sediment below commonly indicates the former presence of a plant, and we infer that much of the hollow may have filled after the standing plant decayed.

The scarcity and poor preservation of plant material associated with the hollows clouds the affinity of the plant(s) responsible for their formation. A single, *Lepidodendropsis* compression (Fig. 43) and several poorly preserved/decorticated specimens of similar affinity were recovered from this bed. Hollow size is similar to the *Lepidodendropsis* casts described by Bell (1960), but the mean value of 21.5 cm is less than half that of the *Protostigmaria* casts described above. We suggest that these structures formed in association with juvenile *Lepidodendropsis* or around the smaller *Archaeocalamites*. In view of the position of hollow fills below large stump casts in shoaling-upward cycles, the latter scenario would support Martel and Gibling's (1991) suggestion that *Archaeocalamites* dominated the nearshore and *Lepidodendropsis* favored more landward swamps.

Tapered mudstone-filled hollows could be an apparent phenomenon caused by a former plant inclined at an angle to the present outcrop face or slumping of sandstone into a hollow left by a decayed plant. Alternately, the hollow may be genuinely tapered, a morphology that could result from infilling of a tuberoid stem base (Bateman, 1991) or a stem that tapered near its point of attachment to a rhizome. Either of the last two options would be consistent with a plant of (archaeo)calamitean affinity.

### 5.6.3 Large mudstone-filled hollows

5.6.3.1 Description.

Twelve large mudstone-filled hollows are present along a 50 m traverse in cycle 51 of the Horton Bluff Formation (Hurd Creek Member) at Blue Beach North (Figs. 41 and 49), where they lie within the basal 47 cm of terrestrial strata in the cycle. These hollows (Fig. 50) have a maximum (basal) diameter of 37 to 106 cm (64.5 cm mean); one

abnormally large hollow with an apparent diameter of 195 cm may have been a composite of smaller structures and was excluded from calculation of the mean. Hollows are most noticeable where they pass through a 25-cm-thick heterolithic (silt/claystone) unit, but closer inspection shows that they continue downward through 22 cm of underlying sediment to terminate at organic-rich zones 1-2 cm above the uppermost nearshore sandstone. The upper boundary of the hollows occurs at the top of the heterolithic unit and all specimens are 47 cm deep. Strata above the heterolithic unit are intensely pedoturbated and hollow fills, if formerly present, are indistinguishable from the associated sediment. Although generally exposed in two dimensions along the cliff face, one hollow fill was partially exposed in the third dimension and had a columnar form (Fig. 51A). Eleven hollows had nearly vertical margins; one tapered from 63 cm width at the base to 38 cm at top, a 40% reduction in the basal 47 cm. The base of one fill flared 6 cm into the adjacent strata. Most fills comprise laminated, concave-up claystone that onlaps the margins (Fig. 51A); two were filled with structureless claystone (Fig. 50A).

The hollow fill with a columnar form also exhibited a glassy, bark-like impression (cf. DiMichele *et al.*, 1996) with vertical ridges and furrows less than 0.5 mm wide and deep (Fig. 51B). Although glassy surfaces associated with pedogenic slickensides occur in Hurd Creek strata, such ped surfaces are smooth and lack the ridged texture. Additionally, the impression wraps around half the circumference of the hollow and is much larger than the observed ped surfaces. We interpret the feature as a bark impression

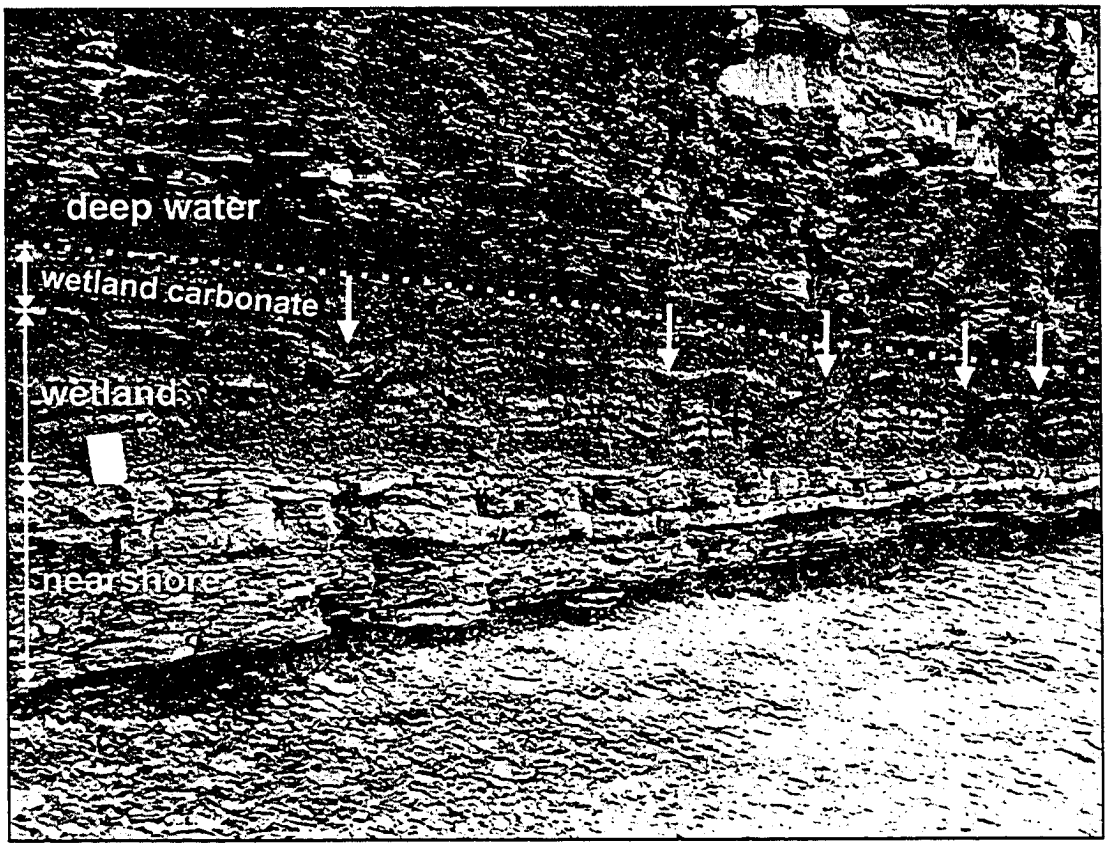



Figure 49: Photograph of nearshore and wetland strata in cycle 51 of the Horton Bluff Formation (Hurd Creek Member), Blue Beach North; photograph accompanies the log in Figure 41. Arrows point to the location of large mudstone-filled hollows, dotted line marks contact with "deep water" strata of the overlying cycle. Book for scale, 19 cm tall.

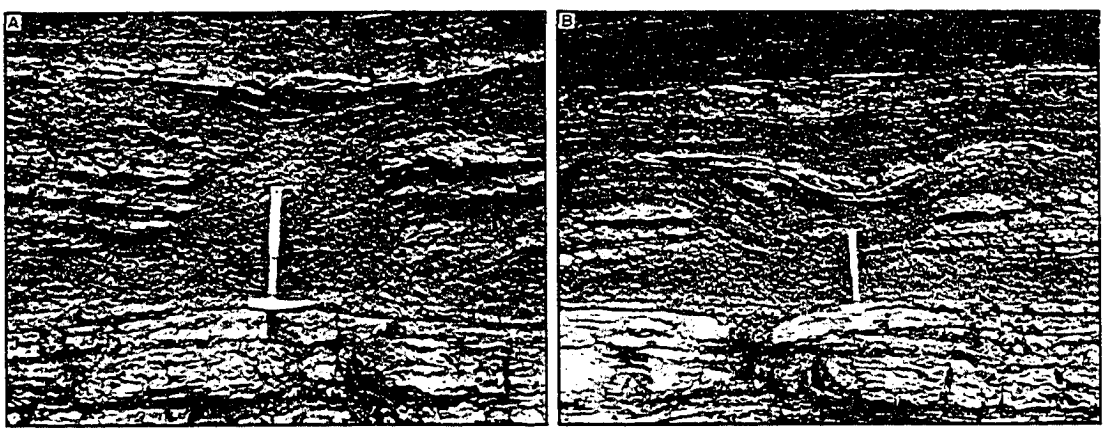
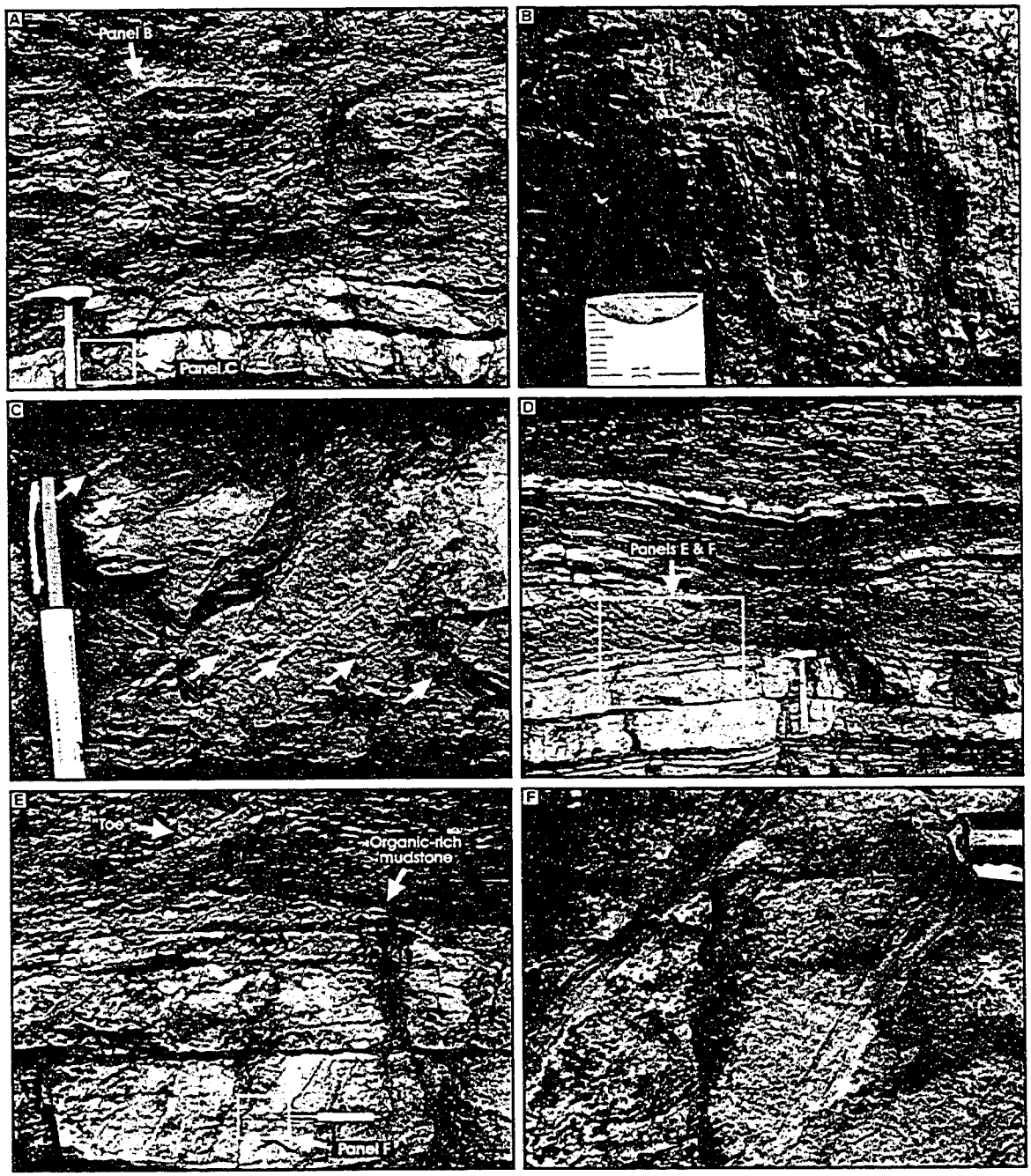



Figure 50: Large mudstone-filled hollows in cycle 51. Hammer for scale, 32 cm. A) Large hollow with massive fill, slightly tapered form, and no overlying concentrically-filled depression. B) Large hollow overlain by well developed concentrically-filled depression.

Figure 51: Evidence linking large mudstone-filled hollows to *Lepidodendropsis*. Scale: hammer in A and D, 32 cm; gradations on ruler in B, 1 mm; pen in C, E and F, 14 cm. A) Large, columnar hollow surrounded by bark impression (B) and underlying slender, lycopsid-like roots (C). D) Large hollow with toe (E) and well preserved roots (F).


A
Panel B
Panel C
B
C
D
Panels E & F
E
Toe
Organic-rich mudstone
Panel F
F

overprinted by pedogenic slickensides. Ten large hollows are underlain by slender, unbranched carbonized roots up to 8 mm wide, 94 cm long, with a medial ridge along their length (Fig. 51; Type E-I-b). They are particularly abundant near hollow margins where they radiate into the underlying strata (Fig. 51E) up to a depth of 93 cm. Although scattered roots occur at this level, the majority occur in association with mudstone-filled hollows.

Concentrically-filled depressions 16 to 35 cm deep and 37 to 210 cm wide are present above six of the twelve large hollow fills (Fig. 52). These depressions are centered on, and up to 74 cm wider than, the underlying hollow fills. Depressions extend down from a level approximately 10 cm above the top of the hollow fills, and contain concentrically laminated sandstone and mudstone. It is unknown whether they are hemispherical or elongate in three-dimensional form.

5.6.3.2. Interpretation

As with the small hollow fills, we infer that these large fills record the former presence of standing vegetation, much of which decayed before infilling of the hollow. Although only one hollow indicates the former presence of periderm, roots are particularly abundant beneath these structures.

Similarities between the large hollows in cycle 51 and the casts in cycle 36 suggest that the former also developed in association with *Lepidodendropsis*. The diameter of the hollow fills (64.5 cm mean) is slightly larger than the mean basal diameter of the stump casts (50 cm), and both occur in association with poorly preserved, ridged bark impressions and roots of lycopsid affinity. As with the casts, roots are most

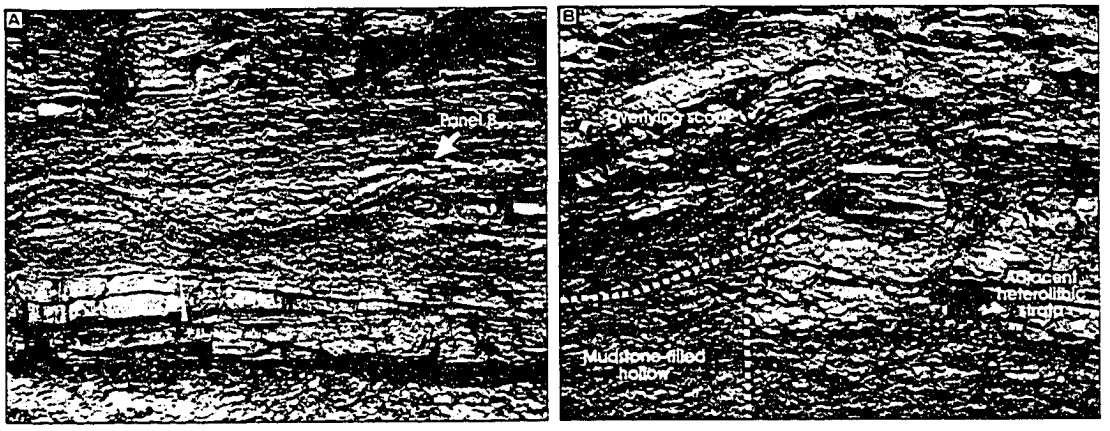



Figure 52: A) Concentrically-filled depression overlying an exceptionally large mudstone-filled hollow. The distribution of roots below this structure suggests that its large size may reflect the decay of two closely-spaced trees. Hammer for scale, 32 cm. B) Detail of the contact between the large mudstone-filled hollow, the concentrically-filled depression, and the adjacent heterolithic strata. Pen for scale, 14 cm.

abundant near the bottom edges of the hollow fills, where one flared "toe" was also preserved.

The depressions above the large hollows probably filled after complete decay of the lycopsid periderm. Such pre-existing lows within the wetland would have localized flow, resulting in broader depressions and deposition of concentric fills, possibly with some slumping. Depressions probably did not develop atop stumps that had filled to the level of the adjacent marsh when the periderm decayed. Centroclinal cross-strata, which reflect hydrodynamic scour around an upright tree (Underwood and Lambert, 1974), differ from concentrically-filled depressions because no tree is present in the center of the feature and because the hollows probably formed after complete decay of the tree. Without the presence of a mudstone-filled hollow or roots below, the concentrically-filled depressions seen in cross-section would be nearly impossible to distinguish from small floodplain scours or channels.

### 5.6.4. Scratch semi-circle

5.6.4.1. Description.

Scratch circles are concentric grooves formed where a fixed obstacle (in this case a plant) rotates around its axis and inscribes grooves in the adjacent substrate (Richter, 1926; Allen, 1982). Such grooves rarely form a complete circle, and those that comprise arcs are more accurately termed "scratch semi-circles" (Kukal and Al Naqash, 1970). One of these structures (Fig. 53) was found in talus of the Hurd Creek Member at Blue Beach North. The exact stratigraphic position could not be determined, but Martel (1990) and Martel and Gibling (1991) described these structures on the basal surfaces of nearshore sandstones – an observation consistent with the lithology of this specimen.

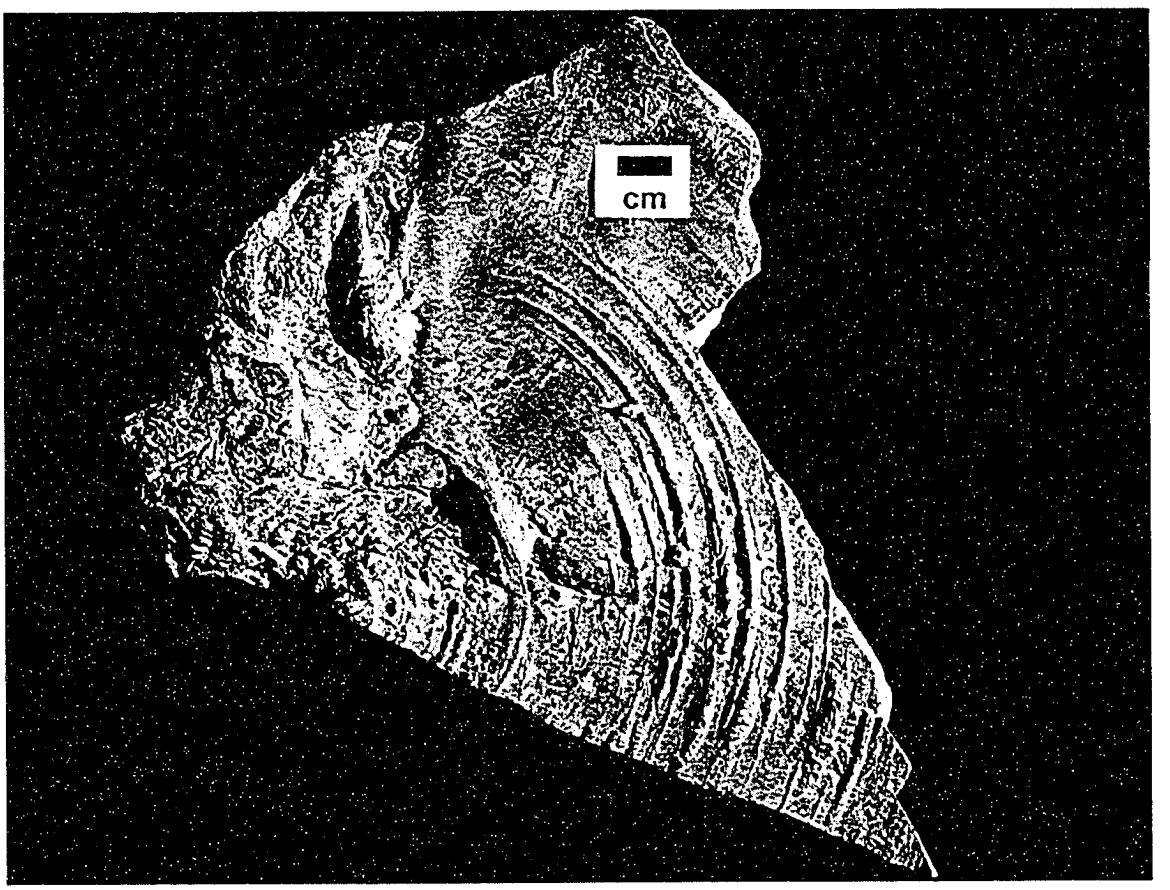



Figure 53: Mold of a scratch semi-circle on the base of a nearshore sandstone from the Hurd Creek Member of the Horton Bluff Formation. Nova Scotia Museum specimen NSM004GF016.002.

The scratch semi-circle occurs as an incomplete mold on the base of a block of very fine-grained sandstone. It comprises a series of ridges 1 to 5 mm high that form arcs of at least 87° (incomplete exposure). No less than 16 distinct grooves occur between 1.5 and 12.2 cm from the center of the circle. The attachment point of the plant was just off the slab. Some grooves exhibit "fretting" where delicate parts of the plant brushed the sediment surface, ornamenting the deeper grooves.

5.6.4.2. Interpretation.

The scratch semi-circle formed where a small plant, bent by a current in wind or water, inscribed grooves into the adjacent sediment. The plant was likely *in situ*, because plant debris of this size would be easily transported unless firmly affixed by roots. Candidates for the scratchmaker (see Table 6) include ferns or small pteridosperms or sphenopsid branches. Circular tool marks have been attributed to vegetation transported by swirling floodwaters (Rigby, 1959), but such structures lack the concentric form of scratch (semi-)circles. The structure provides little information about the generating current because circle form is largely controlled by the torsional strength of the stem and plant architecture (Allen, 1982) and because the circle is incompletely exposed. Based on morphology alone, it is difficult to determine whether this structure formed subaqueously or subaerially, but its nearshore setting suggests a shallow subaqueous origin. The Horton Bluff specimen is the oldest known scratch circle formed by plants; previously described examples come from Pennsylvanian to Cretaceous strata in the United Kingdom, United States, and Canada (Prentice, 1962; Metz, 1991, 1999; Rygel *et al.*, Chapter 4).

### 5.6.5. Obstacle marks

5.6.5.1. Description.

Obstacle marks are formed where a current excavates sediment from the front and sides of an obstacle (Allen, 1982), in this case a plant. Obstacle marks around *in situ* vegetation are common in modern environments (see reviews in previous chapter and Nakayama *et al.*, 2002), but this is the first report of an ancient example.

Twenty obstacle marks were examined on a 37 $m^2$ bedding plane exposure of the Albert Formation located at km-marker 171 on the east side (northbound lane) of Highway 1. Although this exposure contains 136 *in situ Lepidodendropsis* stems (Fig. 54), only 20 had clearly distinguishable obstacle marks developed around them. The surface lies within a fine-grained sandstone in the upper part of a fluvio-deltaic coarsening upward cycle (Fig. 55). Only the bedding surface was exposed across much of the outcrop and it was impossible to determine if all the stems were rooted in exactly the same horizon. Much of the surface was covered with an "egg crate" texture characteristic of closely spaced obstacle marks (Fig. 56), but the reported number is a minimum because only those with a plant preserved in the center (Fig. 57) were counted and studied in detail. There is no obvious pattern as to which plants have obstacle marks and which do not. Mean stem diameter for plants with obstacle marks (4.2 cm) is similar to those without (3.8 cm), and there are no systematic trends in distribution of obstacle marks across the outcrop face. Obstacle marks occur around individual plants that are both isolated and closely spaced (Figs. 57A and C).

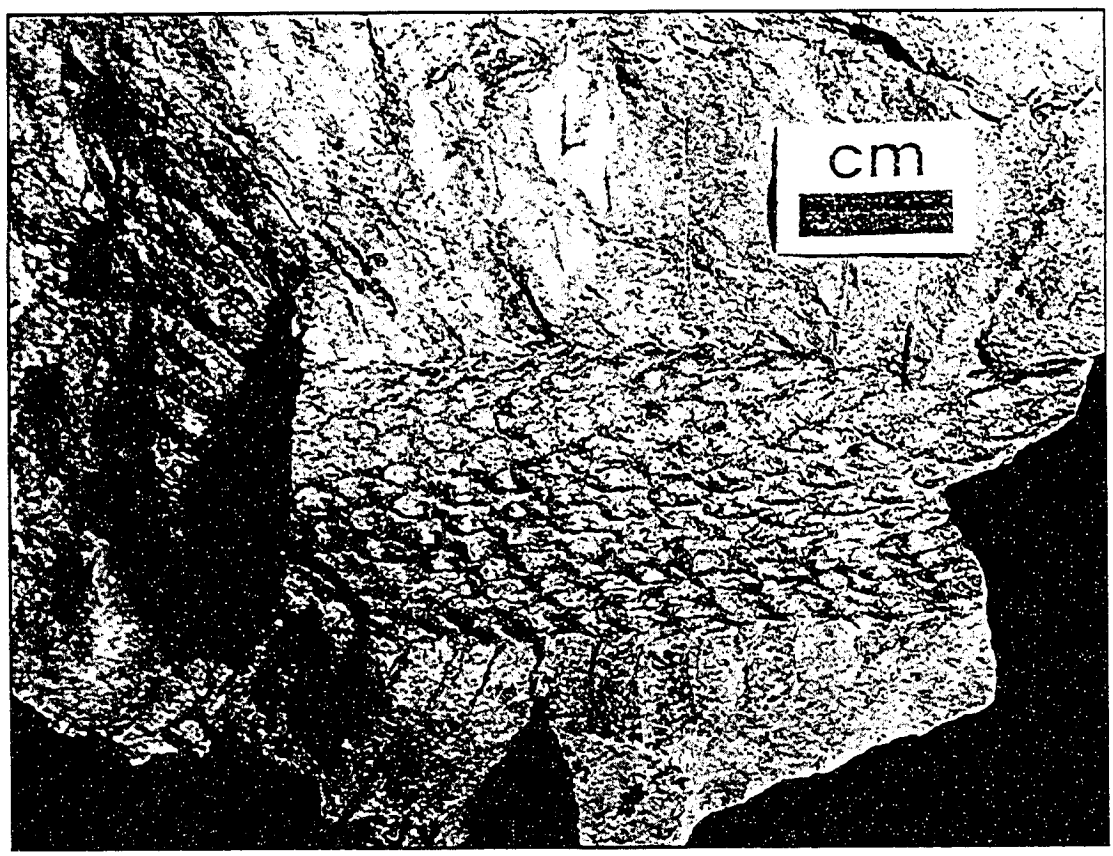



Figure 54: *Lepidodendropsis* stem with attached microphyllous leaves collected from the Albert Formation at km-marker 171 (northbound lane) of Highway 1. Specimen was *in situ* and is identical to the stems with obstacle marks developed around them. New Brunswick Museum specimen NBMG 12157.

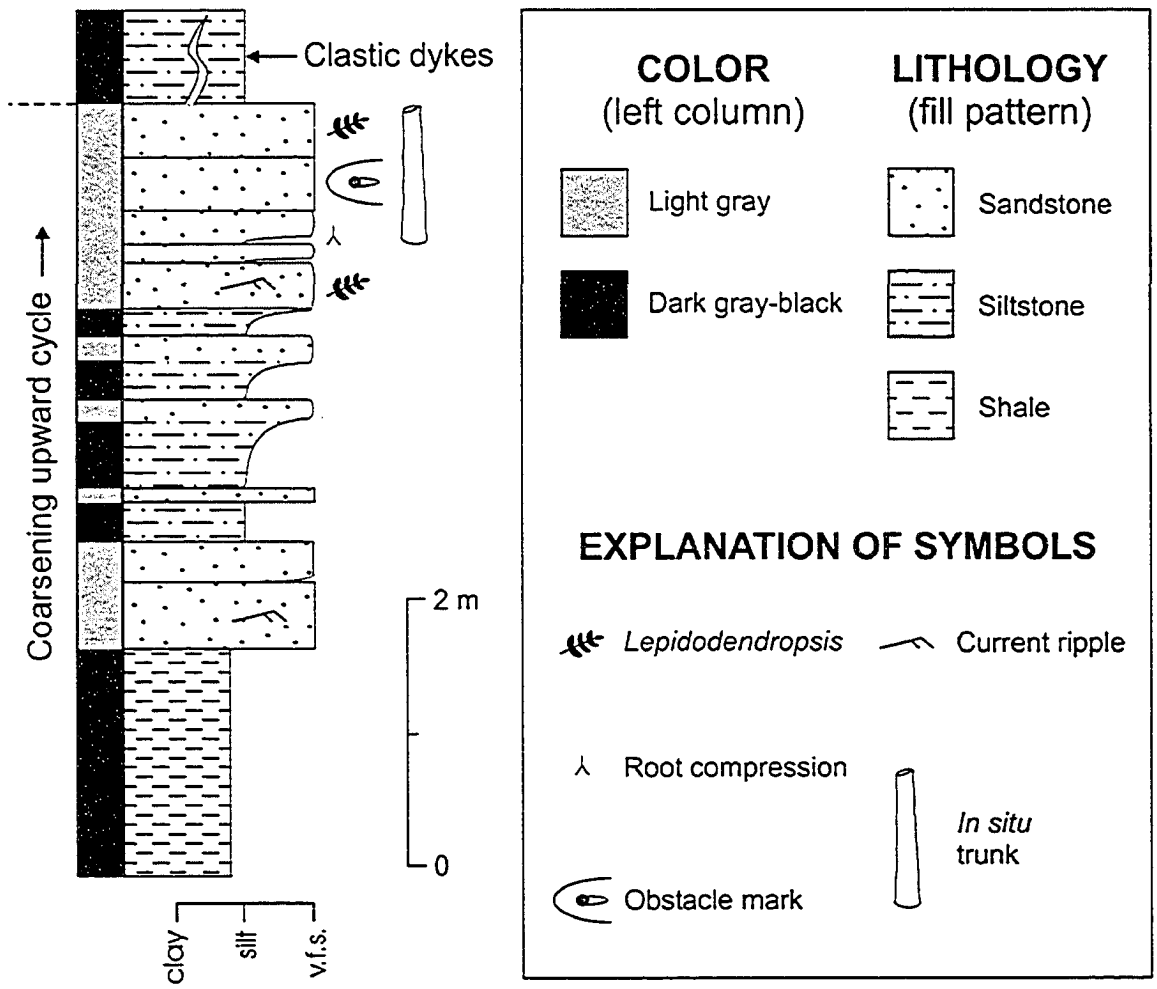



Figure 55: Sedimentological log of a portion of the Albert Formation exposed at km-marker 171 (northbound lane) of Highway 1 showing the location of *in situ* vegetation and obstacle marks.

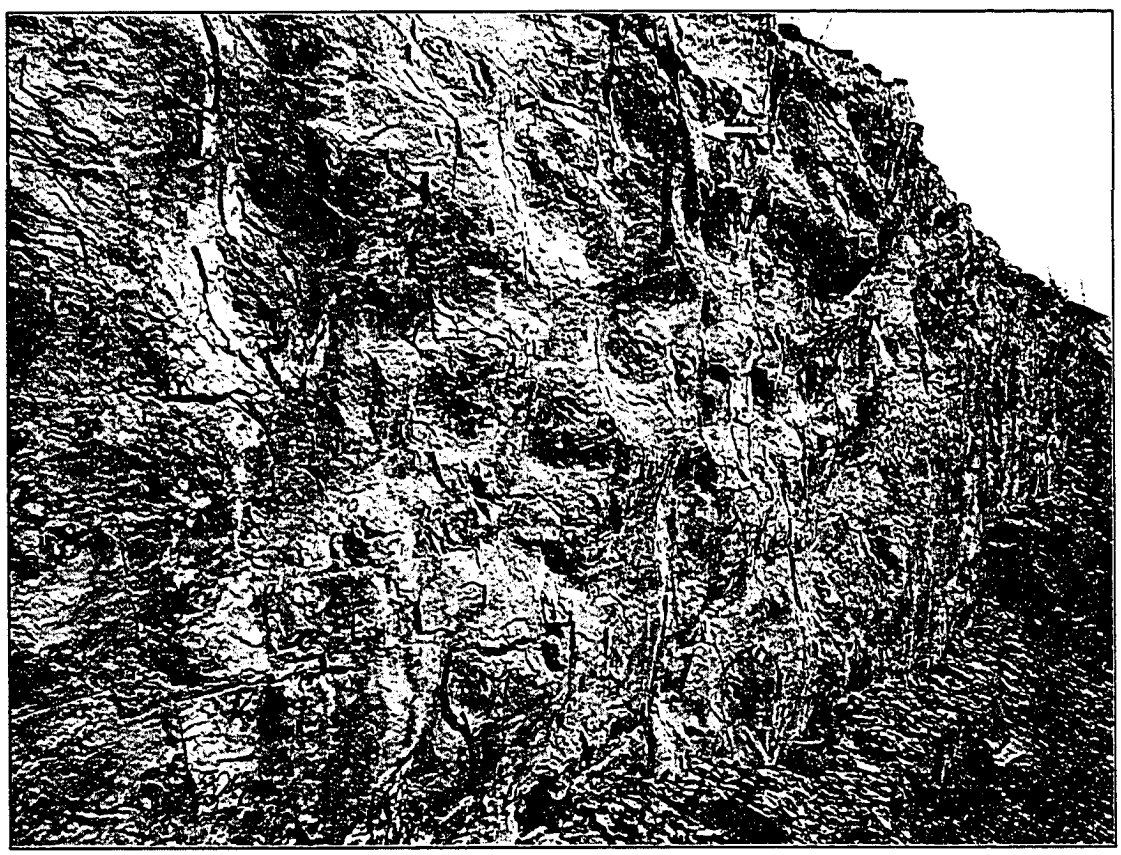


Figure 56: Bedding plane exposure of the Albert Formation with numerous obstacle marks that give the outcrop its characteristic "egg crate" texture. Strata are vertical and stratigraphic up is to the right. Arrow points to hammer for scale, 32 cm.

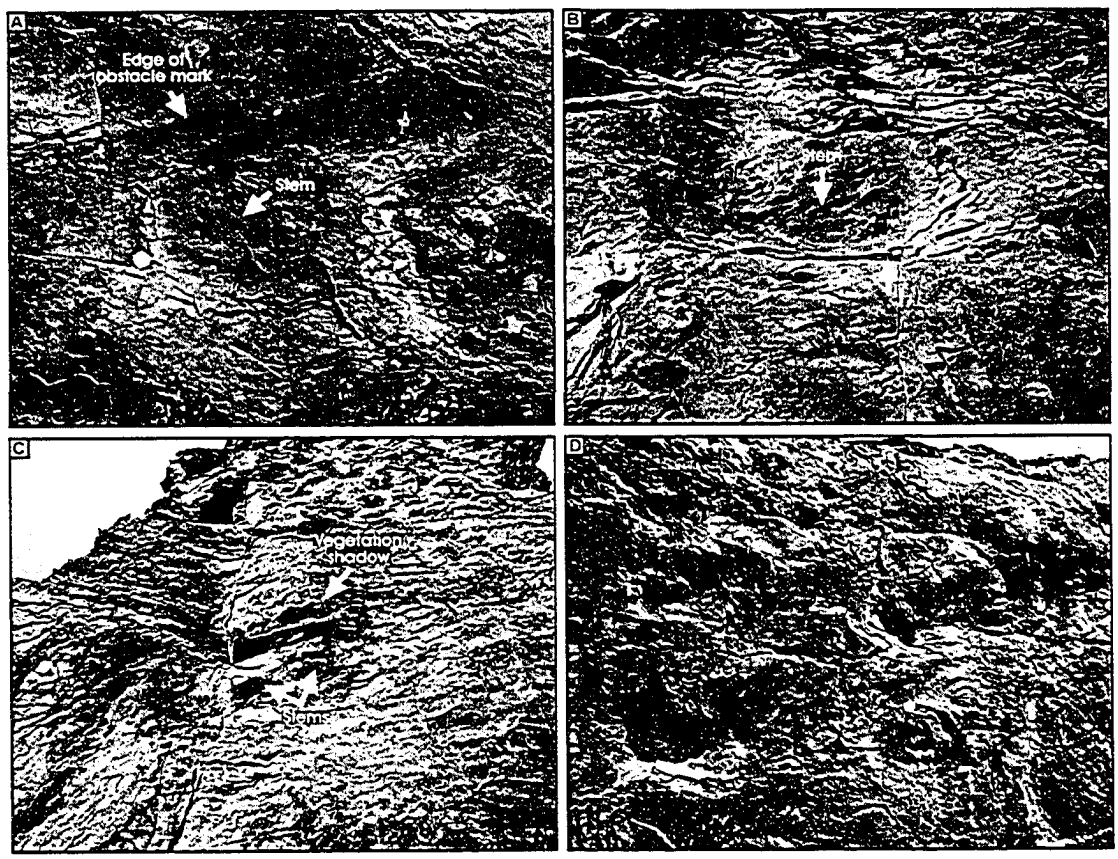



Figure 57: Obstacle marks in the Albert Formation. Photographs are taken from the perspective of being above the bedding plane. A) Well preserved three dimensional obstacle mark developed around *in situ* stem. Coin for scale, 19 mm. B) Downstream view of obstacle mark shown in A, this view emphasizes the three dimensional form of the structure. Arrow points to coin for scale, 19 mm. C) Downstream view of a large, three dimensional obstacle mark developed around two closely spaced stems. Note large body of sediment, possibly a vegetation shadow, in the lee of the obstruction. Hammer for scale, 32 cm. D) Four closely spaced obstacle marks developed around *in situ* stems. Coin for scale above bottom right obstacle mark, 24 mm.

The obstacle marks are u-shaped scours that open in a downstream direction and have a stem at their center (Fig. 57A). Maximum scour depth of 1.5 to 11 cm (4.1 cm mean) occurs just upstream of the obstacle-forming plant.

Despite the similarity between mean values for scour depth and stem diameter, scour depth ranges from 30 to 170% of stem width. The downstream-trailing segments of most scours become indistinguishable within about 10 cm of the stem, but six examples extend 8 to 110 cm behind the plant. The trend of these elongated obstacle marks fall within a 25° range. It is difficult to distinguish uneroded sediment from a vegetation shadow accumulated behind the plant, but two stems appear to have 1 to 1.5 cm high elongate sediment accumulations in their wake (Fig. 57C). Closely spaced stems may act as a single obstruction or each may have a discrete obstacle mark (Fig. 57D). Although there is no clear correlation between individual stem diameter and scour depth, the two deepest scours (9.5 and 11.0 cm) occur around stems separated by a distance less than two times their diameter.

5.6.5.2. Interpretation.

The Sussex obstacle marks represent an episode of erosional unidirectional flow through a juvenile *Lepidodendropsis* forest growing on a fluvio-lacustrine delta plain. Obstacle marks form where erosive downflow degrades the sediment bed in front of an obstacle (plant stem) while horseshoe vortices remove sediment from the sides and wake (Allen, 1982). Recent studies of bridge scour have established that maximum scour depth is primarily a function of obstacle width and flow depth, and that flow velocity determines only how quickly the scour reaches maximum depth (Jain, 1981; Melville and Coleman, 2000). These studies provide equations relating flow depth to obstacle width,

but they disregard the influence of Froude number and cannot be applied to obstructions less than 10 cm in diameter (Melville and Coleman, 2000). Unraveling the conditions responsible for scour formation is further complicated by interference between plants that develop when the stem centers are closer than twelve times their diameter (Karcz, 1968) – a condition that is true for the majority of stems in this outcrop. Insufficient experimental data are available to attempt paleohydraulic reconstructions for these obstacle marks, but the occurrence of the deepest scours with the widest (composite) obstructions suggests that scour depth is related to obstacle width even at this scale.

### 5.7. Density of forested horizons

The superb two-dimensional cliff exposures of the Horton Bluff Formation and the bedding plane exposure of the Albert Formation provide insight into the organization and density of these ancient forests. Spatial analyses of lepidodendrid lycopsid forests have been reported for the Pennsylvanian (Beckett, 1845; Gastaldo, 1986; DiMichele and DeMaris, 1987; DiMichele *et al.*, 1996) and juvenile *Lepidodendropsis* from the Tournaisian (Falcon-Lang, 2004), but this is the first such study to document mature stands of *Lepidodendropsis*. At Horton Bluff, forest density was estimated by modifying the strip-cruise method of timber inventory (Chapman and Meyer, 1949; Avery and Burkhart, 1983). Specifically, the outcrop face was treated as a swath through the forest with a width equal to twice the mean basal diameter of the casts. Forest density of the Albert Formation horizon was calculated by counting all the *in situ* stems in the measured area and extrapolating these values to a hectare; a similar approach was employed by Gastaldo (1986). Application of forestry techniques to fossil forests can be problematic because the basic unit of mensuration is trunk diameter at breast height (1.3 m) – a unit

that is challenging to measure given the limitations of outcrop exposure and incomplete preservation. Fortunately, lycopsid trunks taper very gradually and a reasonable estimate of diameter at breast height can be achieved if the trunk is measured above the basal flange (Calder *et al.*, 1996). Using the trunk diameter, biomass (basal stem area ($m^2$) per hectare) was calculated and compared to previously described lycopsid forests (Table 7). Statistical analysis of plant distribution (Hayek and Buzas, 1997) was not performed because of the narrow width of the exposures.

Given the 26% mean reduction in trunk width for the *Protostigmaria/ Lepidodendropsis* in cycle 36 of the Horton Bluff Formation, the casts probably attached to trunks that were no more that 12 to 82 cm wide (36.9 cm mean) at breast height (Fig. 58A). The distribution of trunk diameters is unimodal and left skewed, suggesting that many trees were mature at the time of death (DiMichele and DeMaris, 1987). All but one of the 47-cm-tall mudstone-filled hollows in cycle 51 had vertical margins, indicating that the original tree did not have a significantly flared base and that the measured widths are representative of trunk diameter. *Lepidodendropsis* from cycle 51 ranged from 37 to 106 cm in diameter, with a mean of 62.2 cm (Fig. 58B). These trunk diameters are unimodal and right skewed, a pattern suggestive of a juvenile forest or one that experienced multiple phases of colonization (Calder *et al.*, 1996). The size distribution of stems in the Albert Formation was not plotted because the stems may not have been rooted at the same level.

In cycle 36 of the Horton Bluff Formation, twenty one *Protostigmaria* casts (rooted in the same horizon) were present in a 110 $m^2$ traverse. At this density, one hectare in this forest contained 1909 trees (0.19 trunks/ $m^2$) and had a biomass of 204 $m^2$

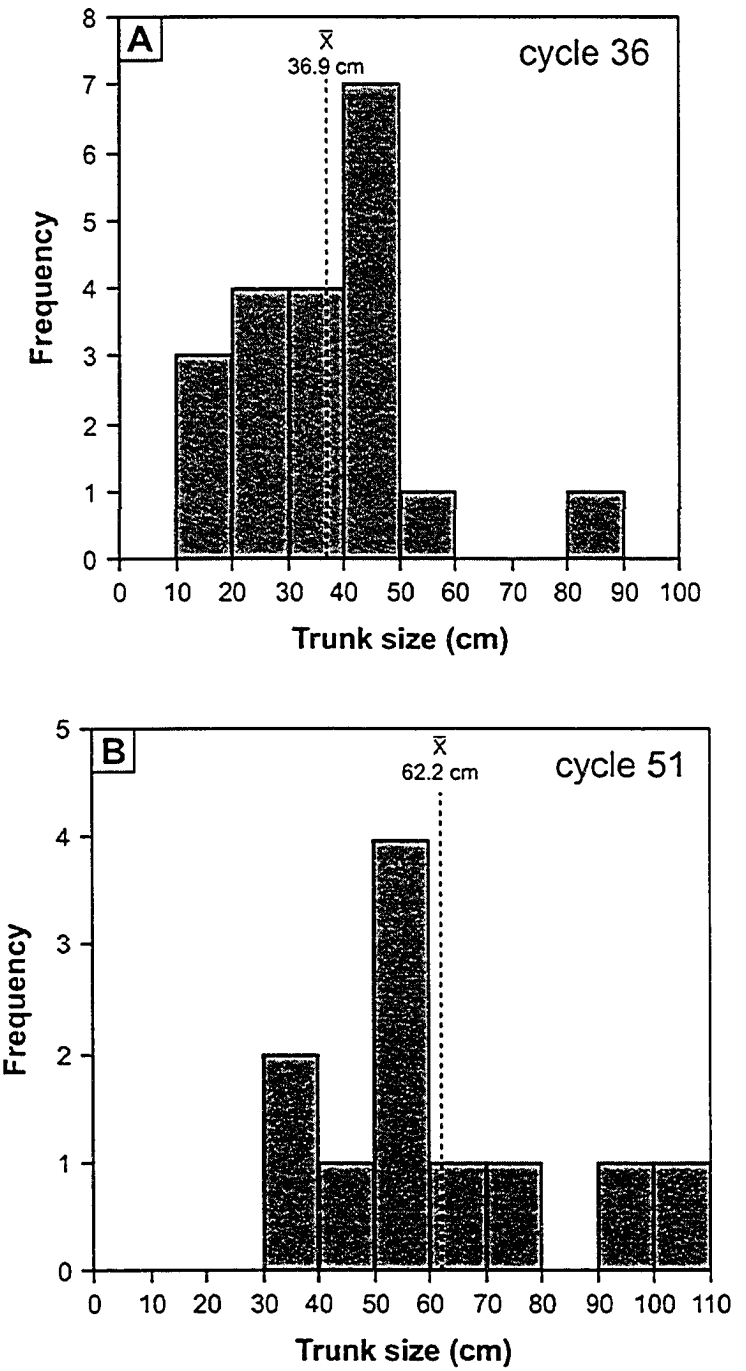



Figure 58: A) Distribution of probable trunk diameters at breast height for the twenty measurable *Protostigmaria/Lepidodendropsis* casts in cycle 36 of the Horton Bluff Formation. B) Distribution of probable trunk diameters at breast height for eleven large mudstone-filled hollows observed in cycle 51 of the Horton Bluff Formation.

per hectare (36.9 cm mean diameter). A density estimate for the underlying mudstone-filled hollows was not calculated because they may have been rooted in multiple horizons and were not unequivocally lycopsid. The forested horizon in cycle 51 had a density of 1846 trees per hectare (0.18 trunks/$m^2$), and their considerably larger trunks (62.2 cm mean diameter) yielded a biomass of 561 $m^2$ per hectare.

It is unclear whether all the stems in the Albert Formation are rooted at the same level, but density estimates are useful for comparison with other horizons. Regardless of where they were rooted, lycopsids could not propagate adventitiously and the sediment-laden floodwaters that inundated the forest encountered a density of standing trees identical to the one now exposed. Average stem density in the Albert Formation is 3.7 stems/ $m^2$, with a range of 1 to 12 stems/ $m^2$. At this density, a hectare would contain 37,000 stems with a basal trunk area of only 50 $m^2$ (0.5% coverage). Extrapolating the observed value to a hectare plot makes the tenuous assumption that the 37 $m^2$ bedding plane is representative of the remaining 99.6% of the plot. This horizon occurs at approximately the same level as two of the forests studied by Falcon-Lang (Falcon-Lang, 2004, his sites 2.105 and 2.112), intervals for which he reported densities of 18,500 and 19,500 stems per hectare, respectively. Our larger estimate could reflect differences in sampling strategy, or could indicate that the bedding surface described in this study contained stems rooted in two stacked horizons. Calculated densities for the *Lepidodendropsis* forests described in this study are within or below the 29,000 to 45,000 trees/hectare values reported by Bell (1960).

Our data shows that *Lepidodendropsis* forests had more trees per hectare than their Pennsylvanian counterparts (Table 7, Fig. 59). Horton Bluff forests were as much

| Author | Outcrop area ($m^2$) | Mean trunk diameter (cm) | Density (trees/hectare) | Biomass) (basal stem area ($m^2$)/hectare) |
|---|---|---|---|---|
| **Pennsylvanian lepidodendrid forests** | | | | |
| Beckett (1845) | 1,005 | 30* | 763 | 215* |
| Gastaldo (1986) | 4,250 | 20.8 | 87 | 38 |
| DiMichele and DeMaris (1987) | 130 | 95 | 1,769 | 992 |
| DiMichele *et al.*, (1996) | 14,200 | 60.2 | 573 | 164 |
| **Tournaisian *Lepidodendropsis* forests (previous studies)** | | | | |
| Bell (1929) | 167 | N.D. (all <30 cm) | 17,609 | N.D. |
| Bell (1960) | 20 | N.D. | 28,892 | N.D. |
| | 4 | N.D. | 45,192 | N.D. |
| Falcon-Lang (2004) | 72 | 4.3† | 18,472 | 27 |
| | 35 | 3.8† | 19,428 | 22 |
| | 10.5 | 12.4† | 10,476 | 127 |
| | 7 | 8.2† | 11,428 | 61 |
| | 149 | 4.4† | 29,060 | 16 |
| **Tournaisian *Lepidodendropsis* forests (this study)** | | | | |
| cycle 36, Horton Bluff Fm. | 110 | 36.9§ | 1,909 | 204 |
| cycle 51, Horton Bluff Fm. | 65 | 62.2# | 1,846 | 561 |
| Albert Formation | 37 | 3.8# | 37,000 | 50 |

Note: Lepidodendrid data compiled by DiMichele *et al.*, (1996), N.D. = no data.

* Value estimated by DiMichele *et al.*, (1996).

† value reduced by 40% to correct for basal flare

§ value reduced by 26% to correct for basal flare

# little/no flare, no correction applied

Table 7: Comparison of Pennsylvanian Lepidodendrid forests and Tournaisian *Lepidodendropsis* forests.

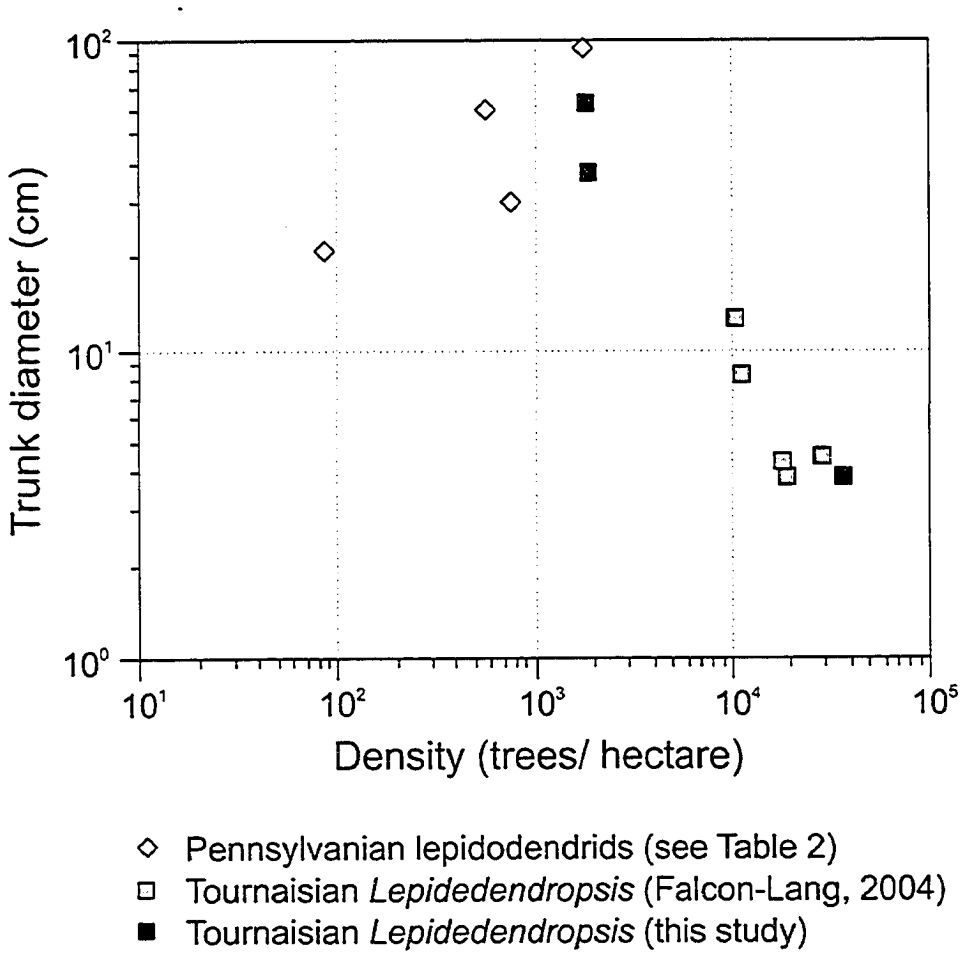



Figure 59: Relationship between trunk diameter and tree density for Pennsylvanian lepidodendrid and Tournaisian *Lepidodendropsis* forests (data from Table 7).

as three times more dense than lepidodendrid forests of similar tree size and biomass. This difference could reflect local variations in environment or substrate, but it could also be the product of diminished competition/interaction between protostigmarian rooting systems (compared with the large and extensive *Stigmaria* of lepidodendrids).

The small size of the Albert Formation trees makes them more difficult to compare with the lepidodendrids, but our size and density values compare well with the range reported by Falcon-Lang (2004). Comparing density values amongst mature and immature *Lepidodendropsis* forests (Fig. 59), the relatively low density of the mature Horton Bluff examples supports Falcon-Lang's (2004) interpretation that these forests experienced competition-induced mortality (self-thinning) as they matured.

## 5.8. Discussion

### 5.8.1. *Protostigmaria* variations

The Horton Group of Atlantic Canada is one of the few *Protostigmaria*-bearing units described to date. The rarity of these specimens is surprising given the nearly global distribution of the Early Mississippian "*Lepidodendropsis* flora" (Chaloner and Lacey, 1973; Wagner, 1979; Raymond *et al.*, 1985). Although poorly preserved, the twenty one specimens described from Blue Beach North during 2002-2003 demonstrate a surprising level of diversity within the genus. These specimens are commonly twice, and possibly as much as three times, as wide as the largest specimen from Virginia (Jennings, 1975; Jennings *et al.*, 1983). In addition to variations in size, the Horton Bluff specimens confirm Jennings *et al.*'s (1983) observation that lobes in large *Protostigmaria* become difficult to identify.

Horton Bluff *Protostigmaria* provide information about how the arborescent *Lepidodendropsis* anchored itself in the substrate and maintained its upright form. Bell (1960) and Jennings (1975) noted that *Lepidodendropsis* had roots similar to those extending away from *Stigmaria*, but lacked the rhizomes themselves. Without this wide support base, Jennings *et al.* (1983) speculated that the lobed base must have anchored itself in the substrate in a Isoëtes-like fashion. As the plant grew new lobes, it was able to support its increasing height as the base became buried in the substrate and the roots anchored themselves (Karrfalt, 1977). Although the sediment adjacent to the trunks and hollows is thoroughly pedoturbated, the "toes" at the base of the plants seem particularly well suited for soil penetration and may have provided a means of entrenchment. If so, their point of attachment with the trunk may represent the depth to which *Protostigmaria* was buried in the soil (generally about 5 cm plus the depth to which the concave-down base extended below the margins). The radiation of roots down and away from the base of the trunk may have provided pre-stigmarian support against wind shear (Jennings *et al.*, 1983; Mosbrugger, 1990). The 93 cm penetration depths attained by these rootlets are much greater than previously reported for early arborescent lycopsids and rival those of Devonian progymnosperms (Algeo and Scheckler, 1998).

### 5.8.2. Tournaisian wetland ecosystems

The recent reinterpretation of these strata as marine-influenced through the identification of key ostracod genera, agglutinated foraminifera and a trilobite specimen at Horton Bluff, profoundly affects our understanding of this Tournaisian wetland ecosystem. Tibert and Scott (1999) documented agglutinated foraminifera in green rooted mudstones that bracket intervals with standing lycopsids in equivalent strata

elsewhere at Blue Beach. Their model agrees well with the setting envisioned for the Price Formation of Virginia, where back barrier *Lepidodendropsis* "swamps" lay just behind sandy beaches bordering the sea (Scheckler and Beeler, 1984; Scheckler, 1985, 1986, 1986). There is equivocal evidence that Pennsylvanian lycopsids may have tolerated some salinity (Gastaldo, 1986), but it is unclear whether Horton Bluff *Lepidodendropsis* was salt-tolerant or if the forests were later inundated (killed?) by marine waters and the resulting increase in salinity. Regardless of their salinity tolerance, it is clear that the *Lepidodendropsis* forests and their inhabitants thrived in close proximity to a body of water that was, at times, marine influenced.

We confirm Martel and Gibling's (1991) suggestion that the Horton shoreline was surrounded by *Lepidodendropsis* wetlands, but the most basinward vegetation (those elements lowest in the cycles) has proved more difficult to identify. The size and morphology of the small mudstone-filled hollows in nearshore sandstones is consistent with both *Archaeocalamites* and juvenile *Lepidodendropsis*, although direct evidence for *Archaeocalamites* is lacking. Detailed paleobotanical studies of plant macrodetritus, or additional study of nearshore vegetation-induced sedimentary structures may help to confirm the identity of nearshore floral communities.

The localities provide little information about inland or upland vegetation during this period. Transported *Lepidodendropsis* stems are ubiquitous throughout the wetland and nearshore facies of the Horton Bluff Formation, but the uncertain affinity of the stump casts previously made the source of the plant macrodetritus difficult to pinpoint. The identification of *in situ Lepidodendropsis* forests suggests that much of the plant macrodetritus accumulated close to its source. In a study of the Mobile Delta, Gastaldo

*et al.*, (1987) observed that floral elements from distant locations (>13 km) were overrepresented within the site of accumulation. A few pteridosperm axes, probably derived from well drained floodplain niches (Scheckler, 1985), are the only evidence of plant material originating from outside the *Lepidodendropsis* forests. Given the ubiquity of *Lepidodendropsis* compressions in the Horton Bluff Formation and the presence of *in situ* lycopsid trunks, it appears that much of the plant material accumulated essentially *in situ*. The abundance of locally-derived plant remains may reflect the paucity of fluvial channels in the Hurd Creek and Blue Beach Members, even though terrestrial strata are important components of the cycles. Without major channels to entrain plant macrodetritus, plant material probably spread by floating in standing bodies of water – a potentially difficult dispersal mechanism in densely vegetated areas. Alternately, the low-diversity, *Lepidodendropsis* forests could have been so widespread that other flora were too distant to contribute significant amounts of plant material.

A growing body of evidence suggests that, unlike most extant species, early amphibians inhabited brackish or even fully marine environments (see reviews in Coates *et al.*, 2000; Laurin *et al.*, 2000). Similarly, several types of fish (acanthodians, lungfish, and elasmobranch sharks) are known to have been tolerant of salt water (Carroll, 1988). Because Horton Bluff tetrapod bones are frequently found in talus or by casual collectors, their precise location relative to known brackish-marine zones is rarely recorded. Although tetrapod footprints have been found within known marine intervals (Bell, 1960; Tibert and Scott, 1999), it is possible that tetrapods occupied discrete freshwater areas within this environment. Without coordinated micro- and vertebrate paleontological

study, the salinity tolerance of the Horton Bluff tetrapod community will remain enigmatic.

### 5.8.3. Plant-sediment interaction: low energy environments and insight into early land plants

The vegetation-induced sedimentary structures described from the Horton Group, particularly those from Horton Bluff, were deposited in a low-energy depositional environment. These structures provide an important counterpoint to the meter-deep erosional structures that feature prominently in the original description of vegetation-induced sedimentary structures from the Pennsylvanian Joggins Formation (Rygel *et al.*, Chapter 4). Although formed within fine-grained sediment deposited under relatively calm conditions, the scale of Horton Bluff vegetation-induced sedimentary structures approaches that of many features from Joggins.

Obstacle marks around plants in the Albert Formation are the oldest known examples from the ancient record. These structures represent the midpoint between the low energy environment at Horton Bluff and the intense floods of the Joggins Formation (Calder *et al.*, in press), and further illustrate that vegetation-induced sedimentary structures can form under a wide range of hydrodynamic conditions.

Unlike traditional mud-cast logs and stumps, mudstone-filled hollows generally bear no direct evidence of having formed in association with a plant (cf. Gastaldo *et al.*, 1989). These structures can only be attributed to formation in association with plants by their sedimentary context and by examining underlying strata for roots or phytoturbation. Without careful study, these structures could easily be mistaken for purely hydrodynamic or soft-sediment deformation features.

Land plants evolved in the Ordovician (Wellman *et al.*, 2003), but *in situ* specimens were rarely preserved until the evolution of arborescent progymnosperms in the Middle Devonian (Driese *et al.*, 1997; Elick *et al.*, 1998). Because vegetation-induced sedimentary structures persist despite the destruction of organic material, identification of these structures has the potential to expand our knowledge about early plant colonization of the terrestrial landscape. The vegetation-induced sedimentary structures described in this study formed in calm, swampy environments similar to those inhabited by early bryophytes and vascular plants. Preservation of delicate scratch circles shows that even small individual stems can interact with the substrate to form sedimentary structures with preservation potential much higher than that of the *in situ* stem itself. Because vegetation-induced sedimentary structures also occur in dryland settings (Rygel *et al.*, Chapter 4) where organic material is unlikely to be preserved, their identification in redbed sequences could be vital in constraining Paleozoic phytogeography.

## 5.9. Conclusions

This study records the former presence of cormose lycopsid forests in Tournaisian strata of the Horton Group, Atlantic Canada. We describe new variations in *Protostigmaria* morphology and resolve the taxonomic affinity of cryptic stump casts. The *Protostigmaria* described here expand upon the morphological differences described by Jennings *et al.* (1983) and provide a contrast to the small individuals commonly depicted in textbooks. Additionally, this study provides compelling evidence that *Lepidodendropsis* inhabited coastal wetlands similar to the ones envisioned for the Price Formation of Virginia (Scheckler and Beeler, 1984; Scheckler, 1985, 1986).

Vegetation-induced sedimentary structures developed in the low energy swamps of the Horton Group provide an interesting contrast to the erosion-dominated forms described from the Pennsylvanian Joggins Formation (Rygel *et al.*, Chapter 4). Without careful sedimentological analysis, the mud-dominated vegetation-induced sedimentary structures of the Horton Bluff Formation could easily be mistaken for channels, hydrodynamic scours, or soft-sediment deformation structures. The expanded descriptions of vegetation-induced sedimentary structures will contribute to our ability to recognize standing vegetation in facies likely to have been colonized by early land plants. Vegetation-induced sedimentary structures provide direct evidence of plant-sediment interaction, an activity that has profoundly influenced clastic depositional systems for over 425 million years.

## 5.10. ACKNOWLEDGEMENTS

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# CHAPTER 6: FLUVIAL SYSTEMS OF THE PENNSYLVANIAN JOGGINS FORMATION, ATLANTIC CANADA: GEOMORPHIC AND ACCOMMODATION INFLUENCES ON CHANNEL-BODY GEOMETRY AND ARCHITECTURE

*Michael C. Rygel and Martin R. Gibling*

## 6.1. ABSTRACT

Eighty two fluvial channel bodies within the Pennsylvanian Joggins Formation were classified as fixed, meandering, and multistorey types, with each type present in coastal wetland and interior dryland facies associations within the Cumberland Basin. Most channel bodies are of fixed type and single storey, with low width/thickness (W/T) values between 2 and 20. A few channel bodies of meandering type consist of a single storey with more extensive lateral accretion sets that onlap flat-lying channel bases. These bodies are generally broader (W/T 12 to 64) than the fixed types, and represent more mobile reaches where incision in some cases penetrated a non-cohesive, sandy substrate. Multiple fixed and meandering channel bodies incise from the same level suggesting that the parent channels were generally anastomosing. The coastal wetland deposits contain a few meandering-channel bodies of unusually large scale, up to 10.5 m thick. Five multistorey bodies up to 9.2 m thick represent paleovalleys filled with the deposits of much smaller fixed and meandering channels.

The channel body types form distinct but non-exclusive clusters in W-T space. Statistical analysis revealed that thickness values for each type were distinct, as were W/T values for fixed and meandering channel bodies; incomplete lateral exposure of multistorey bodies prevented similar W/T analysis. However, paleochannel depth and width/depth determined for channel bodies of all types were statistically similar, apart

from a small group of unusually deep meandering channels in the coastal wetlands. This study suggests that, although forcing factors (tectonics, Milankovitch-scale changes in climate and sediment supply, etc.) probably influenced the system, the Joggins channel bodies collectively reflect much of the geomorphic variability of the original drainage network, with systems of small fixed channels and a few large mobile channels in the coastal zone. The paleovalley fills are an integral part of the associated floodplain deposits and do not represent a basinward advance of facies belts. They may reflect a modest response to falls in relative sea level or to climatic or tectonic changes. Preservation of a relatively representative drainage network reflects rapid subsidence and accommodation creation within the Cumberland Basin through fault motion and salt withdrawal, damping down base-level falls and preserving a little-modified suite of channel bodies.

## 6.2. INTRODUCTION

Apart from their intrinsic value in paleogeographic and paleoenvironment interpretation, understanding the external form and internal architecture of fluvial channel bodies is crucial in order to fully exploit their potential as hydrocarbon reservoirs, aquifers, and hosts for economic mineral deposits and carbon sequestration. Many studies have focused on the links between accommodation and channel-body form (Van Wagoner *et al.*, 1990; Shanley and McCabe, 1993, 1994; Van Wagoner, 1995, and many others), but relatively few have presented large, detailed datasets to explore this linkage.

In interpreting suites of channel deposits, a key question is whether they collectively represent the original geomorphic variability of drainage networks across a landscape (Tye, 2004), or whether the variation in form largely represents fluctuations in

forcing factors such as climate, eustasy and tectonics (which may greatly influence accommodation), as well as changes in sediment supply and the equilibrium profile of the rivers. The basin's subsidence rate may influence the preservation of drainage networks, for preserved channel bodies in rapidly subsiding basins are less likely to be connected and reworked and are more likely to approximate the original channel form. Ideally, this question should be evaluated by mapping fluvial stratigraphic units or individual channel bodies over large areas. For example, Siever (1951) and Dolson *et al.* (1991) mapped drainage networks on unconformities, and Nichols (1987) and Hirst (1991) documented a systematic downstream variation in channel-body architecture in megafan deposits. Ardies *et al.* (2002), Lukie *et al.* (2002) and Plint (2002) mapped extensive Cretaceous channel and valley systems in western Canada, and inferred that channel-body architecture and composition in part reflect tectonic and eustatic factors. Additionally, most field- and core-based datasets are hampered by limited exposure or subsurface control, insufficient paleoflow data, and inadequate constraints on the aspect ratio (width/thickness) of channel bodies, as well as by the difficulty of inferring instantaneous channel dimensions from complex channel deposits. Although 3D seismic data are rapidly advancing our ability to visualize fluvial deposits in the subsurface (Posamentier, 2001; Carter, 2003), presently such studies rarely extend more than a few kilometers along depositional dip and cannot image many of the small-scale architectural features seen in outcrop that have implications for sand body heterogeneity.

Where a large number of channel bodies are well exposed, statistical analysis allows a quantitative approach for comparing the forms of channel bodies and their parent channels through stratigraphic sections. The present study documents the

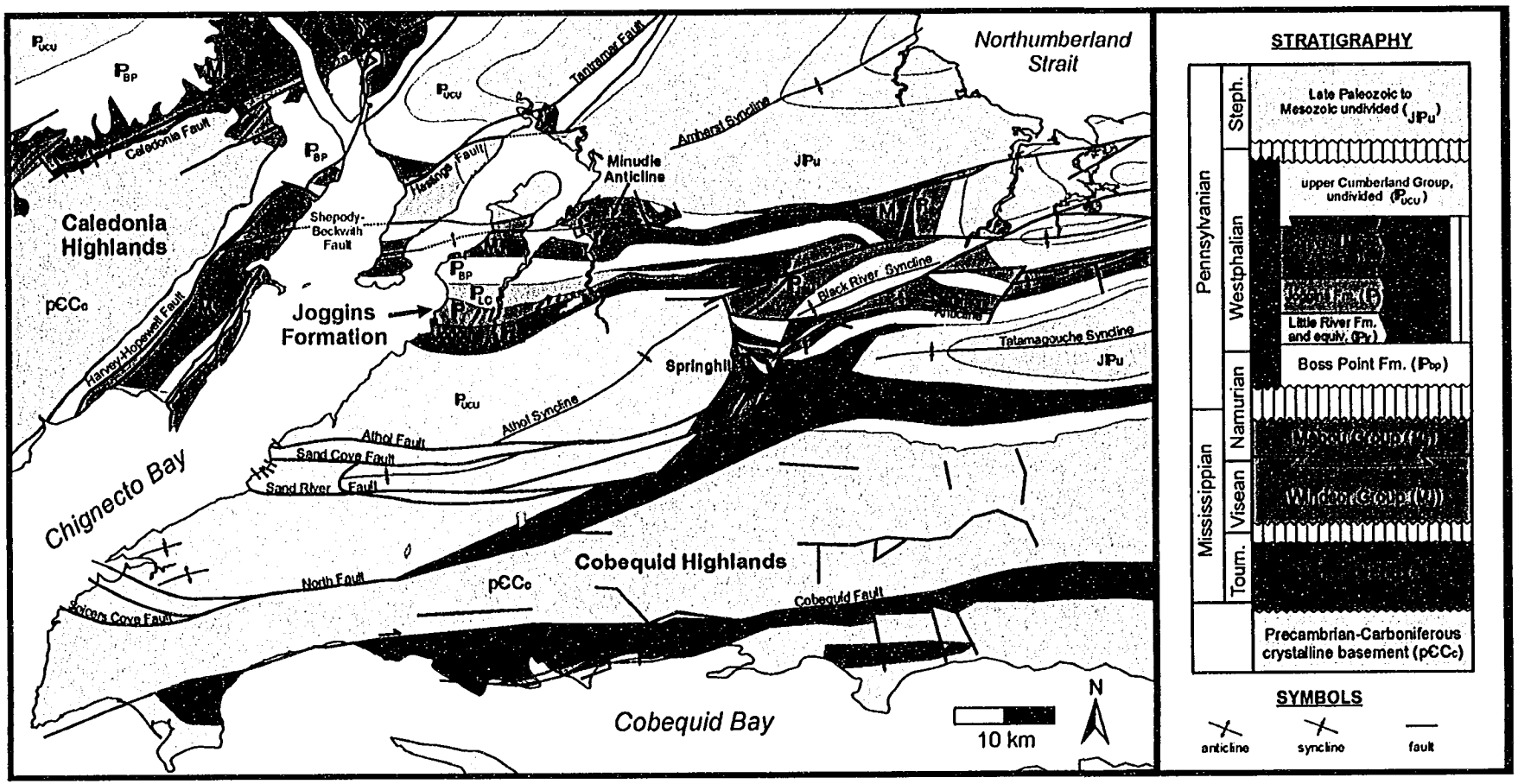
geometry and architecture of 82 channel bodies in a coastal exposure of the the Pennsylvanian Joggins Formation, which was deposited in the rapidly subsiding Cumberland Basin of Nova Scotia. These channel bodies crop out in an almost completely exposed and accessible coastal area, and can be positioned within a detailed measured section, which allows their geometry and architecture to be linked precisely with their position within parasequence sets. The size and quality of this dataset permits a statistical comparison of dimensions and aspect ratios for different types of channel body, as well as for the depth of the parent channels, across inland and coastal paleogeomorphic settings. The results suggest that, although forcing factors influenced the system, Joggins channel bodies collectively represent much of the range of variation of the original drainage network of the river plains.

## 6.3. Geological Setting

### 6.3.1. Overview

The Pennsylvanian Joggins Formation was deposited within the Cumberland Basin of Nova Scotia, a fault-bounded depocenter within the regional Maritimes Basin of Atlantic Canada (Davies and Gibling, 2003; Davies *et al.*, submitted). The margins of the 3,600 $km^2$ Cumberland Basin are defined by the Harvey-Hopewell Fault to the west, the Spicer's Cove Fault to the south, and the Caledonia-Dorchester Faults to the north (Browne and Plint, 1994). The northeastern margin lies below the Gulf of St. Lawrence and may in part be defined by a basement horst along the Hastings Fault (Martel, 1987). A poorly constrained and complex history of dip-slip and strike-slip motion generated the 8 km thickness of Carboniferous strata in the basin (Webb, 1963; Nance, 1987; Browne and Plint, 1994)

Figure 60: Geologic map of the western Cumberland Basin (Ryan *et al.*, 1990; Ryan *et al.*, 1990; Keppie, 2000; New Brunswick Department of Natural Resources and Energy, 2000; St. Peter, 2001).


Northumberland Strait
Caledonia Highlands
Joggins Formation
Chignecto Bay
Cobequid Highlands
Cobequid Bay
Minudie Anticline
Amherst Syncline
Tatamagouche Syncline
Black River Syncline
Springhill
Athol Syncline
Caledonia Fault
Harvey-Hopewell Fault
Shepody-Beckwith Fault
Hastings Fault
Tatamagouche Fault
Athol Fault
Sand Cove Fault
Sand River Fault
North Fault
Salcombe Cove Fault
Cobequid Fault
10 km
N
STRATIGRAPHY
Pennsylvanian
Mississippian
Steph.
Westphalian
Namurian
Visean
Toum.
Late Paleozoic to Mesozoic undivided (JPu)
upper Cumberland Group, undivided
Little River Fm. and equiv.
Boss Point Fm.
Precambrian-Carboniferous crystalline basement (pCCo)
SYMBOLS
anticline
syncline
fault

The Joggins Formation is preserved on the northern limb of the Athol Syncline, the dominant structural feature of the western Cumberland Basin (Fig. 60). This 25-km-wide by 75-km-long syncline is bounded by the Caledonia and Cobequid Highlands massifs to the south and west, the salt-cored Minudie Anticline to the north, and two unnamed salt diapirs to the east (Calder, 1994; Waldron and Rygel, Chapter 9). Thinning of stratal units against these salt structures indicates that halokinesis was syndepositional and greatly contributed to the creation of accommodation in the Athol Syncline, particularly in the early Pennsylvanian (Waldron and Rygel, Chapter 9). Although age control is poor, the 915.5-m-thick Joggins Formation (Figs. 61 and 62) was likely deposited over ~1 Ma in the early Langsettian (Dolby, 1991; dates of Menning *et al.*, 2000), during a period of subsidence that ranks among the most rapid recorded in Pennsylvanian coalfields (Calder, 1991).

Constantly hewn and renewed by the world's highest tides, the Joggins Formation is continuously exposed in a gently dipping coastal section with sea cliffs 20 m high and an intertidal zone 500 m wide (Fig. 61). The Joggins cliffs are widely considered to be the world's best exposure of coal-bearing Pennsylvanian strata, and an application for UNESCO World Heritage Site status is in preparation (Falcon-Lang and Calder, 2004).

### 6.3.2. Facies associations and cycles.

Joggins Formation strata have been divided into three facies associations and fourteen cycles (Davies and Gibling, 2003; Davies *et al.*, submitted; Table 8; Figs. 61 and 62). Cycles range from 16 to 212 m in thickness and probably record Milankovitch-scale glacioeustatic fluctuations within a rapidly subsiding basin (Davies and Gibling, 2003; Falcon-Lang, 2003). Climate change may have influenced these cyclic strata, but its

Figure 61: Labeled air-photograph showing the coastal exposure of the Joggins Formation at its type section; labels designate cycles and the stratigraphic position of prominent outcrops in the intertidal zone. The image is a mosaic created from air-photographs A18580-125 (1:15,840) and 85314-3 (1:10,000), available from the Nova Scotia Department of Housing and Municipal Affairs, Land Information Services Division.

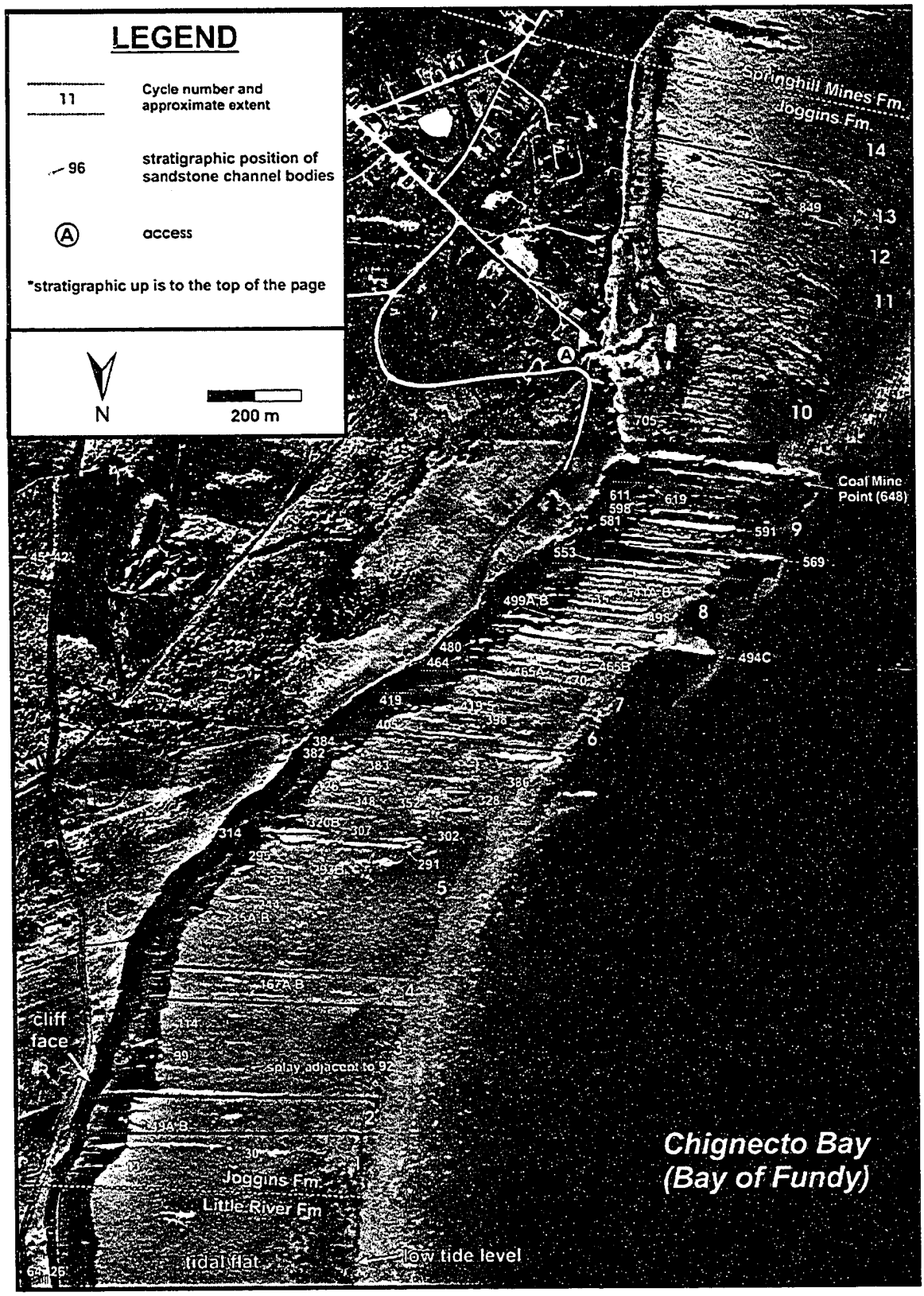
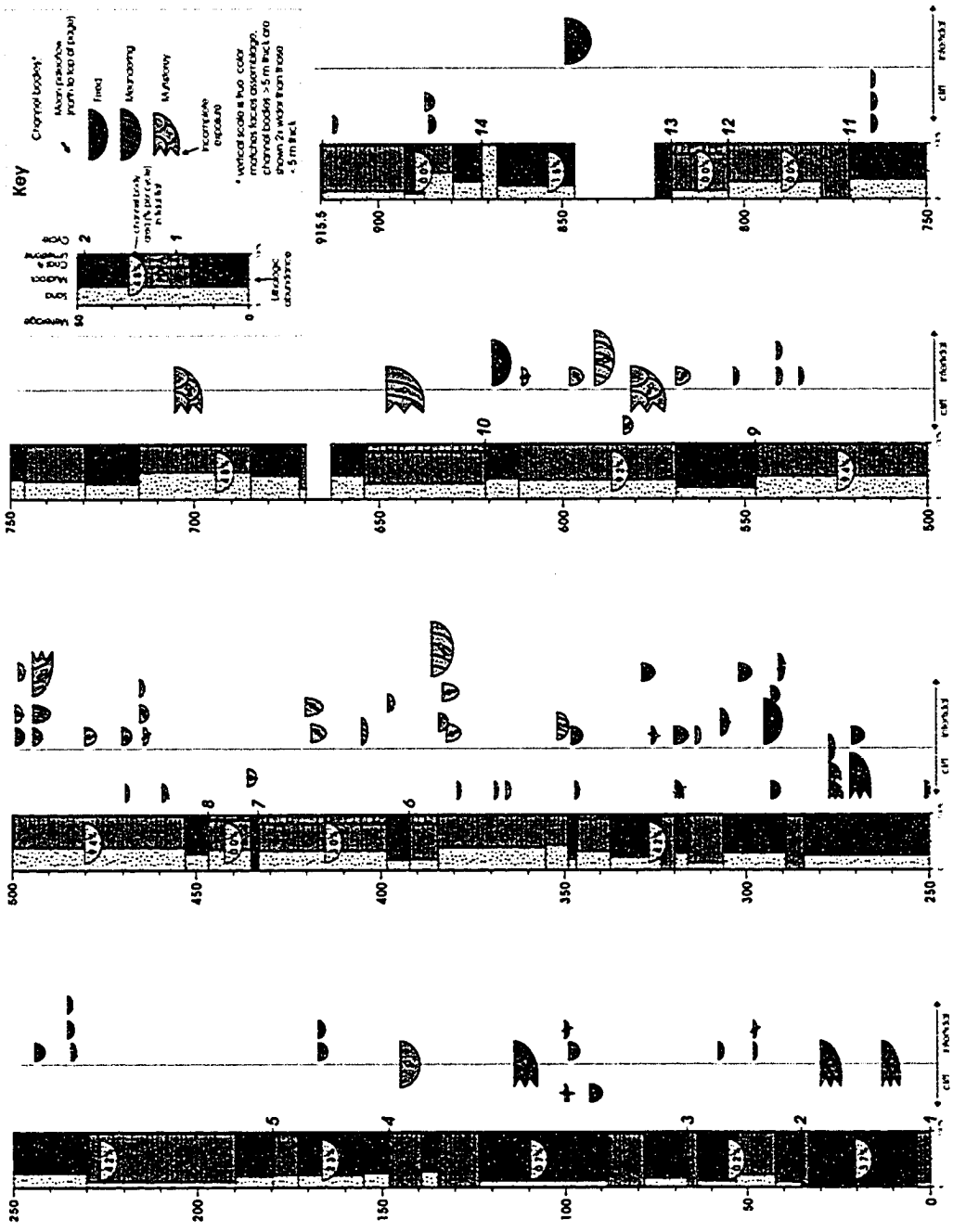

LEGEND
11
Cycle number and approximate extent
96
stratigraphic position of sandstone channel bodies
A
access
*stratigraphic up is to the top of the page
N
200 m
Springhill Mines Fm.
Joggins Fm.
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Coal Mine Point (648)
705
611
619
598
581
591
553
569
499A-B
494C
480
464
466A
466B
419
384
382
383
380
328
314
307
302
291
167A-B
99
splay adjacent to 92
Joggins Fm.
Little River Fm.
tidal flat
low tide level
cliff face
Chignecto Bay
(Bay of Fundy)

Figure 62: Summary log of the Joggins Formation showing meterage, cycles, channel body location, types, and paleoflow (based on detailed measured section in Davies *et al.*, submitted). OW = Open Water association, PDF = Poorly Drained Floodplain association, WDF = Well Drained Floodplain association.


Key
Channel bodies*
Main reservoir
Inlet
Meandering
Migratory
Incomplete
outcrop
Lithofacies
Landscape
downstream
Cliff
Cliff

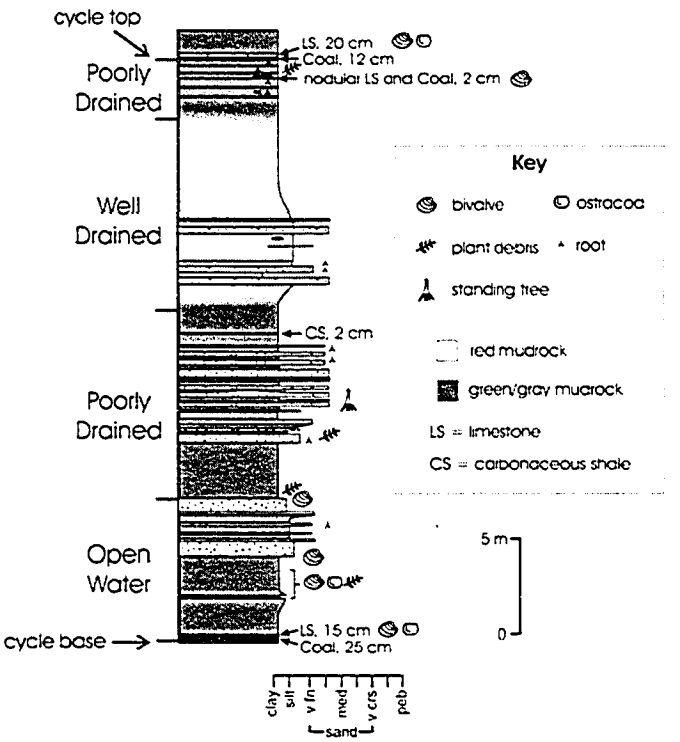



Figure 63: Facies succession and sedimentology of cycle 2, a representative Joggins cycle.

| | Well Drained Floodplain | Poorly Drained Floodplain | Open Water |
|---|---|---|---|
| **Common Lithologies** | Red mudrock, channel bodies, sheet sandstone, thin limestone and carbonaceous shale (both rare) | Green and grey mudrock, channel bodies, sheet sandstone, coal (<1 m thick), thin limestone, carbonaceous shale | laminated grey to black mudrock, carbonaceous limestone, sharp-based sandstone |
| **Other Features** | Rare standing lycopsids up to 1 m tall, poorly developed paleosols | Standing lycopsids commonly 5-6 m tall, poorly developed paleosols | Some evidence of marine influence (Archer *et al.*, 1995; Tibert and Dewey, 2005) |
| **Formation-scale abundance** | 284.6 m = 31.1% | 516.4 m = 56.4% | 85.5 m = 9.3% |
| **% of cycle thickness** | 0 to 90% (20% mean) | 8 to 100% (40% mean) | 0 to 30% (9% mean ) |
| **Thickness of individual occurrences** | 2.2 to 57.8 m (16.7 m mean) | 1.8 to 93.2 m (17.1 m mean) | 0.6 to 22.0 m (7.8 m mean) |
| **Amount of sandstone within each occurrence** | 4 to 43% (25% mean) | 0 to 97% (24% mean) | 1 to 32% (16% mean) |
| **Total channel bodies** | 37 | 45 | 0 |
| **Channel bodies/ 100 m of section** | 13.0 | 8.7 | 0 |

Table 8: Sedimentological information for the three facies associations of the Joggins Formation, based in part on Davies and Gibling (2003) and Davies *et al.* (submitted). Note that the formation-scale abundance row only adds up to 96.8%; the remaining 3.2% is covered.

influence is not clear, given the rapid subsidence and probable changes in relative sea-level that affected this area in the Pennsylvanian.

A typical cycle (Fig. 63) commences with a pronounced flooding event, as recorded by the fresh to brackish facies of the open water (OW) association (Table 8). This association represents only 9% of the formation, but the flooding events covered much of the basin, as indicated by floral evidence (Falcon-Lang, 2003b) and the lateral extent of flooding surfaces (Copeland, 1959; Calder, 1991), and may have been at least periodically marine influenced (Duff and Walton, 1973; Archer *et al.*, 1995; Skilliter, 2001; Falcon-Lang, 2005; Tibert and Dewey, 2005). These incursions probably entered the basin from the northeast (Gibling *et al.*, 1992), indicating that facies belts extended no more than a few tens of kilometers in any direction (the adjacent highlands are separated by ~60 km).

The poorly drained floodplain (PDF) association represents wetlands that flourished in coastal areas of the floodplain with high water tables, as well as locally inland. This association comprises 56% of the formation, and comprises drab-colored mudrock, channel and sheet sandstones, coal, and thin lacustrine limestones (Table 8; Davies and Gibling, 2003; Davies *et al.*, submitted) The thickest PDF deposits formed during progradation of the floodplain after a cycle-bounding flood event, but thinner, retrogradational and aggradational occurrences are present locally. Two channel bodies encased within OW deposits in cycle 9 represent the most basinward expression of poorly drained floodplain conditions.

The well drained floodplain (WDF) association represents a floodplain that was above the water table for much of the year. Well drained deposits make up 31% of the

formation, and comprise red mudrock, channel and sheet sandstones, and rare (thin) limestones and carbonaceous shales (Table 8; Davies and Gibling, 2003; Davies *et al.*, submitted). The WDF probably represents progradational and aggradational phases of dryland floodplain sedimentation.

### 6.3.3. Sequence stratigraphy.

Davies and Gibling (2003) and Davies *et al.* (submitted) interpreted the Joggins Formation as having a "tectonic architecture," wherein cycles bounded by flooding surfaces are stacked parasequence sets with predominantly progradational and aggradational sedimentation patterns. They inferred that the section lacks Exxon-style sequence boundaries (Van Wagoner *et al.*, 1990) on the grounds that multistorey channel bodies do not mark a basinward shift in facies and cannot be traced into well developed paleosols or erosional surfaces in the adjacent floodplain sediments – observations confirmed in this study. Paleosols are immature, cumulative alluvial types (Smith, 1991; Davies and Gibling, 2003). Thin limestones and laminated shales represent widespread flooding events, but water depth was probably never more than a few meters. This flooding-dominated stratal architecture probably represents rapid subsidence, and records the delicate balance between subsidence, sediment supply, and glacioeustasy that persisted throughout deposition of the formation (Davies and Gibling, 2003; Falcon-Lang, 2003)

### 6.3.4. Nature and proportion of overbank deposits.

The abundance and mud content of overbank deposits in a fluvial system can profoundly affect the behavior and geometry of the associated channels (Allen, 1978; Bridge and Leeder, 1979). Based on the measured section (Davies *et al.*, submitted) and

air-photographs of the tidal flats, overbank deposits in the well drained and poorly drained floodplain successions contain similar proportions of sandstone (25% and 24%, respectively) and have comparable numbers of channel bodies per unit thickness (13.0 and 8.7 bodies per 100 m, respectively). Airphoto analysis of outcrop surface areas also shows that channel bodies make up 3.5% of the Joggins Formation, a significantly lesser value than the 9.7% present in the measured section. This analysis shows that channel bodies comprise a small proportion of the formation and that, on aggregate, the poorly and well drained facies associations contain similar overbank sand:mud proportions, with little upward change through the section. Despite the marked decrease in the amount of sandstone that crops out in the tidal flat above the 650 m level (Fig. 61), the measured section shows that the proportion of overbank sandstone stays relatively constant above the 150 m level (Fig. 62). Comparison of the surface area of channel bodies and overbank deposits in the tidal flat shows that the change above the 650 m level reflects a marked decrease in the abundance of channel sandstones, from 4.3% in the lower ten cycles to 0.7% in the upper four cycles (Fig. 62). This is the second of three apparent coarsening upwards cycles in the western Cumberland Basin (Gibling, 1987), the lowest (and most dramatic) of which corresponds to a change from sand-rich to sand-poor facies which can be traced across the Maritimes Basin (Rehill, 1996).

### 6.4. Dataset and Methods

Eighty-two channel bodies ≥1 m thick are exposed in cliff and accessible tidal-flat exposures (Figs. 61 and 62). Channel bodies are identified with a number that corresponds to the meterage at their uppermost level (Figs. 61 and 62), and multiple channels at a given horizon are designated with letters (alphabetically from cliff top to

Table 9: Nomenclature used to describe the channel bodies of the Joggins Formation, based on Thomas *et al.* (1987), Miall (1996), and Gibling (submitted).

## Alluvial Lithofacies

| | | | |
|---|---|---|---|
| Gp | Planar cross-bedded gravel | Sl | Low-angle laminated sandstone |
| St | Trough cross-bedded sandstone | Fl | Laminated mudrock |
| Sp | Planar cross-bedded sandstone | Fm | Massive mudrock |
| Sr | Ripple cross-laminated sandstone | Fr | Rooted mudrock |
| Scr | Climbing ripple-cross laminated sandstone | IS | Inclined Strata |
| Sh | Horizontally-laminated sandstone | IHS | Inclined Heterolithic Strata |
| Sm | Massive sandstone | | |

## Architectural Elements

| | | | |
|---|---|---|---|
| CH | Channel (predominantly sandstone) | GB | Gravel bar or bedform |
| AF | Abandoned channel fill (mudrock) | DA | Downstream-accretion macroform |
| LA | Lateral-accretion macroform | SB | Sandy bedform |

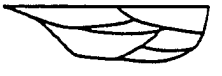
## Bounding Surfaces

| | | | |
|---|---|---|---|
| 6th order | Channel-belt bounding | 3rd order | Macroform reactivation and growth |
| 5th order | Channel-element bounding | 2nd order | Coset bounding |
| 4th order | Macroform bounding | 1st order | Set bounding |

| Channel Body Width (W) | | Channel Body Thickness (T) | | Channel Body W/T | |
|---|---|---|---|---|---|
| 100-1000 m | Medium | 5-15 m | Medium | 100-1000 | Broad Sheets |
| 10-100 m | Narrow | 1-5 m | Thin | 15-100 | Narrow Sheets |
| 1-10 m | Very Narrow | | | 5-15 | Broad Ribbons |
| | | | | <5 | Narrow Ribbons |

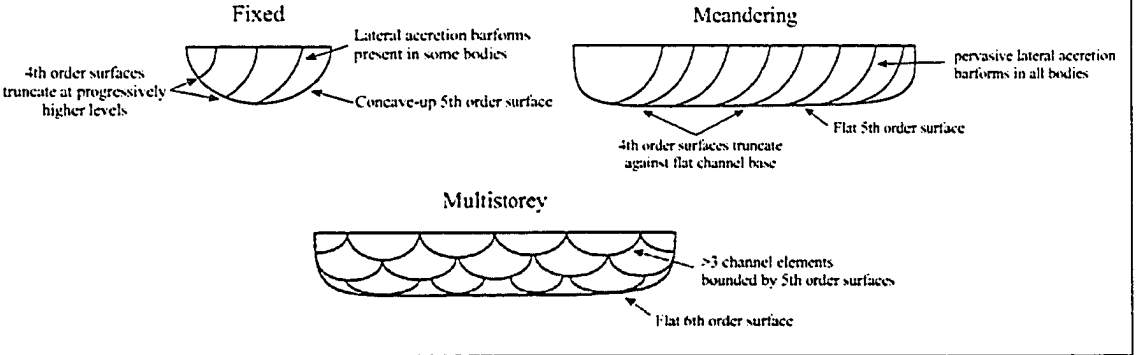
## Internal Organization

Erosion-dominated: Poorly preserved channels, numerous erosion surfaces



Succession Dominated: Nearly complete channels, only modest erosion of upper beds

## Channel Body Type



low-tide level). Photomosaics of bodies exposed in the cliff and enlarged air-photographs of those exposed in the tidal flat served as a base upon which detailed sedimentological 60 bodies, and only bidirectional indicators (channel margins, primary current lineation, tool and groove casts) in 7 bodies. Where available, paleoflow indicators were used to distinguish between lateral accretion and downstream accretion barforms, the former with flow near-perpendicular to the dip direction of the inclined sets. The gentle inclination of the section (<22°) made it unnecessary to correct linear paleoflow measurements for structural dip (Potter and Pettijohn, 1977). The EZ-ROSE program of Bass was used to conduct statistical analysis and construct rose diagrams. Mean paleoflow values for each channel body (Fig. 62) were calculated by averaging measurements from the most reliable structures available (generally channel margins, trough cross-beds, and ripple cross-laminae).

### 6.4.2. Channel-body geometry.

The apparent width of the 67 bodies with paleoflow data were corrected for paleoflow obliquity relative to the outcrop orientation using the equation:

$$W_C = W_A \times \text{cosine (variance of mean paleoflow from tectonic strike } (\pm 90°))$$

where: $W_C$ = corrected width

$W_A$ = apparent width

Following convention, the geometry of the channel bodies was characterized by dividing their corrected width by their maximum thickness to provide a true width/thickness (W/T) value. Despite the superb exposure, true width (and thus W/T) values could only be calculated for 54 channel bodies, and reported W/T values for the

| True thickness | Paleoflow data | Complete lateral exposure | Type of W/T value | Number of channel bodies |
|---|---|---|---|---|
| yes | yes | yes | True W/T | 54 |
| yes | yes | no | Minimum W/T | 12 |
| yes | no | yes | Maximum W/T | 16 |

Table 10: Quality of channel body exposure in the Joggins Formation.

remaining 28 bodies are minima or maxima due to incomplete exposure or lack of paleoflow data, respectively (Table 10). W/T values discussed below refer to these 54 bodies, unless otherwise indicated. Detailed information about channel body type, geometry, location, and paleoflow are provided in Appendix 4.

### 6.4.3. Paleochannel reconstruction

Where possible, data from the channel bodies were used to estimate the original (decompacted) dimensions of the parent channels. For all single storey, untruncated channel bodies and for completely preserved storeys, channel elements (CH) and abandoned channel fills (AF), maximum bankfull depth (D) was derived by decompacting the thickness of the body by 10% (Bridge and Mackey, 1993). For these sediment bodies, the maximum width represents the bankfull channel width ($W_b$). For meandering bodies, $W_b$ was calculated assuming that the lateral extent of a fourth order surface within lateral accretion deposits represents 2/3 of the former bankfull channel width when measured perpendicular to the orientation of the channel margin (Allen, 1965; Leeder, 1973).

### 6.4.4. Statistical analysis.

Width and thickness were plotted on log-log diagrams, with a best-fit trendline fitted to points with W/T values. Dimensional values were statistically analyzed to answer the following questions:

1) For a given channel body type, are there significant differences in thickness and W/T between examples in the poorly drained and well drained facies associations?

2) Are there significant differences in thickness and W/T between the three channel body types when data from the two facies associations are combined?

3) How similar (or dissimilar) were the width and depths of the active channels that formed the different types of channel bodies?

Geometric parameters were analyzed for variance using single factor Analysis of Variance (ANOVA) tests in Microsoft Excel. When comparing the means of two populations, both ANOVA and t-tests produce the same probability value (p-value), but the ANOVA test has the capacity to simultaneously analyze more than two populations in a single test (Moore, 1994). Results of the statistical analyses are reported as p-values displayed on box plots of the data. In all cases where a statistically significant p-value is reported, the accompanying F-value (a measure of the distance between distributions) was greater than the critical value needed for statistical validity.

### 6.5. Channel Body Classification

The channel bodies are divided into three types, each of which is represented in both well drained and poorly drained associations (Table 9; Fig. 64). The majority of channel bodies are of *fixed* type (n = 63), relatively thin and narrow (ribbons to narrow sheets) with prominent incised margins, and almost all comprise a single storey. Where the fills include lateral accretion sets, successive inclined strata onlap the basal erosional surface at progressively higher levels (Table 9), indicating that the rate of migration of bank-attached bars outpaced the rate of bank retreat and that lateral migration was of limited extent.

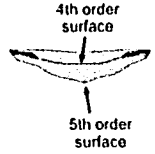
A few channel bodies are of *meandering* type (n = 14), consisting of a single storey with incised margins and more extensive lateral accretion sets that onlap flat-lying

Figure 64: Summary diagram showing the three types of channel bodies present in the Joggins Formation. Channel bodies are at the same scale and have been drafted to show a cross-sectional view that is perpendicular to the mean flow direction and corrected for tectonic dip. Examples from each facies association and distinctive subtypes are shown; bounding surface orders are labeled one example of each channel body type.

## Well Drained Fixed Channel Bodies

Form: Narrow to broad ribbons (W:T = 2.5 to 14.3)

Thickness: Thin to medium (1.3 to 7.5 m)




Through-going anastomosed rivers (channel body 271, Fig. 67)

Crevasse-splay channels (channel body 93, similar to Fig. 68)

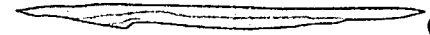
## Poorly Drained Fixed Channel Bodies

Form: Narrow to broad ribbons, one narrow sheet (W:T = 2.5 to 19.5)

Thickness: Thin (1.0 to 5.5 m)

Anastomosed tributaries and distributaries; crevasse-splay channels (channel body 887, Fig. 69)

Mudrock-filled abandoned distributaries (channel body 145, similar to Fig. 70))



Distal distributaries (channel body 569, Fig. 71)

## Key

All channel bodies shown at same scale

Sandstone

Mudrock

Overbank sandstone

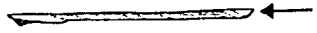
Incomplete exposure

bounding surfaces from Table 9

## Well Drained Meandering Channel Bodies

Form: Narrow sheets (W:T = 22.0 to 63.9)

Thickness: Thin (1.8 to 3.5 m)



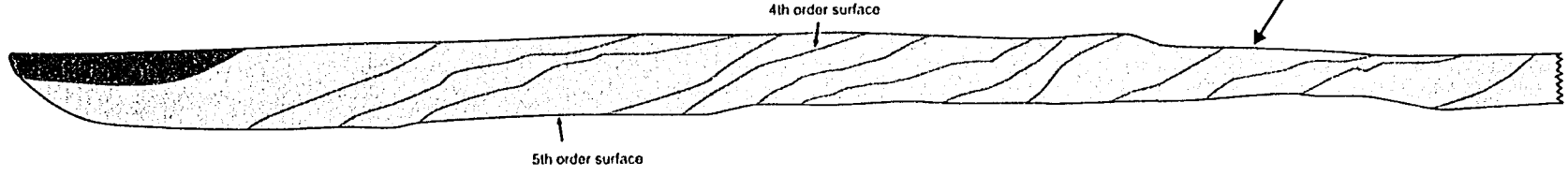
Late-stage, seasonally active channels (channel body 274C, Fig. 67)

## Poorly Drained Meandering Channel Bodies

Form: Broad ribbons to narrow sheets (W:T = 11.8 to 35.0)

Thickness: Thin to medium (1.7 to 10.5 m)

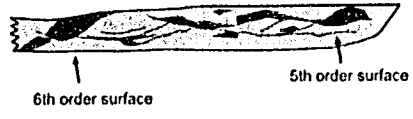
Small tributaries and crevasse splay channels; major drainages (channel body 648, Fig. 73)




## Well Drained Multistorey Channel Bodies

Form: Narrow to broad sheets? (minimum W/T = 7.8 to 56.3)

Thickness: Medium (5.3 to 6.5 m)




Paleovalleys filled by smaller channels (channel body 114, Fig. 74)

## Poorly Drained Multistorey Channel Bodies

Form: Narrow to broad sheets? (minimum W/T = 8.1 to 12.4)

Thickness: Medium (7.4 to 9.2 m)

Paleovalleys filled by smaller channels (channel body 581, Fig. 75)

channel bases. They are broader than the fixed types (mostly narrow sheets) but of similar thickness, and may represent local reaches within arrays of anastomosed channels where rates of bank retreat and bar advance were in balance for a prolonged period. Fixed and meandering channel bodies are incised through floodplain deposits from the same level at numerous horizons, suggesting that they formed part of through-going anabranching systems or, in a few cases, of distributary crevasse systems within sandy overbank deposits. A few meandering channel bodies in coastal deposits are considerably thicker and more extensive than the others and represent mobile channel belts (Friend *et al.* 1979), rather than local meandering reaches.

Five *multistorey* bodies are relatively thick but appear narrow because only one margin was observed; if completely exposed these bodies would probably form narrow to broad sheets. They comprise a complex of erosional lenses or a vertically stacked succession of storeys, and are interpreted as valley fills on the grounds that their component channels are much smaller in scale than the bodies themselves (Dalrymple *et al.*, 1994). However, there is clear evidence that these valley fills represent major events of incision and basinward facies migration. Consequently, the term "paleovalley" is used only to describe the paleogeomorphology of the fluvial systems, not to imply sequence stratigraphic significance. Multistorey channel bodies are commonly associated with Exxon-style sequence boundaries (Van Wagoner *et al.*, 1990; Shanley and McCabe, 1991, 1993; Olsen *et al.*, 1995), but it is unclear whether the Joggins examples represent paleovalleys formed by sea level fall (Type 1 paleovalleys) or by other factors such as tectonism or climate change (Type 2 paleovalleys, terminology of Dalrymple *et al.*, 1994).

## 6.6. Fixed Channel Bodies

### 6.6.1. Well drained floodplain

6.6.1.1. Description.

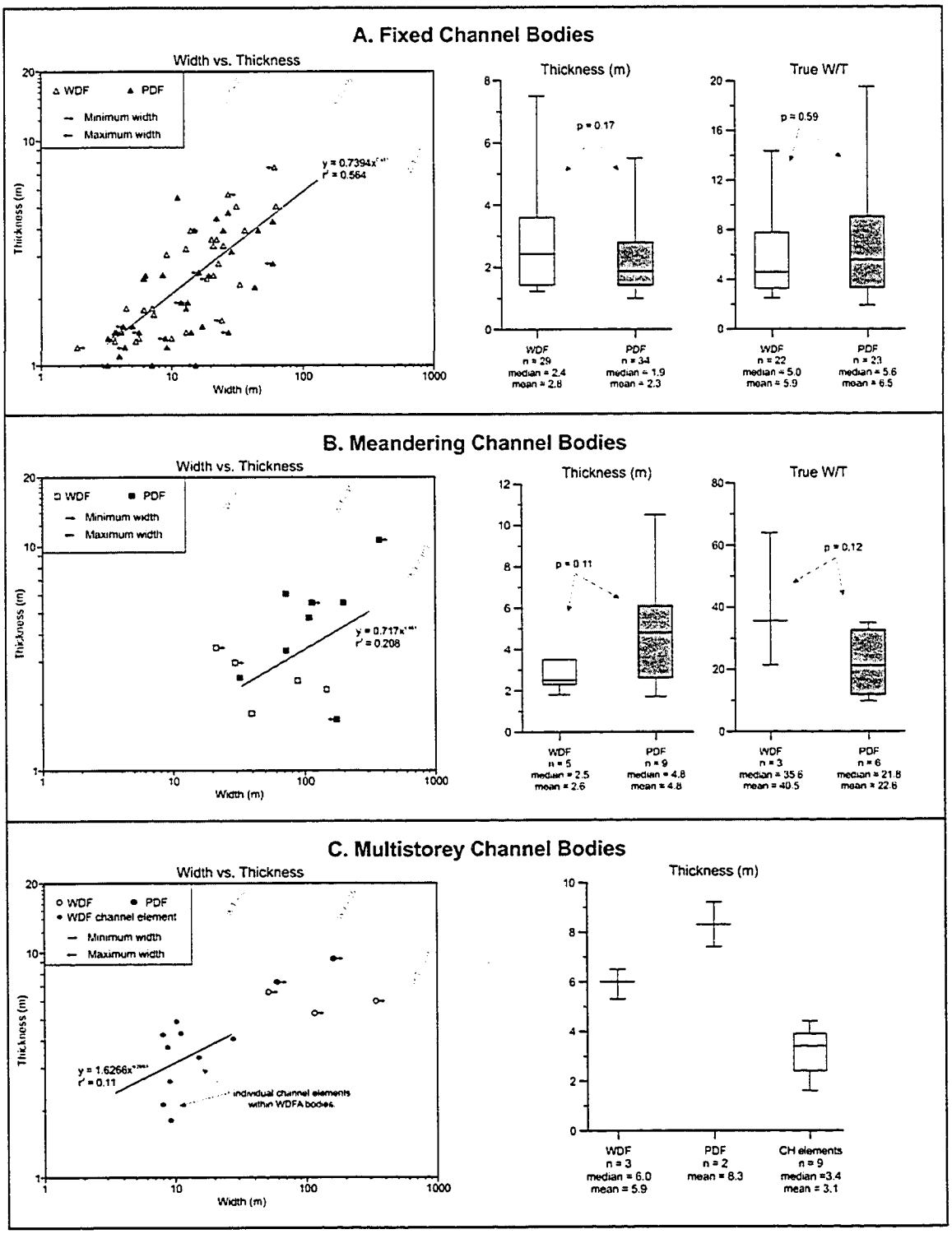
Twenty nine fixed channel bodies occur in the well drained association (Table 11). These bodies are up to 7.5 m thick with W/T less than 14.3 (Fig. 65A). Channel bases are concave-up, cut into the underlying floodplain sediments, and some channel bodies pass laterally into sandy wings whereas others terminate abruptly against mudstone. Although most bodies contain only a single storey, two examples have two stacked storeys. Multiple (2-3) fixed channels incise from the same horizon at five different levels (Fig. 66), and fixed and meandering channel bodies incise from the same level at two horizons.

Sandy bedforms, downstream accretion, and lateral-accretion barforms are the most common architectural elements (271, 271.5, and 274A in Fig. 67), and fourth-order, inclined surfaces commonly cut through the channel fill to define bar forms. Trough cross-beds, horizontal and low-angle laminae comprise the basal fill of large fixed channel bodies, whereas smaller bodies and the upper portions of larger bodies are composed almost entirely of ripple cross-laminated sandstone. Laminated to massive mudrock forms beds within accretion sets and at body tops, with local plugs near the terminal end of lateral accretion deposits. Stems and finely comminuted fragments of plants (calamites and other dryland floras described by Falcon-Lang, 2003) are abundant throughout channel fills.

Table 11: Characteristics of fixed channel bodies in the Joggins Formation.

| | Well Drained Floodplain | Poorly Drained Floodplain | | |
|---|---|---|---|---|
| | | Sandstone-filled | Mudrock-filled | Distal Distributaries |
| **Total Number** | 29 | 30 | 2 | 2 |
| **Thickness** | 1.2 to 7.5 m (2.8 m mean) | 1.0 to 4.8 m (2.2 m mean) | 4.0 and 5.5 m | 1.5 and 4.3 m |
| **True W/T** | 2.5 to 14.3 (6.1 mean) | 2.5 to 19.5 (5.9 mean) | 11.3 and 2.0 | 11.3 and 13.5 |
| **Other W/T** | Min: 1.6 to 4.8 (n = 3)<br>Max: 7.8 to 14.1 (n=4) | Maximum: 2.7 to 20.0 (n = 10) | NA | NA |
| **Channel Base** | Concave-up fifth order surface | Concave-up fifth order surface | Concave-up fifth order surface | Concave-up fifth order surface |
| **Storeys** | 1, two examples have 2 | Generally 1, minor overlap in several others | 1 | 1 |
| **Fill Organization** | asymmetric, concentric, and horizontal | asymmetric, concentric, and horizontal | Horizontal | horizontal |
| **Macroforms** | SB, DA, LA, AF | SB, DA, LA AF | AF with minor SB | SB and DA |
| **Grain Size** | Fine- to medium-grained sandstone (FS and MS, respectively); mudrock and pebble-sized intraformational conglomerate (IFC) locally | FS to MS; mudrock and pebble-sized IFC locally | Mudrock with FS, MS, and pebble-sized IFC locally | Fine- to medium-grained sandstone; mudrock locally |
| **Common Lithofacies** | Sr, St, Sl, Sh, Fl and Fm | Sr, Sm, St, Sl, Sh, Fl and Fm | Fl, Fm, Sr, Scr | St, Sr, Scr |
| **Paleochannel Depth** | 1.3 to 8.3 m (3.3 m mean) | 1.1 to 6.1 m (2.4 m mean) | | |
| **Paleochannel W/D** | 2.3 to 13.0 (5.6 mean) | 1.8 to 17.8 (5.7 mean) | | |
| **Modern Analogues** | Channel Country of Australia (Gibling *et al.*, 1998); crevasse channels in the Northern Plains of Australia (Schumm *et al.*, 1996; Tooth, 1999). | Magdalena and Columbia Rivers (Smith and Putnam, 1980; Smith and Smith, 1980; Smith, 1986); Saskatchewan River (Morozova and Smith, 1999; Pérez-Arlucea and Smith, 1999; Morozova and Smith, 2000); Atchafalaya Delta of Louisiana (van Heerden and Roberts, 1988) | Barwon and South Alligator Rivers (Taylor and Woodyer, 1978; Woodyer *et al.*, 1979; Woodroffe *et al.*, 1989) | mouth bar-crevasse channel couplets in the Mississippi River (Coleman *et al.*, 1964; Elliott, 1974) |
| **Ancient Analogues** | Cutler Formation (Eberth and Miall, 1991); Springhill Mines Formation (Rust *et al.*, 1984); Willwood Formation (Kraus and Gwinn, 1997); Cutler Formation (Eberth and Miall, 1991) | Paleo-Mississippi and Rhine-Meuse systems (Törnqvist, 1993; Törnqvist *et al.*, 1993; Aslan and Autin, 1999); Dakota Formation (Kirschbaum and McCabe, 1992); St. Mary's River Formation (Nadon, 1994); Willwood and St. Mary's River Formations (Nadon, 1994; Kraus and Gwinn, 1997). | Upper Cretaceous Units in Alberta (Eberth, 1996) | Olsen's (1993) channel-mouth complexes; Fielding's (1984) medial crevasse splay/minor delta |

Figure 65: Log-log width/thickness (W/T) plots for the three different types of channel bodies in the Joggins Formation. Thickness and W/T information is also presented as box diagrams labeled with the results of the statistical analyses. Following convention, the box defines the area between the $25^{th}$ and $75^{th}$ percentiles and the center line represents the median. For populations with less than 4 points, the box is omitted and the center line represents the median (n = 3) or mean (n = 2).


A. Fixed Channel Bodies
Width vs. Thickness
WDF
PDF
Minimum width
Maximum width
y = 0.7394x^0.4
r² = 0.564
Thickness (m)
Width (m)
Thickness (m)
p = 0.17
WDF
n = 29
median = 2.4
mean = 2.8
PDF
n = 34
median = 1.9
mean = 2.3
True W/T
p = 0.59
WDF
n = 22
median = 5.0
mean = 5.9
PDF
n = 23
median = 5.6
mean = 6.5
B. Meandering Channel Bodies
Width vs. Thickness
WDF
PDF
Minimum width
Maximum width
y = 0.717x^0.4
r² = 0.208
Thickness (m)
Width (m)
Thickness (m)
p = 0.11
WDF
n = 5
median = 2.5
mean = 2.6
PDF
n = 9
median = 4.8
mean = 4.8
True W/T
p = 0.12
WDF
n = 3
median = 35.6
mean = 40.5
PDF
n = 6
median = 21.8
mean = 22.8
C. Multistorey Channel Bodies
Width vs. Thickness
WDF
PDF
WDF channel element
Minimum width
Maximum width
y = 1.6266x^0.2
r² = 0.11
individual channel elements within WDFA bodies
Thickness (m)
Width (m)
Thickness (m)
WDF
n = 3
median = 6.0
mean = 5.9
PDF
n = 2
mean = 8.3
CH elements
n = 9
median = 3.4
mean = 3.1

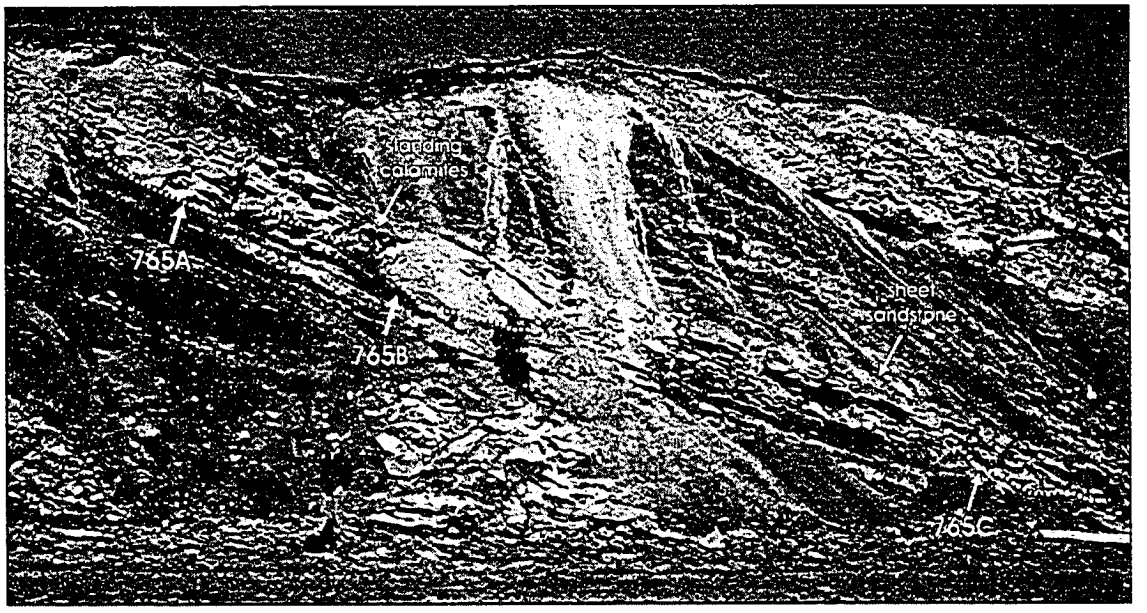
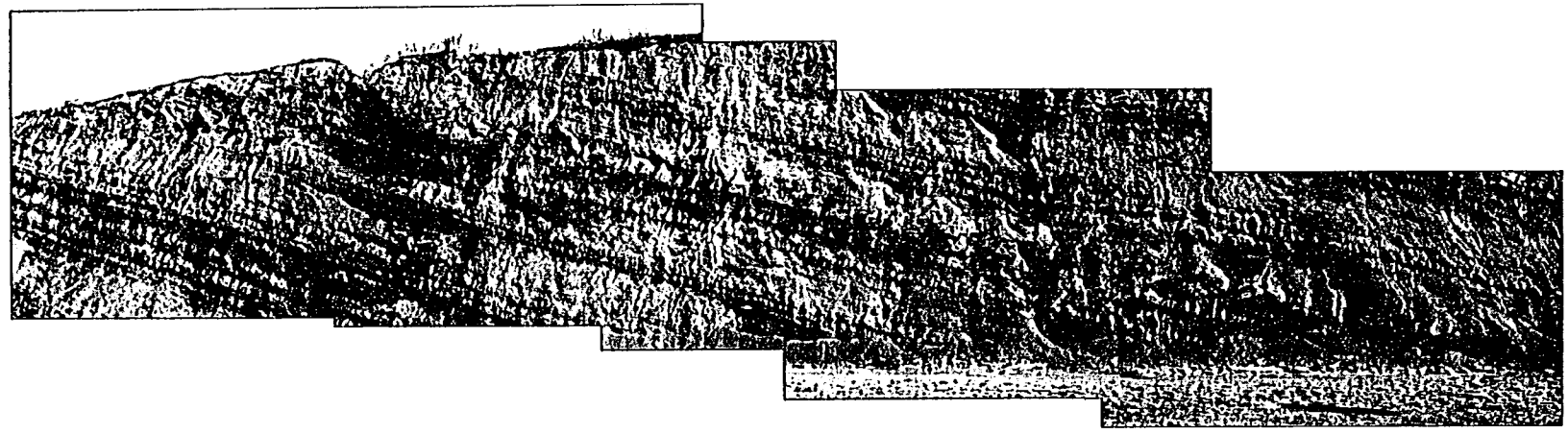
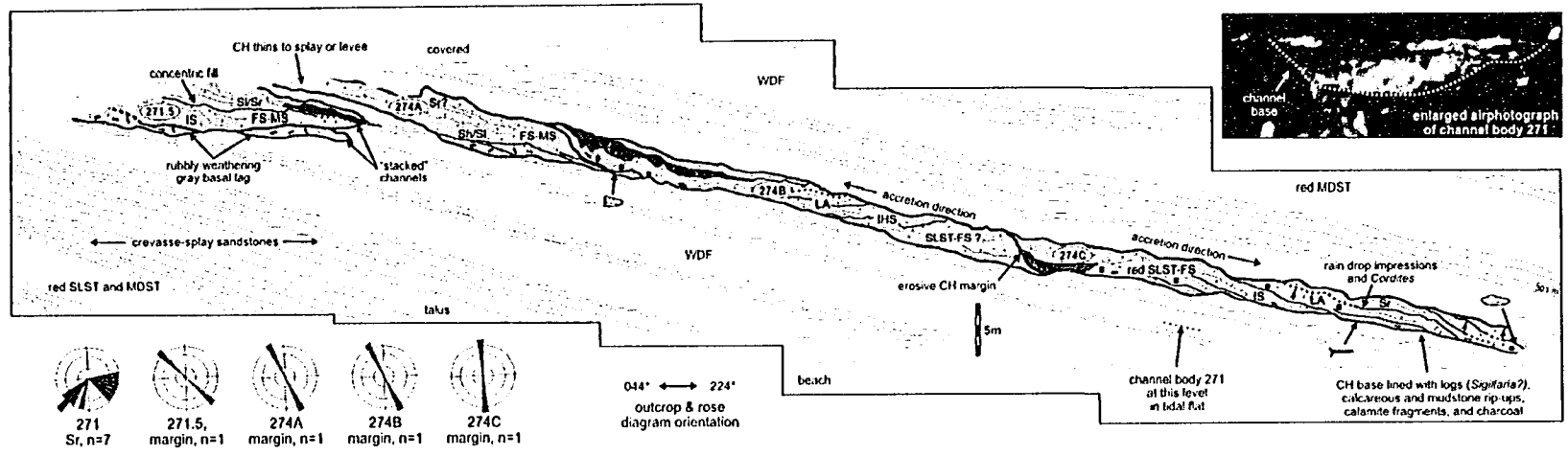



Figure 66: Photo of multiple channels at 765 m in the measured section. Person for scale.

Figure 67: Photograph and interpretive tracing of fixed (271, 271.5, 274) and meandering (274B-C) channel bodies within the well drained facies association of cycle 5. Circled numbers indicate the stratigraphic position of each channel body. Enlarged air-photograph of channel body 271 presented at the same scale as the photograph. Fixed channels encased predominantly by mudrock are interpreted as the deposits of a through-going anastomosed system. Modified after Falcon-Lang *et al.* (2004).






**Bounding Surfaces**

- 5th order surface (channel belt bounding)
- 4th order surface (channel element bounding)
- 3rd order (macroform reactivation surface)
- 1st - 2nd order (bounds sets or cosets, defines bedding)
- * lines dashed where exact location unclear

**Grain Sizes**

MDST = undiff. mudstone; FS = fine-grained sst.
SLST = siltstone; MS = medium-grained sst

**Lithofacies and Architectural Elements**

Fl = laminated to massive mudrock
Sh, Sl = horizontally- or low angle laminated sandstone
Sr = ripple laminated sandstone
St = trough cross-bedded sandstone
IS, IHS = inclined- or inclined heterolithic stratification
LA = lateral accretion deposits

**Genetic Interpretations**

- sandy channel-fill (FS-MS)
- muddy channel fill (MDST-SLST)
- crevasse-splay sandstones (FS-MS)
- overbank deposits (red MDST-SLST)

**Facies Associations**

PDF = Poorly Drained Floodplain; OWFA = Open Water
WDF = Well Drained Floodplain

**Fossils and Sedimentary Features**

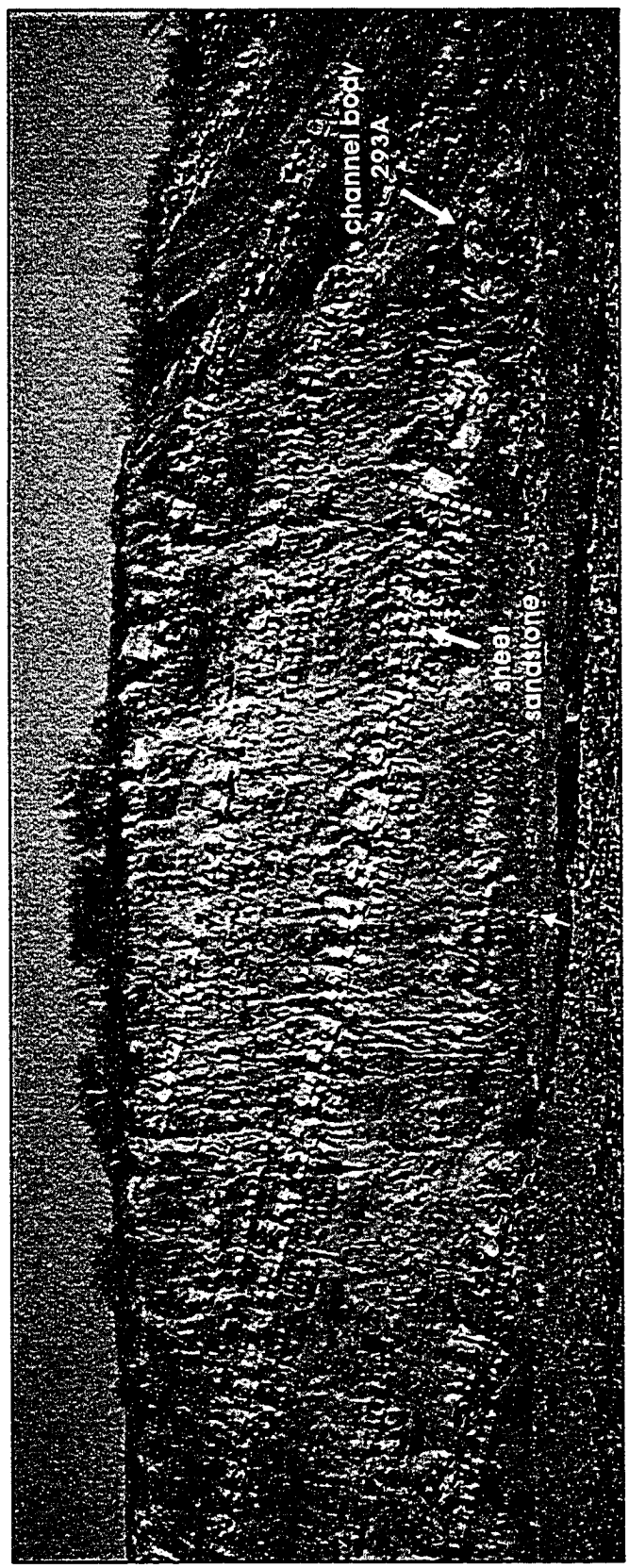
- bivalve
- mud chip rip up clasts
- calcareous rip up clasts
- charcoal
- drab haloed root compression
- transported log
- transported calamite

6.6.1.2. Interpretation.

The WDF fixed bodies are narrow to broad ribbons of thin to medium thickness (Fig. 64; Table 9) with average W/T of 5.9. The active channels responsible for these deposits were 1.3 to 8.3 m deep and had width/depth (W/D) of 2.3 to 13.0. Fixed channel bodies that are cut into muddy overbank deposits (Figs. 65 and 67) are interpreted as the deposits of stable, through-going anastomosed rivers and streams. They exhibit many of Makaske's (2001) characteristics of anastomosed deposits and, in particular, multiple channels incise from exactly the same level at seven different horizons. The active channels correspond to Nanson and Knighton's (1996) stable-sinuous, mud-dominated anabranching rivers, which are common in the Channel Country of Australia. Where present, bank-attached bars filled the channels faster than cutbank migration, perhaps because of the cohesive nature of the red floodplain bank material (Friend *et al.*, 1979; Rust and Legun, 1983) or because of riparian vegetation (Smith, 1976; Falcon-Lang *et al.*, 2004). This relationship underscores the abundance of sediment supply on the Joggins floodplain, a situation that may record rapid channel avulsion and marked seasonality (Cecil, 1990). Given the rapid subsidence of the Joggins floodplain, the anastomosed morphology may have been favored by rivers as a means of increasing channel roughness in order to maximize sediment transport into the rapidly subsiding Cumberland Basin (Nanson and Knighton, 1996; Nanson and Huang, 1998).

Fixed channel bodies that lie within sandy overbank sheets (Fig. 68) are interpreted as crevasse channels within overbank or avulsion deposits. Several such bodies incised from the same level provide compelling evidence that these channel body-overbank packages represent "tiers" formed as a network of crevasse channels spread

Figure 68: Photograph of channel 293A, a fixed channel within the well drained facies association of cycle 5. The thick, sandy overbank deposits associated with this channel body suggest that it was a short-lived crevasse splay channel. Person for scale (above lowermost arrow).


channel body
293A
sandstone
shale

across the floodplain (Kraus and Wells, 1999). The active crevasse channels may have resembled those of rivers in the Northern Plains of Australia (Tooth, 1999).

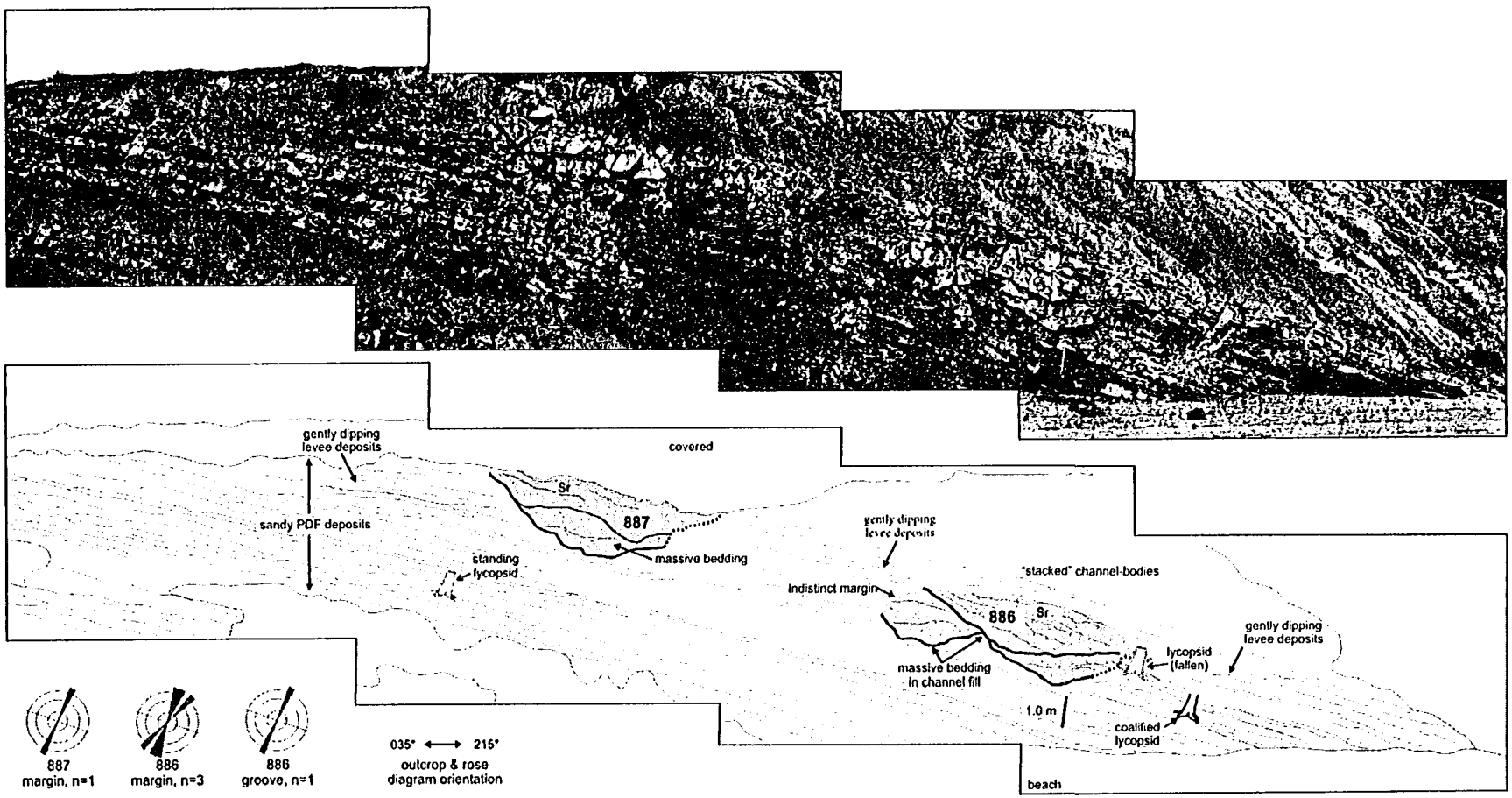
### 6.6.2. Poorly drained floodplain

6.6.2.1. Description.

Thirty channel bodies occur within poorly drained strata (Table 11), and are up to 5.5 m thick with W/T up to 19.5 (Fig. 65A). As in the well-drained association, channel bases are concave-up and almost all bodies comprise a single storey. The exceptions are channel body 886, which contains three storeys (Fig. 69), and minor overlap between bodies 382 and 384 (Fig. 70), which are largely separate. Multiple fixed channels incise from the same level at four horizons, and a fixed and a meandering channel body cut down from 499 m. Fill organization, macroforms, and lithofacies are also similar for the two facies associations (Table 11; Fig. 69), although root-penetrated mudrock is common and bedding structures are commonly obscured by soft-sediment deformation in PDF bodies. Mud-chips commonly line erosional surfaces. Nearly all sandstone-filled channel bodies pass into sandy wings; thin coals and mounded levee deposits flank channel bodies locally (Fig. 69). Stems and finely comminuted fragments of lycopsids and other wetland plants (Falcon-Lang, 2003) are abundant throughout channel fills.

Two fixed channel bodies with predominantly mudrock fills are present at 145 and 382 m, just below cycle-bounding flooding surfaces (Fig. 70). These single-storey bodies are filled with inclined heterolithic strata composed of laminated mudrock and ripple cross-laminated sandstone, which interfingers with ripple cross-laminated sandstone (<20% of the cross sectional area) that abuts against one edge of the channel

Figure 69: Photograph and interpretive tracing of sandstone-filled fixed channel bodies 886 and 887, which occur within the poorly drained facies association of cycle 14.




**Bounding Surfaces**

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- 3rd order (macroform reactivation surface)
- 1st - 2nd order (bounds sets or cosets, defines bedding)
- * lines dashed where exact location unclear

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SLST = siltstone; MS = medium-grained sst.

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- St = trough cross-bedded sandstone
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- LA = lateral accretion deposits

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- muddy channel fill (MDST-SLST)
- crevasse-splay sandstones (FS-MS)
- overbank deposits (red MDST-SLST)

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- drab-haloed root compression
- mud chip rip-up clasts
- transported log
- calcareous rip-up clasts
- transported calamite
- charcoal

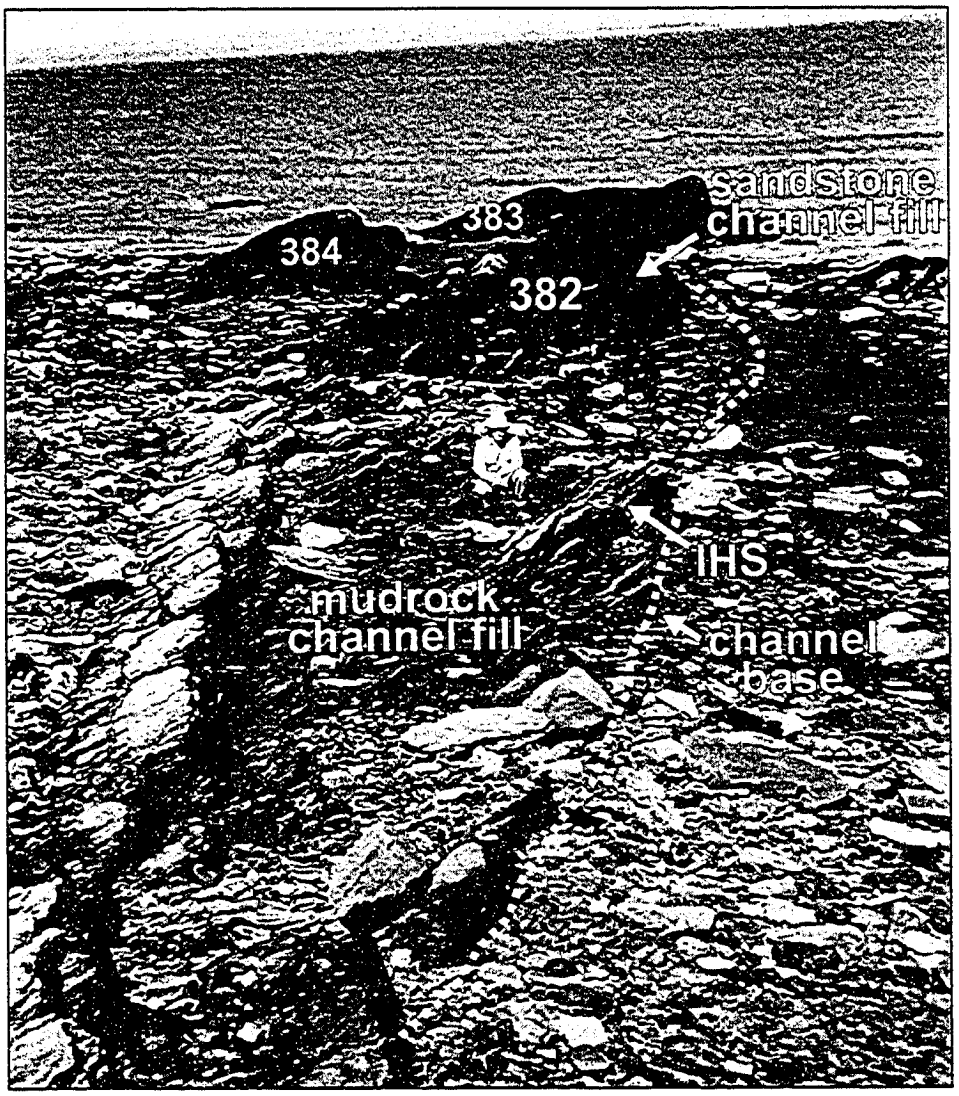
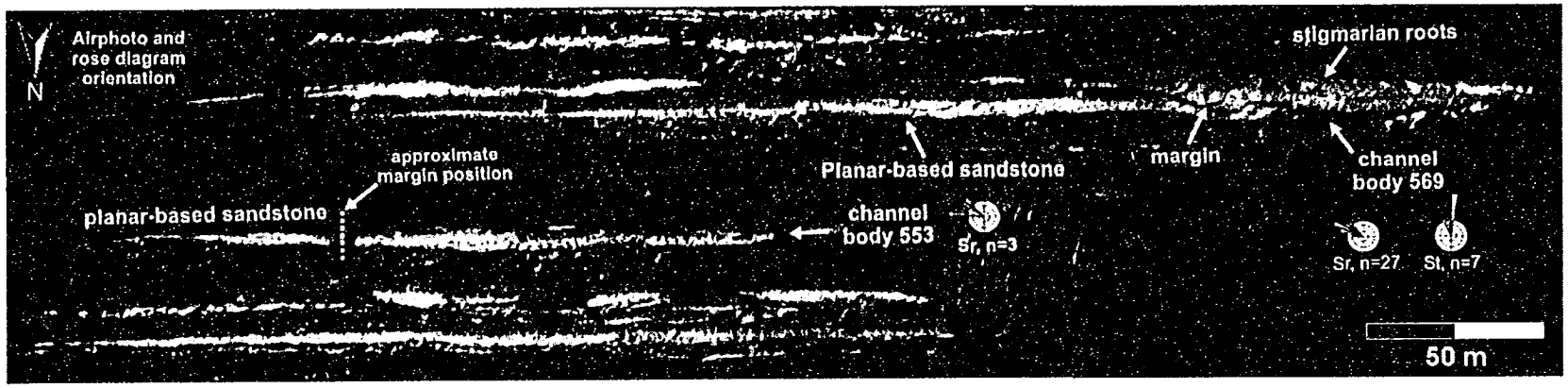



Figure 70: Photograph showing channel body 382, a mudrock-filled fixed channel body within the poorly drained strata of cycle 5. Channel bodies 383 and 384 are visible in the background. Person for scale.

Figure 71: Labeled air-photograph showing two fixed, distal distributaries within cycle 9 (image is an enlarged portion of Figure 61). These bodies are encased within strata of the open water facies association and represent the most basinward extent of the poorly drained facies association.


Airphoto and
rose diagram
orientation
N
stigmarian roots
approximate
margin position
Planar-based sandstone
margin
channel
body 569
planar-based sandstone
channel
body 553
Sr, n=3
Sr, n=27
St, n=7
50 m

body. The base of channel body 145 is lined with a lag of mud clasts, bivalve and ostracod shells.

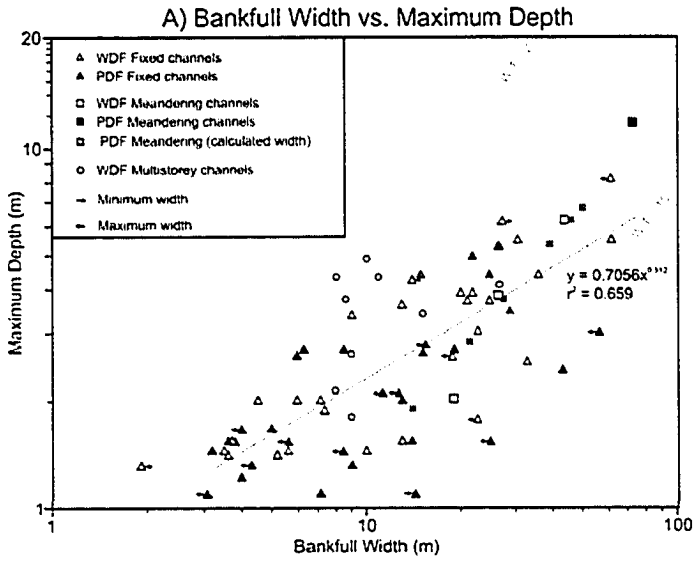
Channel bodies 553 and 569 represent the transition between open water and poorly drained conditions (Fig. 71). These bodies are up to 4.3 m thick and comprise downstream-accretion and sandy bedforms, both of which are locally cut by erosional surfaces. Trough cross-beds pass upwards into ripple cross-laminae and climbing ripples. These channel bodies cut and/or grade into planar-based, distal mouth-bar deposits emplaced by floods or hyperpycnal flows with wave reworking (Davies and Gibling, 2003). Soft-sediment deformation obscures bedding locally, and the uppermost surfaces of the channel bodies contain the stigmarian roots of lycopsid trees.

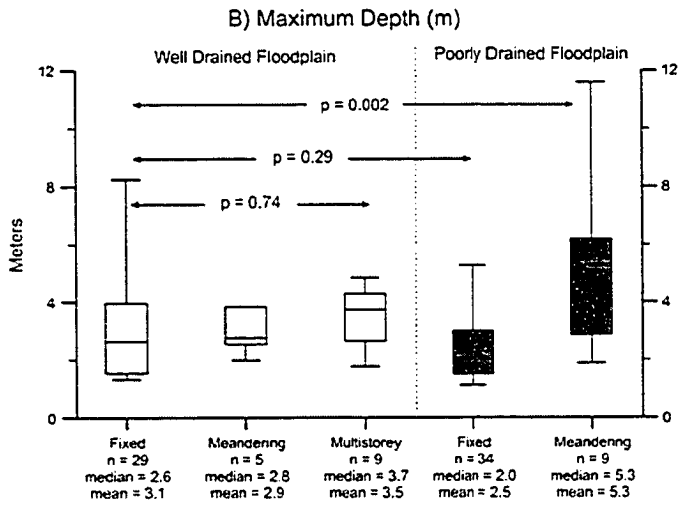
6.6.2.2. Interpretation.

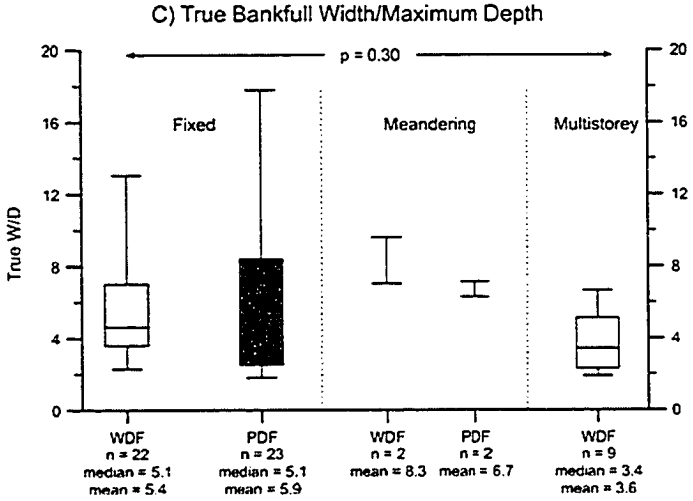
The bodies are thin, narrow to broad ribbons, with one narrow sheet (W/T 19.5). The parent channels were 1.1 to 6.1 m deep with W/D between 1.8 and 17.8 (Fig. 72). Lateral accretion barforms locally filled the channels without significant channel widening, perhaps due to the influence of the adjacent vegetated levees, peats, and muddy overbank deposits (Smith, 1976; Törnqvist, 1993).

Like their WDF counterparts, these sandstone-filled bodies are interpreted as the deposits of anastomosed drainages because multiple channels incise from the same level, they have low W/T values (6.5 mean), and they exhibit all or most other characteristics of anastomosed river deposits (Makaske, 2001). Because nearly all the bodies are associated with sandy overbank deposits, it is difficult to distinguish through-going drainages from distributary (crevasse) systems, but many larger bodies probably represent through-going networks similar to Type 1B organo-clastic systems

Figure 72: Paleochannel depth (D), bankfull width (W), and W/D information presented as a log-log plot and box diagrams. The results of the statistical analyses are shown on the box diagrams.


A) Bankfull Width vs. Maximum Depth
WDF Fixed channels
PDF Fixed channels
WDF Meandering channels
PDF Meandering channels
PDF Meandering (calculated width)
WDF Multistorey channels
Minimum width
Maximum width
y = 0.7056x^0.5112
r² = 0.659
Maximum Depth (m)
Bankfull Width (m)
20
10
1
1
10
100


B) Maximum Depth (m)
Well Drained Floodplain
Poorly Drained Floodplain
p = 0.002
p = 0.29
p = 0.74
Meters
12
8
4
0
Fixed
n = 29
median = 2.6
mean = 3.1
Meandering
n = 5
median = 2.8
mean = 2.9
Multistorey
n = 9
median = 3.7
mean = 3.5
Fixed
n = 34
median = 2.0
mean = 2.5
Meandering
n = 9
median = 5.3
mean = 5.3


C) True Bankfull Width/Maximum Depth
p = 0.30
Fixed
Meandering
Multistorey
True W/D
20
16
12
8
4
0
WDF
n = 22
median = 5.1
mean = 5.4
PDF
n = 23
median = 5.1
mean = 5.9
WDF
n = 2
mean = 8.3
PDF
n = 2
mean = 6.7
WDF
n = 9
median = 3.4
mean = 3.6

(Nanson and Knighton, 1996), such as the modern Magdalena and Columbia Rivers (Table 11). Smaller channel bodies probably represent anastomosing distributary or crevasse-splay channels similar to those of the modern Atchafalaya Delta or Cumberland Marshes (Table 11).

Given their proximity to a cycle-bounding flood event, the two mudrock-filled bodies are interpreted as deltaic distributary channels formed during a retrogradational phase of floodplain sedimentation. They may have been part of an anastomosed drainage (a common form in deltaic settings: Makaske, 2001) that may reflect high sedimentation rates and impending transgression (Törnqvist, 1993; Törnqvist *et al.*, 1993). The abnormally fine-grained fill may reflect an anomalous absence of sand-sized bedload or, more likely, the channel body represents a failed avulsion (Guccione *et al.*, 1999) and was abandoned shortly after incision. Eberth (1996) described similar fluvial deposits from Upper Cretaceous units in southern Alberta and attributed their fine-grained fill to rising sea level and limited connection to inland drainages.

Channel bodies 553 and 569 are associated with mouth-bar deposits, and are interpreted as the deposits of distal distributary channels, recording the most basinward extent of channelized flow at the transition to open water conditions. They appear similar to distal deposits of the Mississippi River and ancient deposits in Australia and Greenland (Table 11).

### 6.6.3. Comparison of fixed channel bodies

Statistical analysis of the geometric information for the 29 WDF and 34 PDF fixed-channel bodies (Fig. 65A) shows that the thickness and W/T values for these

populations are indistinguishable from one another (p = 0.17 and 0.59, respectively). PDF and WDF paleochannel dimensions (D and W/D: Fig. 72) are also indistinguishable, because their dimensions are directly related to the geometry of the resulting channel body.

## 6.7. Meandering Channel Bodies

### 6.7.1. Well drained floodplain

6.7.1.1. Description.

Five meandering channel bodies occur in well drained floodplain deposits within cycle 5 (Table 12). They are up to 3.5 m thick with W/T of 22 to 64 (Fig. 65B). Channel bases are flat lying surfaces. The bodies are generally single storey, although 274B-C are in erosional contact over a short portion of their perimeter. A meandering channel body and a fixed channel body both incise from the 370 m level. Channel bodies 274 B and C cut into preexisting sandy deposits, but the nature of the bank material for the other three channel bodies is unclear.

Channel bodies are almost entirely composed of inclined- and inclined heterolithic strata that constitute lateral-accretion barforms (Figs. 65 and 67). These beds are commonly cross-cut by subparallel, third and fourth order surfaces that extend 15 to 30 m laterally and are traceable throughout the thickness of the channel body. Inclined heterolithic sets are composed of ripple cross-laminated sandstone that is interbedded with or grades upward into laminated to massive mudrock, whereas inclined sets are composed almost entirely of ripple cross-laminated sandstone. Less common sandy bedforms and downstream-accretion barforms are composed of trough cross-bedded and elements near the channel margin. Erosion surfaces are commonly lined by lags of mud

| | Well Drained Facies Association | Poorly Drained Facies Association |
|---|---|---|
| **Number** | 5 | 9 |
| **Thickness** | 1.8 to 3.5 m (2.6 m mean) | 2.6 to 10.5 (4.8 m mean) |
| **True W/T** | 22.0 to 63.9 (40.5 mean) | 11.8 to 35.0 (22.6 mean) |
| **Other W/T** | Minimum: 5.8 and 9.3 | Minimum: 22.0 and 38.4<br>Maximum: 94 |
| **Channel Base** | Flat fifth order surface | Flat fifth order surface |
| **Storeys** | Generally one, but 274B and C are multilateral (but described individually) | Generally one, 648 is multilateral |
| **Fill Organization** | Single accretion direction defined by dipping fourth order surfaces | Single accretion direction defined by dipping fourth order surfaces |
| **Macroforms** | LA, SB, DA, and rare AF | LA, SB, DA, and rare AF |
| **Grain Size** | FS to MS; mudrock and pebble-sized IFC locally | FS to MS; mudrock and pebble-sized IFC locally |
| **Common Lithofacies** | Sr, St, Sl, Fl and Fm | St, Sr, Sl, Sh, Fl and Fm |
| **Paleochannel Depth** | 2.0 to 3.9 m (2.9 mean) | 1.9 to 11.6 m (2.4 mean) |
| **Paleochannel W/D** | 7.0 and 9.6 (n = 2) | 6.3 and 7.1 (n = 2) |
| **Modern Analogues** | Waterholes in the Channel Country of Australia (Gibling *et al.*, 1998; Falcon-Lang *et al.*, 2004) | Mississippi River (Fisk, 1944; Tye and Coleman, 1989; Aslan and Autin, 1999); Rhine-Meuse Delta (Törnqvist, 1993; Törnqvist *et al.*, 1993; Törnqvist, 1994) |
| **Ancient Analogues** | Clear Fork Group (Edwards *et al.*, 1983) | Scalby Formation (Alexander, 1992); Morien Group (Gibling and Rust, 1987) |

Table 12: Characteristics of meandering channel bodies in the Joggins Formation.

plane-laminated sandstone. In some bodies, massive mudrock fills discrete channel clasts, and channel bodies 274B and C contain reworked carbonate rhizoconcretions. Drab-haloed root compressions, rain-drop impressions, and mud cracks are present within some bodies. Plant fragments are common; tetrapod remains, unionoid bivalves, and dryland vegetation from channel body 274C (Figs. 64 and 67) were described by Hebert and Calder (2004) and Falcon-Lang et al (2004).

6.7.1.2. Interpretation.

The meandering channel bodies are thin, narrow sheets. Active channels were up to 3.9 m deep with W/D between 7.0 and 9.6 (Table 12; Fig. 72). These small channels are essentially laterally mobile variants of the dryland anastomosed river system inferred for WDF fixed channels, and may have resembled Nanson and Knighton's (1996) mixed load, laterally active anabranching rivers (Type 3) and the sinuous anastomosed channels described by Schumm (1996). The fixed and meandering channel bodies at the 320 m level provide strong evidence that these two channel types were part of the same river system and in some cases may have been coeval. At least two meandering channel bodies are encased in sandy bank materials, suggesting that cut-bank migration was a function of, or at least enhanced by, poorly cohesive banks (Schumann, 1989). Desiccation indicators suggest that some meandering channels were only seasonally active and may have been late-stage channels similar to those described by Schumm (1996). Meandering channel bodies share many paleoecological traits with modern waterholes in the Channel Country of Australia (Falcon-Lang *et al.*, 2004; Hebert and Calder, 2004).

### 6.7.2. Poorly drained floodplain

6.7.2.1. Description.

Nine meandering channel bodies occur in poorly drained strata (Fig. 65B; Table 12). These bodies are 2.6 to 10.5 m thick and have W/T of 11.8 to 35.0 (Table 12). Three meandering channel bodies cut down from 494 m, and a meandering and a fixed channel body cut down from the 499 m level. As with WDF bodies, the basal surfaces are flat-lying, and the bodies are filled largely with lateral accretion sets (Fig. 73), with some downstream-accretion barforms and sandy bedforms. Soft-sediment deformation and poor exposure on the tidal platform obscures the transition between channel bodies and adjacent overbank deposits.

Trough cross-bedded sandstone predominates in basal parts of the fills, passing up into ripple cross-laminated, low-angle and horizontally laminated sandstone with primary current lineation. A 2.9 m thick abandonment fill in the cliff exposure of Coal Mine Point (648) is filled with ripple cross laminated sandstone and massive mudrock. Erosion surfaces lined with mud clasts and plant debris are common.

6.7.2.2. Interpretation.

The bodies are narrow sheets to broad ribbons of thin to medium thickness (Fig. 64). The active channels which created them were 1.9 to 11.6 m deep with W/D of 6.3 to 7.1 (Fig. 72). The presence of multiple channel bodies at two levels suggests that these meandering channels formed part of an anastomosed network similar to Nanson and Knighton's (1996) mixed-load, laterally active anabranching rivers. The channels may have resembled modern and Holocene systems of the Mississippi River and Delta and the

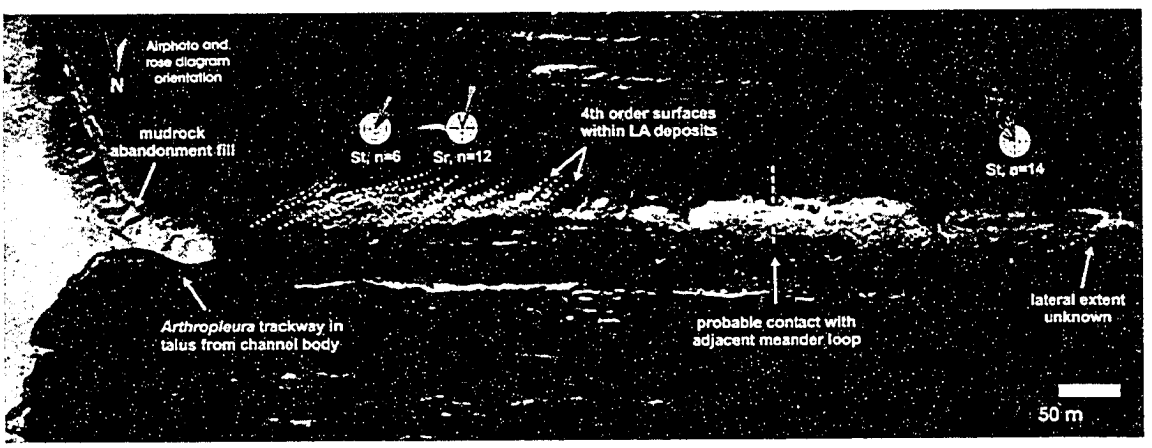



Figure 73: Labeled air-photograph showing Coal Mine Point (body 648), a large meandering channel body within poorly drained strata of cycle 10 (image is an enlarged portion of Figure 61).

Rhine-Meuse Delta, in both of which fixed and meandering bodies are present (Table 12; Törnqvist *et al.*, 1993, b; Aslan and Autin, 1999).

"Coal Mine Point" is a 10.5 m thick, meandering channel body (channel body 648; Figs. 64 and 73) with a channel that was at least 30% deeper than all other channels recorded on the Joggins floodplain. This large river probably represents a higher order stream than others seen in the section and may represent a mobile trunk drainage.

### 6.7.3. Comparison of meandering channel bodies

Geometric and statistical information for the 5 WDF and 9 PDF meandering channel bodies (Fig. 65B) shows that, although some PDF channel bodies are much thicker than WDF channels (10.5 m and 3.5 m maximum thickness, respectively), the two populations are statistically indistinguishable ($p = 0.11$). Similarly, W/T values for WDF bodies (40.5 mean) and PDF bodies (22.6 mean) are statistically indistinguishable ($p = 0.12$). Channel body width does not increase significantly with channel body depth ($r^2 = 0.208$), although two of the largest channel bodies are incompletely exposed (648 and 494C).

Because these channel bodies are one storey high, paleochannel depths represent decompacted thickness values and were similarly indistinguishable ($p = 0.11$). Unlike fixed channel bodies, the instantaneous width of meandering paleochannels was much smaller than the resulting deposits (Fig. 72) and the two W/D values from the WDF bodies (7.0 and 9.6) match well with the two values from PDF bodies (6.3 and 7.1).

The similarity of paleochannel W/D values and relatively low channel body W/T values indicates that there is an overlap in form and processes between meandering and fixed channel body types. This continuum in channel body geometry probably records

meandering reaches in anastomosed systems where individual channels widened and perhaps became more sinuous, a phenomenon described from both modern anastomosed systems and ancient fixed channel deposits (Olsen, 1993).

## 6.8. Multistorey Channel Bodies

### 6.8.1. Well drained floodplain

6.8.1.1. Description.

Three multistorey channel bodies up to 6.5 m thick occur in well drained strata (Fig. 64; Table 13). These bodies are incompletely exposed and have minimum W/T ratios of between 7.8 and 56.3 (Fig. 65C). Flat-lying basal surfaces have small erosional "steps" with up to 0.5 m of relief. The channel bodies pass laterally into thin (<1 m thick) sandy wings that extend ~250 m into the adjacent floodplain sediments, but no distinctive surfaces that correlate with the channel base or wings can be identified away from the channel bodies.

Internally, multistorey channel bodies are divided into three or more storeys by concave-up surfaces (Fig. 74). These channel bodies are succession-dominated (Table 9), and nine completely preserved storeys range from 1.6 to 4.4 m thick and have W/T between 2.1 and 7.3. Lateral- and downstream-accretion barforms are the most abundant architectural elements, with gravelly and sandy bedforms and abandonment fills locally. Channel body 114 has slump blocks that record failure of the adjacent muddy channel deposits (Fig. 74). The channel fills contain sandstone and red or green clayey siltstone, with lags of pedogenic carbonate nodules and mud clasts on erosion surfaces. The lag at the base of channel body 13 contains fragments of the land snail *Dendropupa*, pedogenic carbonate nodules, and carbonate rhizoconcretions cored by gymnospermous roots (see

Table 13: Characteristics of multistorey channel bodies in the Joggins Formation.

| | Well Drained Facies Association | Poorly Drained Facies Association | |
|---|---|---|---|
| **Internal Architecture** | Succession Dominated | Erosion Dominated | Succession Dominated |
| **Number** | 3 | 1 | 1 |
| **Thickness** | 5.3 to 6.5 m (5.9 m mean) | 9.2 | 7.4 |
| **Minimum Width/Thickness** | >7.8 to 56.3 (28.6 mean) | >12.4 | >8.1 |
| **Channel Base** | Flat 6$^{th}$ order surface with erosional steps locally; passes into well defined margin | Flat 6$^{th}$ order surface; passes laterally into well defined margin | |
| **Storeys** | >3, defined by concave-up fifth order surfaces | 2, each of which is subdivided into >5 channel elements defined by concave-up fifth order surfaces | >3, defined by concave-up fifth order surfaces |
| **Channel Element Thickness and W/T** | T = 1.6 to 4.4 m (3.1 m mean)<br>W/T = 2.1 to 7.3 (3.9 mean) | Very poor preservation | Inaccessible, appears identical to WDFA examples |
| **Fill Organization** | Cross-cutting channel elements defined by fifth order surfaces; fully preserved storeys near top | Cross-cutting channel elements and scours defined by fifth order surfaces; poor preservation of storeys throughout | Cross-cutting channel elements defined by fifth order surfaces; fully preserved storeys near top |
| **Macroforms** | DA, LA, AF, SB, GB | SB and DA | LA, DA, SB, AF |
| **Grain Size** | FS to MS with mudrock abandonment fills; pebble-sized IFC locally | FS to MS; pebble-sized IFC locally | FS to MS with mudrock abandonment fills; pebble-sized IFC locally |
| **Common Lithofacies** | Sr, St, Fm, Fr, Sp, Scr, Sl, Gp | Sr, St, Sl | St, St, Fm, Fl, Sl |
| **Paleochannel Depth** | 1.8 to 4.8 m (3.5 m mean) | Poorly preserved, appear similar in size and shape to paleochannels in WDF bodies | |
| **Paleochannels W/D** | 1.9 to 6.7 (3.6 mean) | | |
| **Modern Analogues** | Similar in size, but muddier than the lower Niobrara River (Ethridge *et al.*, 1999; Skelly *et al.*, 2003); mixed sandbed and meandering characteristics similar to the Old Brahmaputra (Bristow, 1999) | Lower Niobrara and South Saskatchewan Rivers (Cant and Walker, 1978; Ethridge *et al.*, 1999; Skelly *et al.*, 2003) | Similar in size, but muddier than the lower Niobrara River (Ethridge *et al.*, 1999; Skelly *et al.*, 2003); mixed sandbed and meandering characteristics similar to the Old Brahmaputra (Bristow, 1999) |
| **Ancient Analogues** | Solling Formation (Olsen, 1988); Campodarbe Group (Bristow, 1999) | Sandy, erosion dominated fills similar in architecture (but not scale) to the Castlegate Sandstone (Miall, 1994) | Solling Formation (Olsen, 1988); Campodarbe Group (Bristow, 1999) |

Figure 74: Photograph and interpretive tracing of channel body 114, a succession-dominated, multistorey body within the well drained facies association of cycle 3. 1 m scale is shown on the tracing where the channel body meets the intertidal zone.

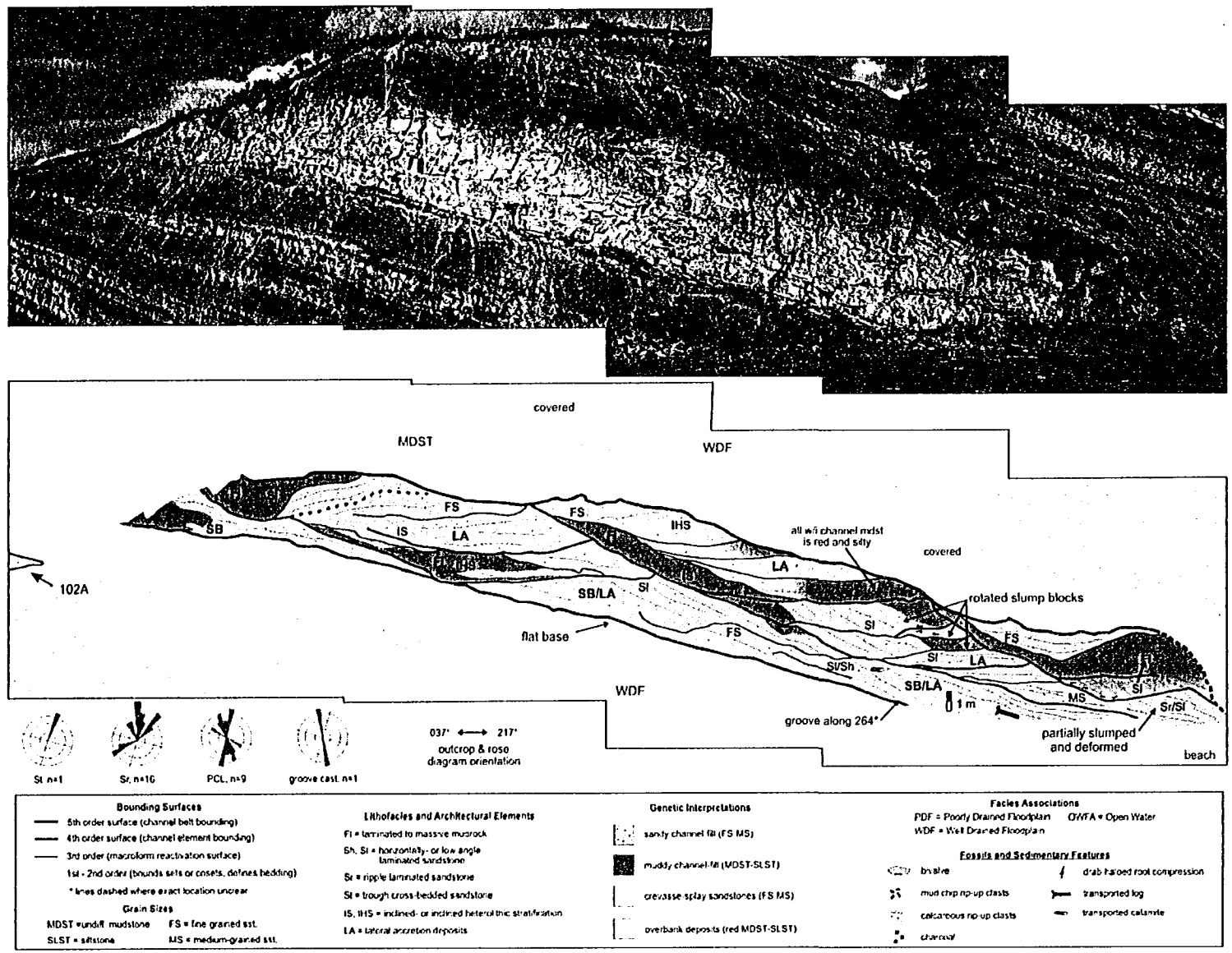

covered
MDST
WDF
FS
SB
IS
LA
IHS
FS
all w/i channel mdst is red and sdty
covered
LA
102A
SB/LA
SI
rotated slump blocks
flat base
FS
SI
FS
SI
LA
SI/Sh
WDF
SB/LA
1 m
MS
SI
SI/SI
groove along 264°
partially slumped and deformed
beach
037° ⟷ 217°
outcrop & rose diagram orientation
St, n=1
Sr, n=16
PCL, n=9
groove cast, n=1
Bounding Surfaces
5th order surface (channel belt bounding)
4th order surface (channel element bounding)
3rd order (macroform reactivation surface)
1st - 2nd order (bounds sets or cosets, defines bedding)
* lines dashed where exact location unclear
Grain Sizes
MDST =undiff. mudstone
FS = fine grained sst.
SLST = siltstone
MS = medium-grained sst.
Lithofacies and Architectural Elements
Fl = laminated to massive mudrock
Sh, Sl = horizontally- or low angle laminated sandstone
Sr = ripple laminated sandstone
St = trough cross-bedded sandstone
IS, IHS = inclined- or inclined heterolithic stratification
LA = lateral accretion deposits
Genetic Interpretations
sandy channel fill (FS MS)
muddy channel-fill (MDST-SLST)
crevasse splay sandstones (FS MS)
overbank deposits (red MDST-SLST)
Facies Associations
PDF = Poorly Drained Floodplain
OWFA = Open Water
WDF = Well Drained Floodplain
Fossils and Sedimentary Features
bivalve
mud chip rip-up clasts
calcareous rip-up clasts
charcoal
drab haloed root compression
transported log
transported calamite

Fig. 6i in Falcon-Lang *et al.*, 2004), as well as ten *in situ* calamites which are rooted in and entombed by sandy lateral accretion deposits. Fragmented and charred plant remains within these bodies are dominated by pteridosperms, cordaites, and sphenopsids (Falcon-Lang, 2003, his (dryland) facies 1).

6.8.1.2. Interpretation.

These partially exposed bodies are of medium thickness with minimum W/T ratios of 8 to 56 (broad ribbons to narrow sheets); the entire bodies probably represent narrow to broad sheets. Active channels averaged 3.5 m deep with W/D of 3.6 (Fig. 72), and were much smaller than the valleys that they filled (5.9 m mean depth, probably >350 m wide). The abundance of inclined heterolithic strata and mudrock abandonment fills indicates that the channels carried a mixed load, and variations in the orientation of channel element margins indicates that they took a sinuous path within the valley. *In situ* vegetation suggests seasonal flow, and fragmented floral associations are consistent with a seasonally dry, well drained alluvial plain and could have been locally derived. Pedogenic carbonate nodules and carbonate rhizoconcretions are rare in the coastal exposure of the Joggins Formation, suggesting that multistorey channel bodies carried sediment derived from upstream drylands where better developed paleosols were present. The overall size of these bodies and the architecture of sandstone intervals are similar to the lower Niobrara River of Nebraska (Ethridge *et al.*, 1999; Skelly *et al.*, 2003), but the presence of abandonment fills and lateral accretion deposits indicates that mixed-load, meandering channels also occurred within the valleys (Olsen, 1988; Bristow, 1999).

As previously mentioned, the channel body-bounding surface has no apparent counterpart in the adjacent floodplain sediments, and the channel fills do not record a

marked basinward shift in facies. The paleovalley fills do not occur in predictable positions within cycles, and not every cycle contains a multistorey body whereas others contain more than one. Thus, it is difficult to confidently tie these bodies to the base-level fluctuations that created the cycles.

### 6.8.2. Poorly drained floodplain

6.8.2.1. Description.

Two multistorey channel bodies occur in the poorly drained facies association at 581 and 705 m (Fig. 64, Table 13). The channel bodies are 9.2 and 7.4 m thick and have minimum W/T of 12.4 and 8.1, respectively. Flat basal surfaces and well-defined margins give these channel bodies a similar shape and geometry to their WDF equivalents. Sandy overbank deposits less than 1.5 m thick extend several tens of meters away from the channel margin but, as with WDF multistorey bodies, channel-bounding surfaces have no apparent counterpart in floodplain strata farther from the channel body.

Channel body 581 has an internal architecture unlike the other multistorey channel bodies in the section (Figs. 65 and 75). Two storeys are separated by a prominent surface that terminates against the channel margin, and each storey contains several individual channel fills defined by concave-up basal surfaces. Overall, the multistorey bodies are erosion-dominated and individual channel fills experienced significant erosional truncation by overlying and adjacent channel elements. Individual channels are filled with sandy bedforms of fine-grained sandstone, with ripple cross-laminae, trough cross-beds, planar cross-beds, horizontal and low-angle laminae, and mud clasts and plant debris on erosional surfaces. Plant fragments include a wetland

Figure 75: Photograph showing channel body 581, a sandstone-filled, erosion-dominated multistorey channel body within the poorly drained facies association of cycle 9.

assemblage composed of lycopsid and sphenopsid remains with rare cordaitalean pith casts and trunks (Falcon-Lang, pers. comm., Facies 5 in Falcon-Lang, 2003). An erect, very large (~1 m diameter) lycopsid was entombed near the edge of the channel body at 581 m.

The internal architecture of channel body 705 is similar to that of the WDF multistorey bodies, particularly channel body 114 (Fig. 64 and 74). This succession-dominated channel body contains several storeys with concave-up basal surfaces, each storey composed of sandy bedforms and/or lateral accretion deposits. Ripple cross-laminated sandstone with laminated mudrock interbeds are the most common lithofacies, with lenses of massive mudrock and slump blocks of muddy channel fill deposits. Plant remains consist of wetland floras, predominantly small calamite and lycopsid fragments.

6.8.2.2. Interpretation.

The multistorey bodies are of medium thickness and would likely be classified as narrow to broad sheets if fully exposed (minimum W/T 12.4 and 8.1). Channel elements appear similar in size and shape to those in the WDF multistorey bodies (Fig. 72), and the bodies are interpreted as paleovalleys filled with the deposits of considerably smaller active channels (probably ~3.5 m deep, W/D = 3.9). These deposits are not considered to mark Exxon-style sequence boundaries because the presence of floral associations similar to those of the surrounding floodplain and the absence of erosion surfaces or well-developed paleosols in overbank areas provides no evidence that there was a hiatus or basinward juxtaposition of facies. Channel body 705 contains abundant mudrock and was deposited by a mixed-load stream similar to those that filled the WDF paleovalleys. The sandstone-dominated fill of channel body 581 is unique amongst the multistorey channel

bodies and was deposited by a sandbed river similar in both size and sedimentology to the lower Niobrara and South Saskatchewan rivers (Cant and Walker, 1978; Ethridge *et al.*, 1999; Skelly *et al.*, 2003). The sandy, erosion-dominated nature of this body suggests that it formed in a fluvial system that experienced strong flow pulses, perhaps a signature of climate-induced changes in sediment supply (Van der Zwan, 2002; Törnqvist *et al.*, 2003). Although channel body 581 sits erosively atop the open water strata of cycle 10 (Skilliter, 2001), the presence of a distal dristributary channel at 569 m and the wetland floral assemblages within channel strongly 581 strongly suggests that it simply records the progradation of a large channel into a standing body of water – a phenomenon that may have resulted in the erosion of underlying strata transitional between the open water and poorly drained facies associations.

## 6.9. Discussion

### 6.9.1. Channel body geometry

Joggins channel bodies are classified into fixed, meandering, and multistorey groups based only on architectural criteria observable in the field (Fig. 64). All three groups are present in poorly drained and well drained floodplain successions, and they occupy distinct but non-exclusive regions in W-T space (Fig. 76). ANOVA analysis for thickness shows that multistorey (6.9 m mean), meandering (4.0 m mean), and fixed (2.5 m mean) channel bodies represent statistically distinct populations ($p < 0.001$, Fig. 76). W/T for fixed (6.2 mean) and meandering (28.6 mean) bodies also belong to statistically distinct populations ($p < 0.001$, Fig. 75); the five multistorey bodies were incompletely exposed and could not be analyzed using this criterion.

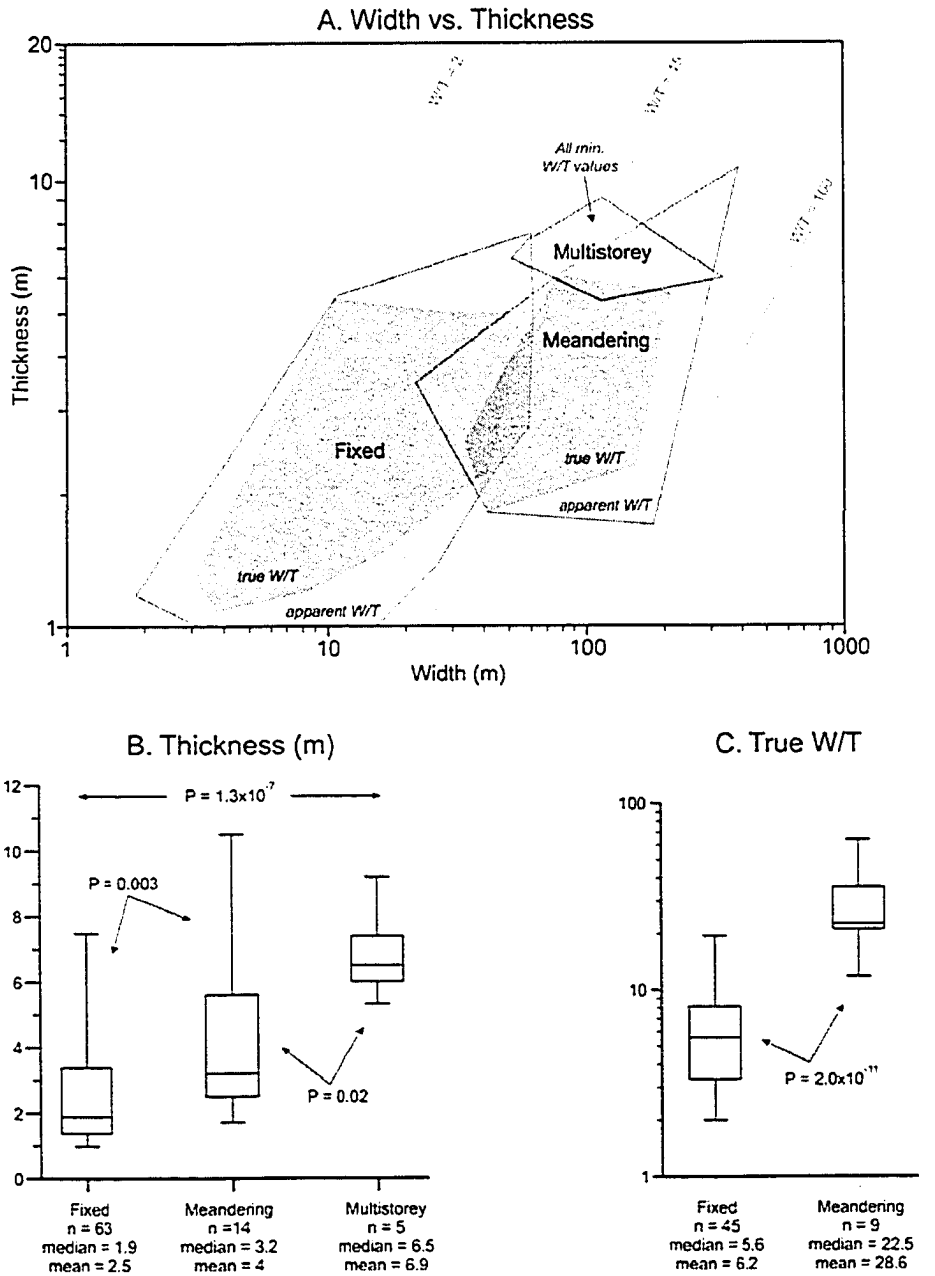



Figure 76: Diagram summarizing the width, thickness, and width/thickness information for the three different types of channel bodies within the Joggins Formation.

ANOVA analysis of paleochannel depth (Fig. 72) shows significant differences for the five different paleochannel groups ($p = 0.002$), a disparity caused by the high values of the PDF meandering channels (5.3 m mean). Excluding the latter group, the four remaining types (no values for PDF multistorey paleochannels available) are indistinguishable ($p = 0.29$).

Conversely, W/D values for all five paleochannel types are similar ($p = 0.30$), indicating that all these active channels had a similar shape (W/D means from 3.6 to 8.3), regardless of the type of body that they would eventually deposit. Although several studies have shown that channel width systematically increases with channel depth (Bridge and Leeder, 1979; Bridge and Mackey, 1993), plots of these parameters for the Joggins data show no such relationship (best fit $r^2 = 0.66$), probably due to the limited range of paleochannel depth.

The present analysis shows statistical similarity between instantaneous depth for four of the five groups of Joggins paleochannels, regardless of the type of channel body preserved and whether they belong to well drained or poorly drained associations. The statistically larger paleochannels of the PDF meandering group may reflect differences in stream order and increased size towards the coast. All Joggins paleochannels had essentially the same shape (as quantified by W/D). Thus, it is reasonable to infer that the preserved bodies at Joggins represent drainage networks that maintained relatively similar dimensions, styles, and planforms throughout the deposition of the 915.5 m formation and from inland to coastal settings. The study attests to the continuum in fluvial forms, processes, and preservation – a relationship that is well known from modern channels and numerical models (Bridge, 1985; Knighton and Nanson, 1993 and

many others). The channel bodies of the Joggins Formation within the rapidly subsiding Cumberland Basin appear to record the geomorphology of the floodplain with relatively little modification due to reworking. In contrast, cratonic basins with low subsidence rates are strongly affected by sea-level change and other forcing factors, resulting in widespread reworking of landscapes, a high proportion of channel bodies, and the preservation of a complex mosaic of channel-body styles (e.g. Batson and Gibling 2002).

### 6.9.2. Controls on fluvial form

#### 6.9.2.1. Bank materials and overbank deposits

Although limited exposure of materials adjacent to many channel bodies precludes comprehensive evaluation of bank composition, the similarity of paleochannel W/D through the formation suggests that differences in bank material did not profoundly influence the instantaneous shape of active Joggins channels. A wide variety of lithologies are present in the section, but the absence of indurated duricrusts and thick coals, the thinly interbedded nature of floodplain muds and sands (floodplain sands are all <1 m thick) and the ubiquity of riparian vegetation probably caused the majority of the channel bodies to interact with bank materials of comparable overall cohesiveness. Evidence at several levels indicates that sandy bank material enhanced channel migration. Channel bodies 274B and C are the only well exposed bodies with predominantly sandy banks and both are meandering types; the 18 completely exposed bodies incised predominantly into mudrock are all fixed channel deposits. The similarity of overbank sand percentages throughout most of the formation suggests that successive cycles formed in response to the same kind of geomorphic setting and processes and that the

variations in fluvial style present in the section represent to a large degree the natural variability in the system.

Numerical models predict that channel-body connectedness largely reflects the abundance of channel bodies, with little or no connectivity in successions composed of less than 40-50% channel body sandstone (Allen, 1978; Bridge and Leeder, 1979, note: these studies describe channel bodies that may or may not be composed of multilateral channel elements). With an overall channel-body proportion of 3.5% and a connectedness ratio of ~0.003 (~10 m of total overlap/2896 m of total channel width using the terminology of Bridge and Mackey (1993), strata of the Joggins Formation support this relationship. Connectivity between channel elements is high only where channels were trapped within incised paleovalleys (see below).

6.9.2.2. Accommodation.

The 915.5 m thick Joggins Formation was deposited during the earliest Langsettian, probably in a period of less than 1 million years. With average subsidence rates of ~ 1 mm/yr (compaction effects neglected), the Joggins Formation records one of the highest average subsidence rates amongst Pennsylvanian coal fields (Calder, 1994; Davies and Gibling, 2003; Waldron and Rygel, Chapter 9). Despite this rapid rate, sedimentation rates closely matched subsidence rates (the accommodation/sediment supply ratio of Martinsen *et al.*, 1999), and the floodplain surface remained close enough to relative base level to preclude development of Exxon-style sequence boundaries and thick deepwater deposits (Davies and Gibling, 2003).

Shanley and McCabe (1993; 1994) suggested that fluvial architecture may be linked to accommodation, with multistorey bodies representing low accommodation periods

during which channels actively reworked their floodplains and fixed and meandering bodies representing periods of high-accommodation. Systematic changes in fluvial architecture could not confidently be identified within individual cycles or within the Joggins Formation as a whole – probably a result of the rapid sedimentation rate, the high proportion of overbank deposits, and the long-term maintenance of an accommodation/sediment supply ratio near unity. The apparent change from narrow to broad channel bodies starting at the base of cycle 8 is an artifact of the transition from dominantly well drained facies below (where multistorey and fixed channel bodies represent the trunk drainages) to poorly drained facies above (where meandering and multistorey channel bodies represent trunk drainages) and the relative abundance of thick heterolithic sandstones exposed in poorly drained facies. The sporadically distributed multistorey bodies are not definitively related to secular variation in subsidence rate, and could for example represent paleovalleys incised as a result of changes in precipitation and discharge (Gibling *et al.*, in press).

Of the 82 channel bodies, significant stacking of channel elements occurs only within the five infilled paleovalleys (multistorey bodies). Plant remains within multistorey bodies were generally derived from the surrounding floodplain, although multistorey channel body 13 and meandering channel body 274C contain an unusual abundance of transported pedogenic carbonate, which is probably a contribution from upstream well drained areas. Given the lack of a paleofloral "mismatch" or other indicators of a basinward shift in facies, these bodies do not exhibit criteria diagnostic of paleovalleys formed in response to falling sea level.

The paleovalleys do, however, record sporadic phases of incision and low accommodation, the cause of which is uncertain. These bodies occur in unpredictable stratigraphic positions within cycles and occur in both the poorly drained and well drained floodplain associations, indicating that the conditions necessary for incision existed periodically, perhaps simultaneously, across the entire Joggins floodplain. Although the Shanley and McCabe model *sensu stricto* cannot be directly applied to the Joggins cycles, the multistorey architecture of these bodies does appear to be a product of low accommodation/sediment supply conditions that existed, perhaps briefly, during their formation. The thickness of multistorey bodies is matched or exceeded by several fixed and meandering bodies, indicating that, although the fill architecture is unique, the degree of incision was comparable to that achieved by other channels. If these bodies did form in response to drops in relative sea level, the dampening of sea-level falls by tectonic subsidence (Gawthorpe *et al.*, 1994) may have resulted in sequence boundaries that are cryptic at best, and where: 1) paleovalleys incised and filled too rapidly for well developed paleosols to form on interfluves, and 2) no basinward superimposition of contrasted facies occurred. Similarly cryptic sequence boundaries from the last glacial period were described by Törnqvist *et al.* (2003).

Two mudrock-filled, fixed channel bodies occur in poorly drained strata just below cycle-bounding flooding surfaces. These channel bodies are encased within sediment that was deposited during transgression of the floodplain and may represent failed avulsions that formed during a period when accommodation was being rapidly generated, a scenario similar to that described by Eberth (1996).

The three lowest cycles in the Joggins Formation rank amongst the thinnest of the Joggins cycles, contain relatively high proportions of well drained strata (55% mean), and have relatively small amounts of overbank sandstone (9% mean, vs. 31% mean for the overlying cycles). This evidence suggests that cycles 1-3 record a phase when the accommodation/sediment supply ratio was low, a situation that decreased the frequency and extent of floodplain inundations and favored the deposition of redbeds. This interpretation may explain why all three WDF multistorey bodies occur within the 80 m of redbeds in this interval, whereas none occur within the overlying 205 m of redbeds.

6.9.2.3. Style of subsidence.

The 1,174-m-thick Boss Point Formation is the oldest Pennsylvanian unit in the Cumberland Basin (Fig. 60); biostratigraphic control is poor, but this unit was probably deposited in a < 1 Ma period in the earliest Langsettian (dates of Menning *et al.*, 2000; Utting and Wagner, 2005). Both the Boss Point and Joggins Formations have similar average subsidence rates of ~1 mm/yr, however they exhibit marked differences in fluvial style, subsidence pattern, and lithology. During deposition of the Joggins Formation this part of the basin probably experienced low-magnitude, high-frequency halokinetic events accompanied by motion along the basin-bounding faults (Waldron and Rygel, Chapter 9). In contrast, halokinesis was not active during Boss Point time, when rejuvenation of the adjacent uplands may have, in part, caused a regional transition to sand-rich facies (Calder, 1998). During deposition of this unit, episodic motion along the basin-bounding faults in the western Cumberland basin caused essentially instantaneous subsidence of several meters in this part of the basin (Browne and Plint, 1994). The resulting Boss Point "event stratigraphy" in this part of the basin consists of alternate 10 to 50-m-thick

lacustrine shales (26% of formation thickness) deposited following downdrop of the basin floor and 20 to 90-m-thick packages of braidplain sandstone (74% of formation thickness) that prograded into the basin to cover hundreds of square kilometers (Plint and Browne, 1994). Despite the differences in the percentage of channel sandstones between the Joggins and Boss Point Formations, the striking contrasts in fluvial architecture and tectonic conditions suggest that both the manner and rate at which a basin subsides can exert strong controls on fluvial architecture. The preservation of a relatively intact drainage network through the stacked cycles of the Joggins Formation may in part reflect the steadier subsidence rate induced by halokinesis.

### 6.9.3. Paleogeomorphology and paleogeography of the Joggins floodplain.

The well drained Joggins floodplain was traversed by a network of laterally stable channels with local meandering reaches, up to 8.3 m deep (Fig. 72), that formed anabranches within a dryland anastomosed river system. Smaller fixed channels represent an anastomosed network of crevasse channels associated with sandy splays. Falling sea level, tectonism, and/or climate change contributed to the development of small (5 to 7 m deep) valleys, where sinuous, mixed-load channels were much shallower than the valleys within which they flowed.

The poorly drained Joggins floodplain was also traversed by fluvial systems with a tripartite organization. Meandering channels up to 11.6 m deep represented the largest active channels in the formation. Meandering and fixed channels up to 6.7 m deep formed an anastomosed network of tributary and distributary channels. Cryptic paleovalleys up to 9 m deep were filled by considerably smaller sand-bed and mixed-load

fluvial systems. Shallow channels cut into mouth-bar deposits represent the most basinward extent of channelized flow.

Paleoflow measurements show that channel bodies greater than 5 m thick (Fig. 77) originated from headwaters in the Caledonia Highlands or beyond in the exposed and eroding New Brunswick Platform (107° mean paleoflow direction, r = 0.67). These measurements have a 168° range, but the variance does not occur systematically through the section and is probably a function of channel sinuosity. Channel bodies less than 5 m thick had extremely variable paleoflow directions, most ranging between northwest to southeast (057° mean; r = 0.43). These measurements are consistent with a pattern of sinuous tributary and distributary channels of major rivers that were themselves sinuous.

Although the extent of the poorly drained floodplain was undoubtedly influenced by climate and sediment supply, it seems likely that poorly drained conditions generally existed downdip of the well drained floodplain, bordering the paleoshoreline and open-water conditions that lay beyond (Fig. 77). This Waltherian interpretation is supported by the observation that three of the four largest channel bodies and five of the seven largest paleochannels occur in poorly drained facies, as would be expected for a downstream traverse through a floodplain with gaining streams. Paleovalleys in the PDF (8.3 m mean) are somewhat thicker than WDF examples (6.9 m mean), but their generally comparable thicknesses suggest that incised drainages extended from well drained drylands downdip through the poorly drained coastal areas. This relationship is

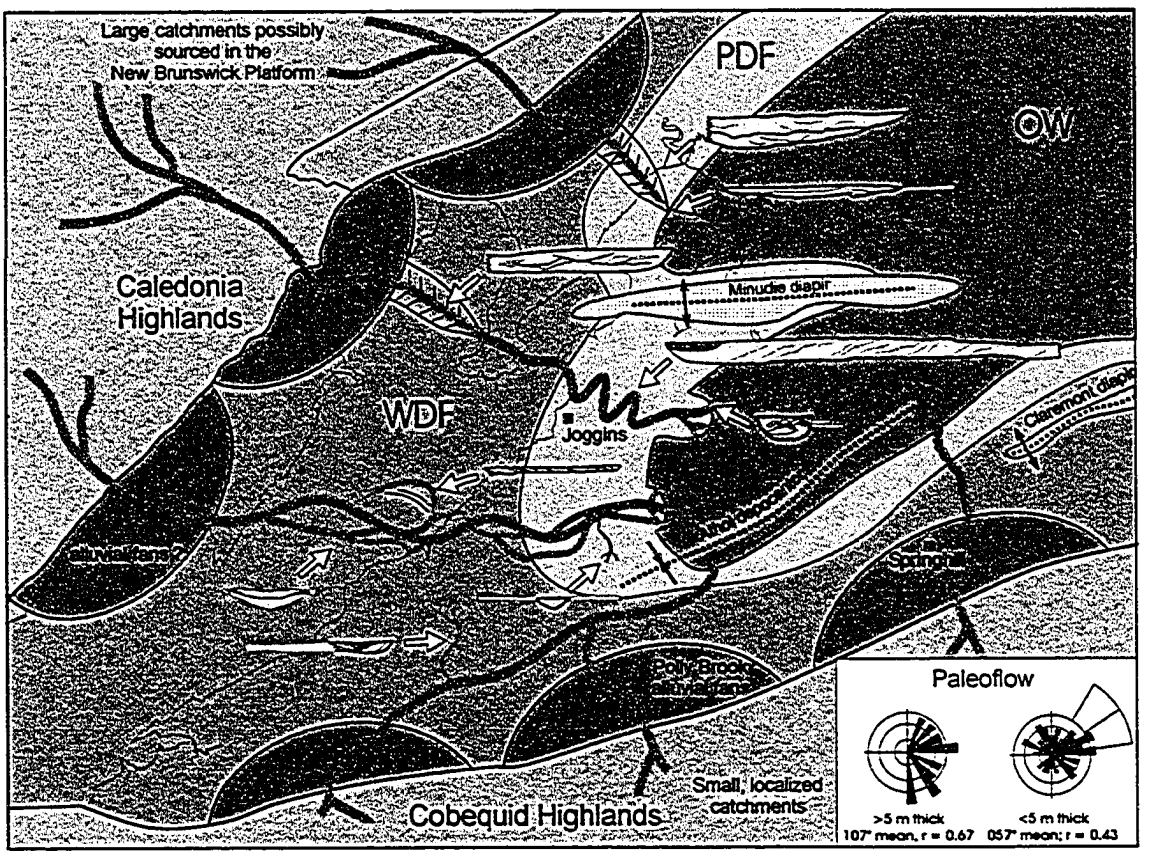



Figure 77: Schematic paleogeographic map of the Cumberland Basin during deposition of the Joggins Formation. Map covers the same area shown in Figure 1. Rose diagrams present paleoflow information for the channel bodies examined in this study.

difficult to prove without additional exposures of the Joggins Formation, and it is equally plausible that WDF and PDF paleovalleys are unrelated and formed independently.

The decrease in channel-body abundance from 4.3% in the first ten cycles to 0.7% in the upper four cycles (Figs. 61 and 62) indicates that major channels draining the floodplain temporarily shifted away from the Joggins area. This change was most likely caused by the advance of the Coal Mine Point channel body and the underlying "avulsion deposits" (sensu Kraus, 1996), which filled the available accommodation in this part of the floodplain (Tye and Coleman, 1989), causing the locus of fluvial activity to migrate to a lower-lying area. Despite the paucity of channels in the upper four cycles, the proportion of sand in the overbank areas remains similar (Fig. 62), indicating that the shift did not cut off the sediment supply. The large channel body at 849 m and those of the overlying Springhill Mines Formation indicate that major channels soon returned to this position on the floodplain.

Exposure of the Joggins section is mainly limited to one large cliff section near the center of the Cumberland Basin, but the section provides us with a wealth of information about the early Langsettian paleogeography of this part of the basin (Fig. 77). The Joggins Formation passes southeastward into the Polly Brook Formation (Ryan *et al.*, 1991), a conglomeratic unit shed from the Cobequid Highlands (Fig. 60). Structural complications and a lack of biostratigraphic information preclude ready correlation with New Brunswick exposures, but it seems likely that the Joggins Formation was laterally equivalent to conglomeratic units (now eroded) shed from the Caledonia Highlands of New Brunswick (cf. Plint and van de Poll, 1982). The Joggins channel bodies' southeasterly paleoflow away from the Caledonia Highlands is broadly similar to

paleoflow in the underlying Boss Point and Little River formations and the overlying Springhill Mines Formation (Fig. 60, Rust *et al.*, 1984; Browne and Plint, 1994). The observed paleoflow variance is within the expected range from sinuous fluvial systems, although some variation may record deflection of drainage by the actively uplifting Minudie diapir into the syndepositional Athol Syncline (Waldron and Rygel, Chapter 9; Calder *et al.*, Chapter 8). Alternatively, the paleoflow variance could reflect proximity to the low-gradient basin center, where rivers from both sides of the basin may have formed axial systems or joined through-going rivers before flowing northeastward out of the basin (Gibling *et al.*, 1992; Calder, 1994). Browne and Plint (1994) noted that, unlike outcrops in the northern part of the basin, exposures of the Boss Point Formation south of the Hastings Fault indicate a southerly paleoflow direction, a trend that they attributed to post-depositional rotation along the curved Harvey-Hopewell Fault zone (Fig. 60).

## 6.10. Conclusions

1. Eighty two fluvial channel bodies within the Pennsylvanian Joggins Formation crop out in 20-m-high sea cliffs and a 500-m-wide intertidal zone along Bay of Fundy. The accessibility and almost complete exposure of this coastal section allowed for detailed description of channel body geometry and internal architecture, as well as determination of original channel depth and width for many bodies. These observations were linked to a detailed measured section, thus allowing a comparison of channel bodies deposited across the full paleogeomorphic spectrum of the Joggins floodplain, from poorly drained coastal areas to well drained, inland alluvial plains.

2. Using only field characteristics, these channel bodies were classified as fixed (n = 63), meandering (n = 14), and multistorey types (n = 5), with each type present in coastal wetland and interior dryland facies associations. Multiple fixed and meandering channels incise from the same level, indicating that these channels formed part of an anastomosed tributary and distributary system which was probably related to a large, meandering trunk river. The multistorey bodies represent small paleovalleys filled with the sandy to mixed-load deposits of much smaller active channels.

3. Graphical plotting and statistical analysis of completely exposed channel bodies show that thickness values for each type are distinct, as are width/thickness values for fixed and meandering channel bodies; incomplete lateral exposure of multistorey bodies prevented similar analysis. Conversely, paleochannel depth and width/depth determined for channel bodies of all types were statistically similar, apart from a small group of unusually deep meandering channels in the coastal wetlands.

4. Joggins channel bodies were deposited during a period of rapid subsidence and preserve a wealth of information about the active channels that formed them. This situation contrasts with low-subsidence basins, which may be strongly affected by sea-level change and other forcing factors, resulting in widespread reworking of landscapes, a high proportion of channel bodies, and the

preservation of a complex mosaic of channel-body styles. Multistorey bodies are present in the section, but it is unclear whether these bodies represent paleovalleys formed by sea-level fall or by other factors such as tectonism, climate change, or sediment supply. Although forcing factors probably influenced the system, the Joggins channel bodies collectively reflect much of the geomorphic variability of the original drainage network, with systems of small fixed channels and a few large mobile channels in the coastal zone.

5. Striking contrasts between the fluvial architecture of the Joggins Formation, which formed during a period of salt withdrawal, and the underlying Boss Point Formation, which formed during a period of fault-related subsidence without halokinesis, suggest that both the style (rapid versus gradual) and magnitude of basin subsidence can profoundly influence channel body architecture.

## 6.11. ACKNOWLEDGEMENTS

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# CHAPTER 7: AN EARLY PENNSYLVANIAN WATERHOLE DEPOSIT AND ITS FOSSIL BIOTA IN A DRYLAND ALLUVIAL PLAIN SETTING, JOGGINS, NOVA SCOTIA

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## 7.1. ABSTRACT

The terrestrial ecology of Pennsylvanian tropical wetlands is understood in detail, but coeval dryland ecosystems remain highly enigmatic. To fill this gap in our knowledge, a Pennsylvanian (Langsettian) continental red bed succession was studied at the classic Joggins locality, Nova Scotia. These units represent the deposits of seasonally dry, alluvial plains traversed by anastomosed drainage networks. One channel complex informally known as the "Hebert beds" (the focus of this study) contains an unusual fossil assemblage and is interpreted as an alluvial waterhole deposit that formed following drought-induced cessation of channel flow. Adpressed and charred fossil plant remains indicate that the alluvial plain surrounding the waterhole was covered by fire-prone cordaite vegetation, with hydrophilic lycopsids and sphenopsids restricted to waterlogged riparian niches. Large unionoid freshwater bivalves, locally in life position, and occurring in large numbers in the waterhole, were probably infaunal suspension feeders during periods of fluvial activity, but aestivated in channel bottom muds when flow ceased. Abundant terrestrial gastropods found clustered around fossil plant detritus may have been deposit feeders scavenging dry portions of channel floors. Common partially articulated remains of small to medium-sized tetrapods possibly represent animals drawn to the waterhole during drought when surface water was scarce elsewhere. In terms of both sedimentology and biology, the Hebert beds alluvial complex bears a very close similarity to the seasonal drainages and waterholes of present-day central and northern

Australia. This unique deposit sheds significant new light on the nature of Pennsylvanian dryland tropical ecology.

## 7.2. INTRODUCTION

The popular image of the Pennsylvanian tropics is of humid coastal wetlands and stagnant peat mires densely forested by lycopsid trees and inhabited by gigantic arthropods and primitive tetrapods (DiMichele *et al.*, 2001). The fossil site most influential in forming this image is the world-famous Joggins cliffs of Nova Scotia, where spectacular fossil forests of upright lycopsid trees and diverse vertebrate and invertebrate remains have been described from grey coal-bearing strata since the mid-nineteenth century (Lyell and Dawson, 1853; Calder, 1998).

However, a much less well-known feature of the Joggins section is the common occurrence of continental red bed intervals, which are intercalated with the coal-bearing strata and contain evidence for tropical dryland environments. Recent sedimentological and sequence stratigraphic studies have indicated that these red beds originated in a well-drained, seasonally dry alluvial plain during periods of lowered base level (Davies and Gibling, 2003) when the Joggins region lay in an intracontinental setting, many hundreds of kilometers from the open ocean (Ziegler *et al.*, 2002).

Although Pennsylvanian-aged continental red bed deposits are widespread across North America and Europe (eg. Wagner, 1973; Gibling and Bird, 1994; Glover and Powell, 1996), associated fossil ecosystems remain poorly documented (Mapes and Gastaldo, 1986; DiMichele and Aronson, 1992; Falcon-Lang, 2003). To fill this gap, this study analyzes the paleoecology of an unusual assemblage of vertebrate and invertebrate fauna and flora in a single dryland alluvial channel complex at Joggins, Nova Scotia (Fig.

12). This unit is interpreted as a waterhole deposit, a term employed to mean a ponded water body in a seasonally dry environment that provided a perennial but localized source of water for organisms especially during sustained drought (Jackson, 1997). This discovery sheds important new light on Pennsylvanian dryland ecology.

### 7.3. GEOLOGICAL SETTING

The Joggins Formation is exposed in a spectacular 4 km long sea-cliff between Little River and Hardscrabble Point, near Joggins village, Bay of Fundy, Nova Scotia (Fig. 12; 45°42'N, 64°26'W). This 915.5 m thick formation, whose strata dip gently at 21° SW, is assignable to the mid- to late Langsettian stage of the Pennsylvanian based on studies of palynofloral and megafloral assemblages (Fig. 13; Dolby, 1991; Wagner, 1999). Strata were deposited close to the paleoequator in the rapidly subsiding Cumberland Basin, a small strike-slip sub-basin within the regional Maritimes Basin (Gibling, 1995; Pascucci *et al.*, 2000).

Davies and Gibling (2003) described the sedimentology of the basal 603 m of the Joggins Formation in terms of three genetically related facies associations (Fig. 17, Table 8): open-water deposits (OW), poorly drained floodplain deposits (PDF) and well-drained floodplain deposits (WDF). These strata are organized into fourteen cycles (Figs. 16 and 17), each typically recording an initial phase of drowning (OW strata), followed by shoreline progradation and bay infilling (PDF strata), and subaerial aggradation of the floodplain (WDF strata). An overview of the changing ecosystems that colonized this evolving environment has recently been given by Falcon-Lang (2003).

The fifth cycle in the Joggins Formation is unique in that it is abnormally thick (212 m), lacks OW units except at the base, and contains numerous alternations between

PDF units (53% of cycle thickness) and WDF units (43% of cycle thickness), the latter of which reach thicknesses of up to 53 m (see third page of Appendix 4). The thickness and relative abundance of WDF units in this cycle suggests that this cycle represents the most sustained period of continental deposition in well drained environments of the Joggins Formation (Davies and Gibling, 2003). Within this cycle, alternations between PDF and WDF units record the interplay between sediment supply, basin subsidence, climate and eustasy, which caused repeated minor progradational and retrogradational cycles.

Paleosols from WDF intervals in the fifth cycle have not been studied in detail, although Smith (1991) documented similar paleosols in the overlying Springhill Mines Formation. The paleosols consist of variegated red mudstone with a weak degree of horizonation and contain scattered calcareous nodules (some with manganiferous coatings), cutans of varied composition (argillans, ferrans, and calcans), drab mottles and local carbonaceous roots. Smith (1991) interpreted the paleosols as alfisol-like, formed under warm, relatively humid, but seasonally dry conditions, and, by association, a similar climate is envisaged for the WDF units of the Joggins Formation.

The 9-m-thick sedimentary unit that forms the subject of this paper occurs within a 53 m thick WDF interval close to the center of the fifth cycle (Figs 17 and 78) as defined by Davies and Gibling (2003). Since 1997, this unit has yielded an unusual fossil assemblage, and has been informally termed the "Hebert beds" in honor of Brian Hebert, the discoverer of most of the fossil material (Hebert and Calder, 2004). This paper presents a detailed description of the sedimentology of the Hebert beds and its fossil biota.

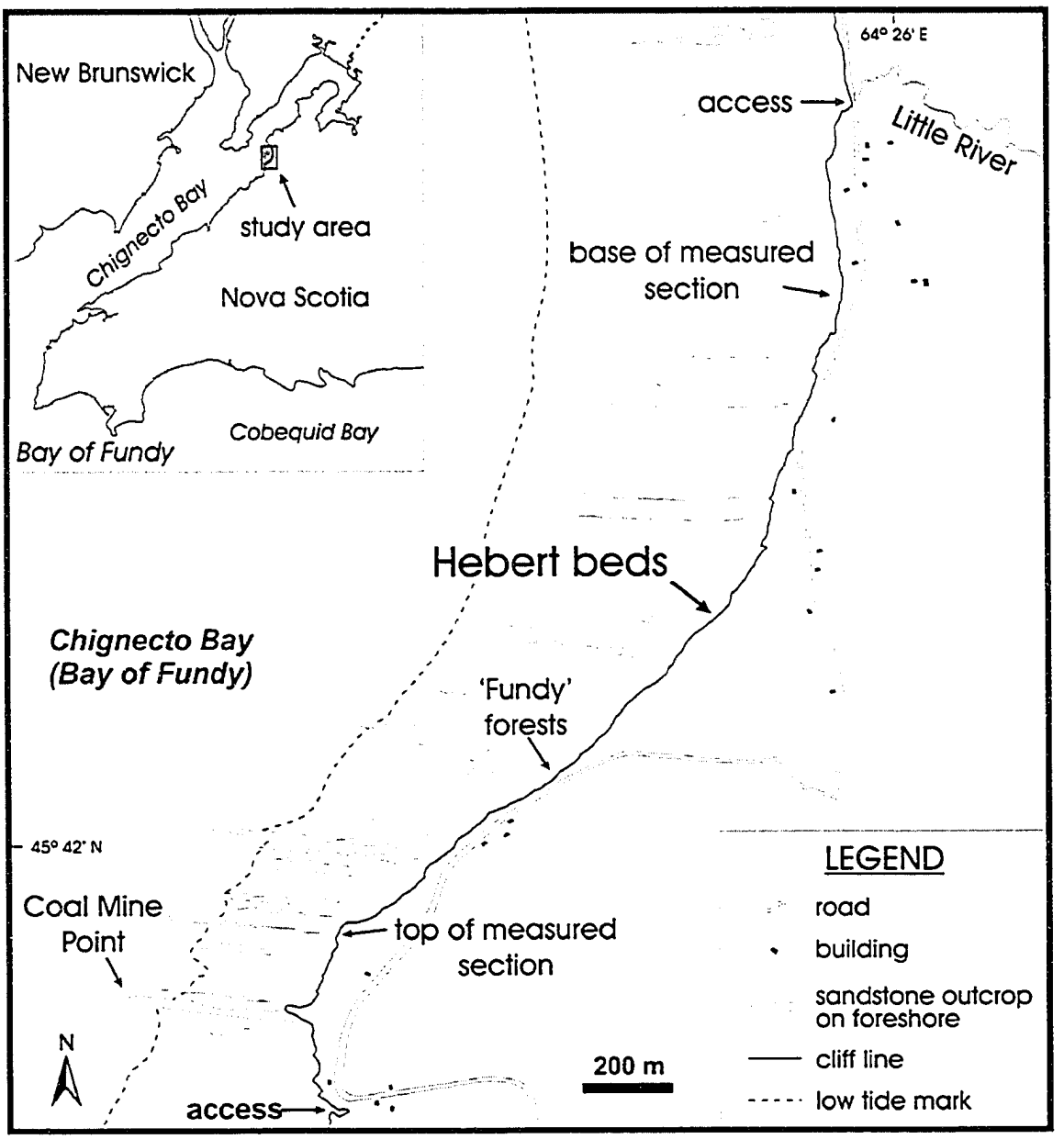


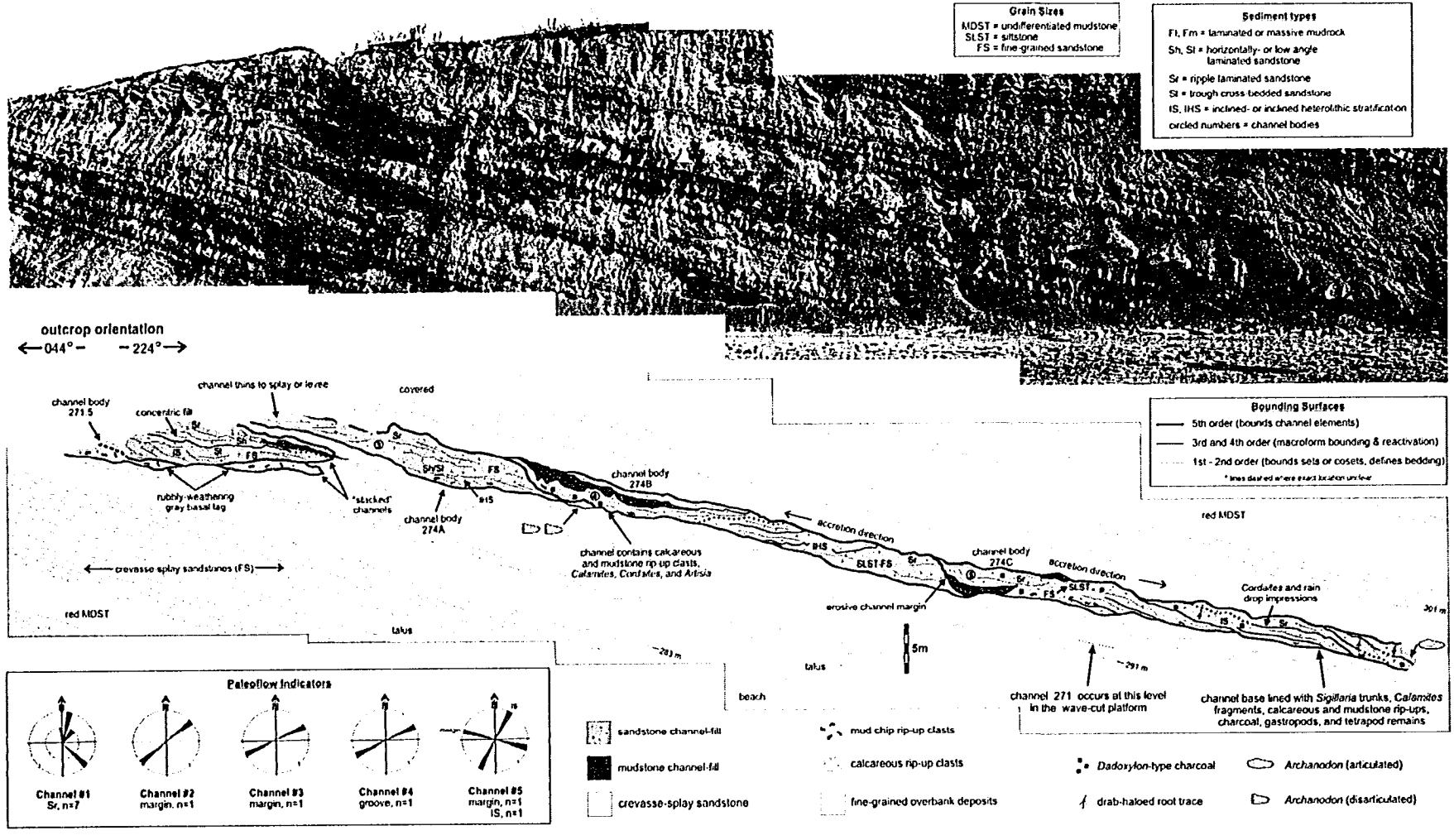

Figure 78: Outcrop map of the Joggins foreshore showing the precise location of the Hebert beds. Beds dip to the south.

## 7.4. SEDIMENTOLOGY OF THE HEBERT BEDS

The WDF interval in which the Hebert beds occur is dominated by small (<5 m thick) isolated channel bodies, sheet-like sandstone to siltstone beds, and red, desiccation-cracked mudstone beds. The Hebert beds themselves consist of five closely spaced channel bodies (271, 271.5, 274A-C), located between 268 and 277 m above the base of the measured section of Davies and Gibling (2003). The channel bodies are best exposed in the vertical cliff section (Figure 79), although water-worn outcrops of channel body 271 also exist on the Joggins foreshore. Compositionally, all the sandstone units are sublithic arenites. In the following description of channel architecture the terminology presented in Table 9 is used.

Channel bodies 271, 271.5, and 274A are 3.4 to 5.7 m thick, and composed of fine-grained sandstone. When measured perpendicular to paleoflow direction, channel body 271 has a width/thickness (W/T) value of 6.2, and channel bodies 271.5 and 274A, which are partly preserved, have minimum W/T values of 4.8 and 3.6, respectively. Laterally, channel bodies may terminate against a well-defined margin or may be associated with sandy 'wings' (Friend *et al.*, 1979) at the transition to the overbank. The base of these U-shaped channel bodies is defined by concave-up fifth-order (channel bounding) erosion surfaces, which cut into the underlying red mudstone. Whereas channel bodies 271 and 274A are single storey, channel body 271.5 has a more complex architecture consisting of two stacked storeys separated by a fifth-order erosion surface. Basal erosion surfaces are locally overlain by a grey pebble-sized lag of mud chip and pedogenic carbonate

Figure 79: Photomosaic and cliff face tracing of the Hebert beds, 268-277 m above the base of Joggins Formation (Davies and Gibling 2003). The orientation of channel bodies with respect to the cliff line varies from near-normal to near-parallel (see rose diagrams). Dip of inclined surface corrected for tectonic dip. The fossil assemblage is found in channel bodies 274B and C.


Grain Sizes
MDST = undifferentiated mudstone
SLST = siltstone
FS = fine-grained sandstone
Sediment types
Fl, Fm = laminated or massive mudrock
Sh, Sl = horizontally- or low angle laminated sandstone
Sr = ripple laminated sandstone
St = trough cross-bedded sandstone
IS, IHS = inclined- or inclined heterolithic stratification
circled numbers = channel bodies
outcrop orientation
←044°– –224°→
channel body 271.5
concentric fill
channel thins to splay or levee
covered
rubbly-weathering gray basal lag
"stacked" channels
channel body 274A
channel body 274B
channel contains calcareous and mudstone rip-up clasts, Calamites, Cordaites, and Arthrophycus
channel body 274C
accretion direction
erosive channel margin
Cordaites and rain drop impressions
crevasse splay sandstones (FS)
red MDST
talus
beach
5m
channel 271 occurs at this level in the wave-cut platform
channel base lined with Sigillaria trunks, Calamites fragments, calcareous and mudstone rip-ups, charcoal, gastropods, and tetrapod remains
Bounding Surfaces
5th order (bounds channel elements)
3rd and 4th order (macroform bounding & reactivation)
1st - 2nd order (bounds sets or cosets, defines bedding)
Paleoflow Indicators
Channel #1 Sr, n=7
Channel #2 margin, n=1
Channel #3 margin, n=1
Channel #4 groove, n=1
Channel #5 margin, n=1 IS, n=1
sandstone channel-fill
mudstone channel-fill
crevasse-splay sandstone
mud chip rip-up clasts
calcareous rip-up clasts
fine-grained overbank deposits
Dadoxylon-type charcoal
drab-haloed root trace
Archanodon (articulated)
Archanodon (disarticulated)

clasts. Sand-grade channel fill is dominantly subhorizontally bedded, concentric with the channel base, but locally may be organized into <2 m thick macroforms consisting of inclined stratification (IS) dipping perpendicular to the channel margin. Internally IS bedsets may contain abundant concave-up third-order (macroform reactivation) erosion surfaces. Common alluvial lithofacies include ripple cross-laminated sandstone, and horizontal to low-angle laminated sandstone with primary current lineation. A minor portion of the channel fills is composed of lenses of massive to laminated mudrock and small-scale trough cross-bedding.

In contrast, channel bodies 274B and C are generally thinner (3.5 and 1.8 m thick, respectively) with much greater mud content; they are composed of red mudstone and fine-grained sandstone. Channel body 274B, which is partly preserved, has a W/T value >5.8. However, a complete abandonment fill 3.5 m thick and 8.3 m wide (measured perpendicular to paleoflow) is preserved within this unit. When measured perpendicular to paleoflow, channel body 274C, which dies out at present beach level below the cliff, has a W/T value of 22. Laterally, both channel bodies truncate against well-defined channel margins and cannot be traced directly into genetically related overbank deposits. The basal surfaces of the channel bodies are concave-up fifth-order erosion surfaces that become flat-based over a distance of ~5 m from the lowest point. Basal erosion surfaces commonly are lined with a ~5 cm thick lag of pebble-sized mud chip and pedogenic carbonate rip-up clasts (including rhizoconcretions), which locally may be matrix-supported. Internally, channel bodies are dominated by macroforms with bedsets of IS and inclined heterolithic stratification (IHS). Both bedset types dip perpendicular to the channel margins, occupy the entire thickness of the channel body, and extend laterally for

10-15 m across the outcrop face. Within the IS-IHS units, common lithofacies include ripple cross-laminated sandstone and laminated to massive red mudrock. The mudrock portion of the channel fill either occurs as isolated lenses (up to 1.5 m thick) or is interstratified with sandstone as IHS. Grain size commonly decreases from fine-grained sandstone near the base of the channel bodies to sandy siltstone near the top. The upper 1 m of the IS bedset in 274C exhibits raindrop impressions, desiccation cracks, adhesion ripples and drab-haloed root traces, features that are absent closer to the channel base.

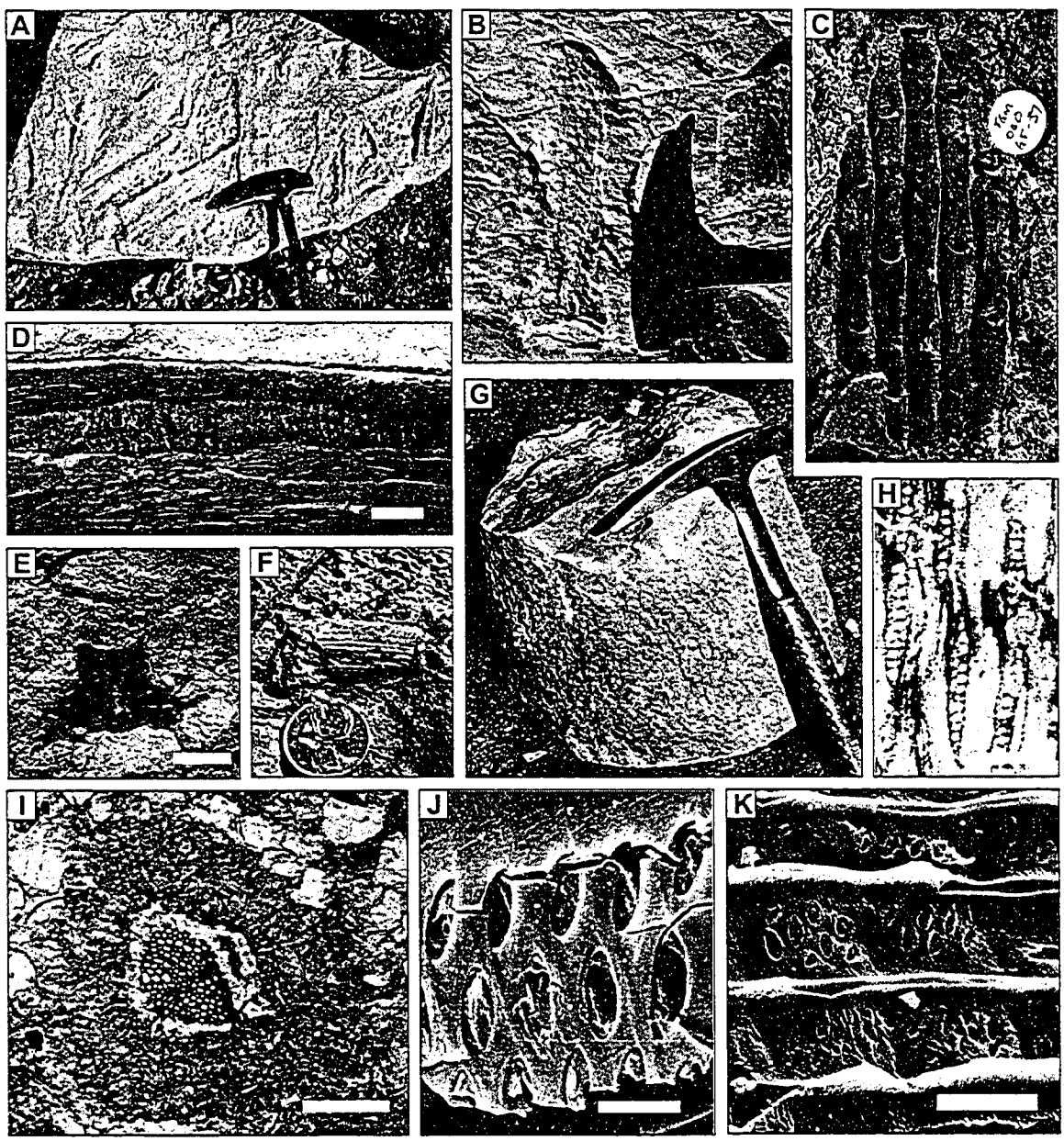
## 7.5. Fossil assemblages in the Hebert beds

Fossiliferous beds were observed only in channel bodies 274B and 274C, and include an unusual and varied biota of flora, and invertebrate and vertebrate fauna. All figured hand specimens are deposited in the Nova Scotia Museum of Natural History, Halifax, Nova Scotia (specimen prefix NSM), and the Fundy Geological Museum, Parrsboro, Nova Scotia (prefix FGM).

### 7.5.1. Flora

The species richness of the plant assemblage is very low (n = 6), being numerically dominated by the remains of cordaite gymnosperms, as generally seen in the WDF association at Joggins (Falcon-Lang, 2003). The most common cordaite fossil consists of compressions and impressions of large (up to 21 cm long), unfragmented, strap-like leaves of *Cordaites principalis* (Germar) Geinitz, which locally occur in both channel bodies associated with basal lag deposits but are most abundant on the upper parts of IS surfaces (Fig. 80A). These are commonly scattered in random orientations, covering up to 80% of some bedding surfaces. Much less common are fragments of woody, coalified cordaite trunks (up to 9 cm diameter), which are locally branched and

Figure 80: Fossil plants in and adjacent to the Hebert beds, (A, C-F, H-K) allochthonous, and (B, G) autochthonous; hammerhead for scale = 15 cm long. A) Abundant impressions of *Cordaites principalis* leaves, not collected, B) *Stigmaria ficoides* root cast, not collected, C) lycopsid trunk impression of *Sigillaria scutellata*, FGM000GF37, Museum tag = 13 mm diameter, D) slender woody cordaite trunk bearing *Artisia* pith, scale = 1 cm, NSM003GF029.001, E) *Dadoxylon*-type cordaite charcoal, scale = 5 mm, NSM003GF029.002, F) fragmentary *Calamites* stems, coin = 20 mm diameter, G) sandstone cast lycopsid stump from sheet sandstone beds 4 m below Hebert beds, possibly *Sigillaria*, H) calcified wood of *Dadoxylon materiarium*, thin section, scale = 50 μm I) calcified gymnosperm roots and rhizoconcretions, scale = 200 μm, NSM003GF029.003, J) charred *D. materiarium* cordaite wood showing multiseriate, alternate bordered pitting on tracheids; SEM image, scale = 15 μm, NSM003GF029.003 and K) charred *D. materiarium* cordaite wood showing araucarioid cross-field pitting; SEM image, NSM003GF029.003, scale = 40 μm.


A
B
C
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may contain sediment-filled pith casts referable to *Artisia transversa* (Artis) Sternberg; these occur in a gravelly lag at the base of channel body 4 (Fig. 80D).

Wood fragments are also common, occurring within the gravel lags of channel bodies 274B and C, but also rarely scattered on IS surfaces in channel body 274C. These may be anatomically preserved as fossil charcoal (up to 6 cm diameter; Fig. 80E), the product of ancient wildfires (Scott, 1989), or more rarely as calcareous permineralizations (up to 0.5 cm diameter). The charcoal consists entirely of pycnoxylic coniferopsid wood characterized by 30-40 μm diameter tracheids with contiguous, oval, 2-3-seriate, alternate, bordered pitting on their radial walls and blank tangential walls (Fig. 80J). Rays are typically biseriate, 4-56 cells high, and exhibit 2-8 araucarioid pits in the cross-field region (Fig. 80K). This wood is identifiable as *Dadoxylon materiarium*-Dawson, a cordaite wood species known from Joggins (Falcon-Lang and Scott, 2000; Falcon-Lang, 2003). Permineralized woods belong to the same cordaite species (Fig. 80H).

Non-cordaite remains are relatively rare. A few *Calamites* cf. *C. goeppertii* Ettinghausen stems (up to 50 cm in length) are locally common in the lower and upper part of IS bedsets in channel body 274C (Fig. 80F). In addition, several lepidodendrid trunks (<1.5m long; 25-30 cm diameter) are preserved on the lower part of an IS surface in channel body 274C; most are decorticated but the best-preserved material belongs to *Sigillaria scutellata* Brongniart (Fig. 80C). The only plant remains in growth position consist of two stigmarian roots preserved as impressions within red-green mottled mudstone layers in levee deposits immediately adjacent to channel body 274B (Fig. 80B), within channel body 274C, and a single upright sandstone-cast calamitean stem located in

channel margin sandstone beds of the latter unit. Centroclinal cross-stratification is well developed around the calamitean. Additionally, an autochthonous sigillarian lycopsid stump occurs 4 m below the Hebert beds within sheet sandstone units (Fig. 80G).

Finally, allochthonous rhizoconcretions are abundant in the gravel lag of channel bodies 274B and C (locally composing 15-20% of the lag), and reach dimensions of up to 2 mm diameter and 27 mm long. In thin section, these consist of sparry calcite axes (0.1-0.35 mm diameter) surrounded by a cylinder of fine-grained or sparry calcite (0.2-2.0 mm diameter) containing silt-grade siliciclastic grains. Similar rhizoconcretions from WDF channel body 13 contains anatomically preserved gymnospermous roots with 8-37 μm diameter tracheids possessing 3-5-seriate alternate pitting (Fig. 80I, see Andrews, 1940; Falcon-Lang, 2003). Although anatomically preserved tissue is not seen in rhizoconcretions from the Hebert beds, their similar size suggests they also may be gymnospermous, probably belonging to cordaites or pteridosperms.

### 7.5.2. Invertebrates

An invertebrate fauna with a moderate abundance and low species richness (n = 2) also is preserved in the Hebert beds, a detailed taxonomic description of which has been provided by Hebert and Calder (2004). The first taxon is *Archanodon westoni* Whiteaves, a unionoid bivalve endemic to Joggins (Weir, 1969). *Archanodon* shells are large (18-23 cm long, 8-9.5 cm high), characterized by 5-15 mm thick valves, and in general form are strongly inequilateral and isomyarian with a depressed umbo. The exterior of the shells exhibit two hierarchies of growth banding; primary well-defined, continuous bands of which there are typically 8-10 on each shell, and secondary subtly defined, discontinuous bands of which there are many tens on each shell. Two

disarticulated and partially fragmented *Archanodon* specimens were collected from a fallen block, probably derived from the gravelly basal lag of channel body 274B. A further 15 specimens were collected from IS bedsets at the western edge of channel body 274C. Some are disarticulated, associated with an intraformational conglomerate lag at the channel base, but others are articulated in fine-grained sandstone units on the medial surfaces of IS bedsets (Figs. 81A and B). One articulated specimen is evidently in life position, vertically orientated posterior-up in the IS bedsets. This specimen and all other articulated specimens are sandstone-cast.

The second invertebrate species is *Dendropupa vetusta* Lyell & Dawson, a small helically coiled pupiform gastropod, which is also apparently endemic to Joggins (Knight *et al.*, 1960; Fig. 82). The shells are 5-10 mm high, possess up to eight or nine whorls, and exhibit a fine axial ribbing (collabral threads). Two specimens occur in the coarse channel lag of channel body 274C, and at least a further 30-50 specimens occur in a dense accumulation within very fine sandstone to siltstone beds that compose the IS bedsets of the same channel body. In the WDF facies association in general, *Dendropupa* locally occurs as dense agglomerations of up to 20 individuals surrounding plant detritus in green-red mottled mudstone units (Hebert and Calder, 2004), although this mode of occurrence is not specifically seen in the Hebert beds.

### 7.5.3. Vertebrates

At least seven tetrapod skeletal elements also were found in the Hebert beds (Fig. 83). This material, which includes both cranial (jaw) and post-cranial fragments (shoulder and pelvic girdles, vertebrae, ribs and limbs), is currently being described by T. Fedak (Fundy Geological Museum) and A. R. Milner (University of London) and is not

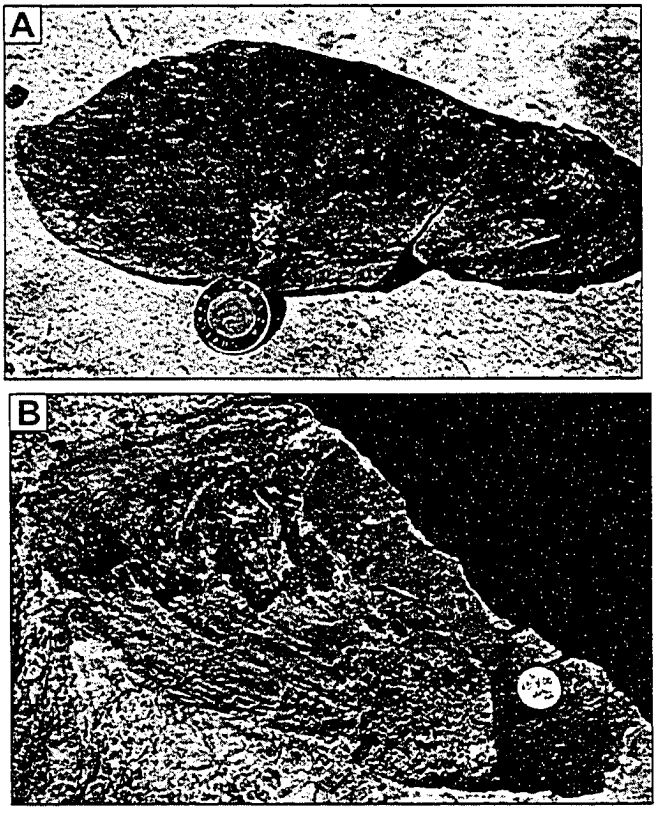



Figure 81: *Archanodon westoni* unionoid bivalves from channel body 274C of the Hebert beds. A) Articulated specimen similar to the one extracted from life position in IS bedsets, coin = 27 mm diameter, FGM998GF70. B) Disarticulated specimen from intraformational conglomeratic basal lag, museum tag = 13 mm diameter, FGM998GF5.

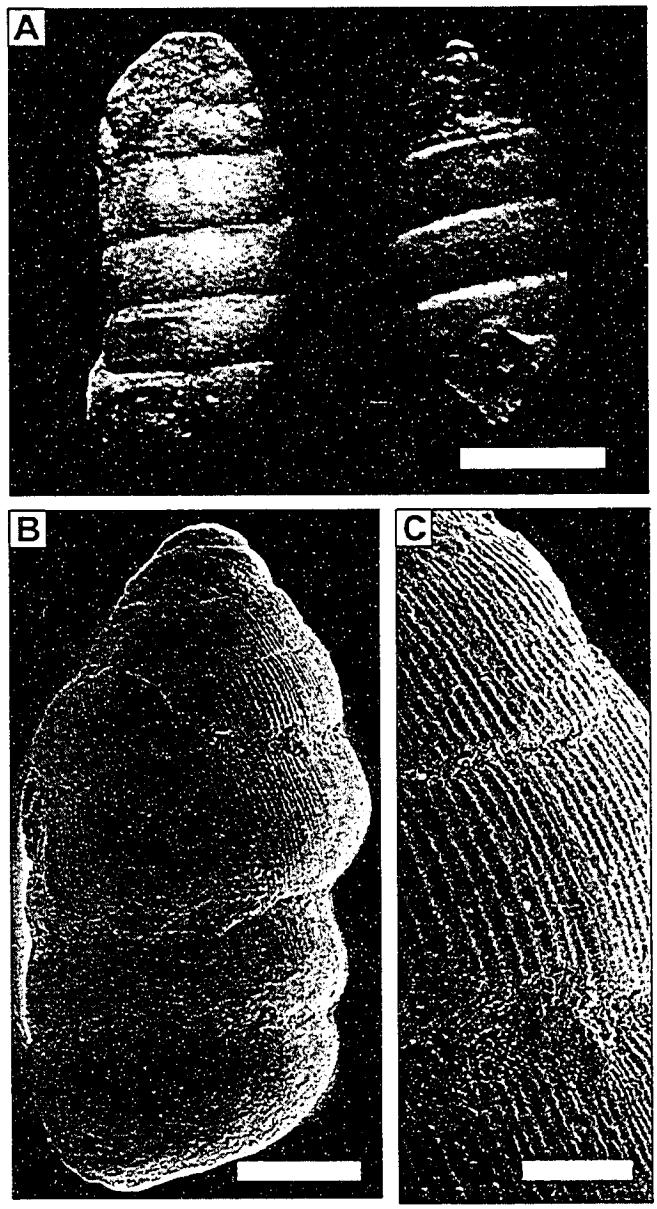



Figure 82: *Dendropupa vetusta* land snail, A) Photograph of two typically pupiform individuals, scale = 3 mm, NSM002GF031.189, Hebert beds, B) SEM image of a well preserved specimen showing fine ribbing, scale = 2 mm, private collection of Brian Hebert of Lower Cove, Nova Scotia, C) Detail of ribbing, scale = 500 μm, private collection. The specimen shown in (B) and (C) is not from the Hebert beds but from a similar red bed facies context elsewhere at Joggins.

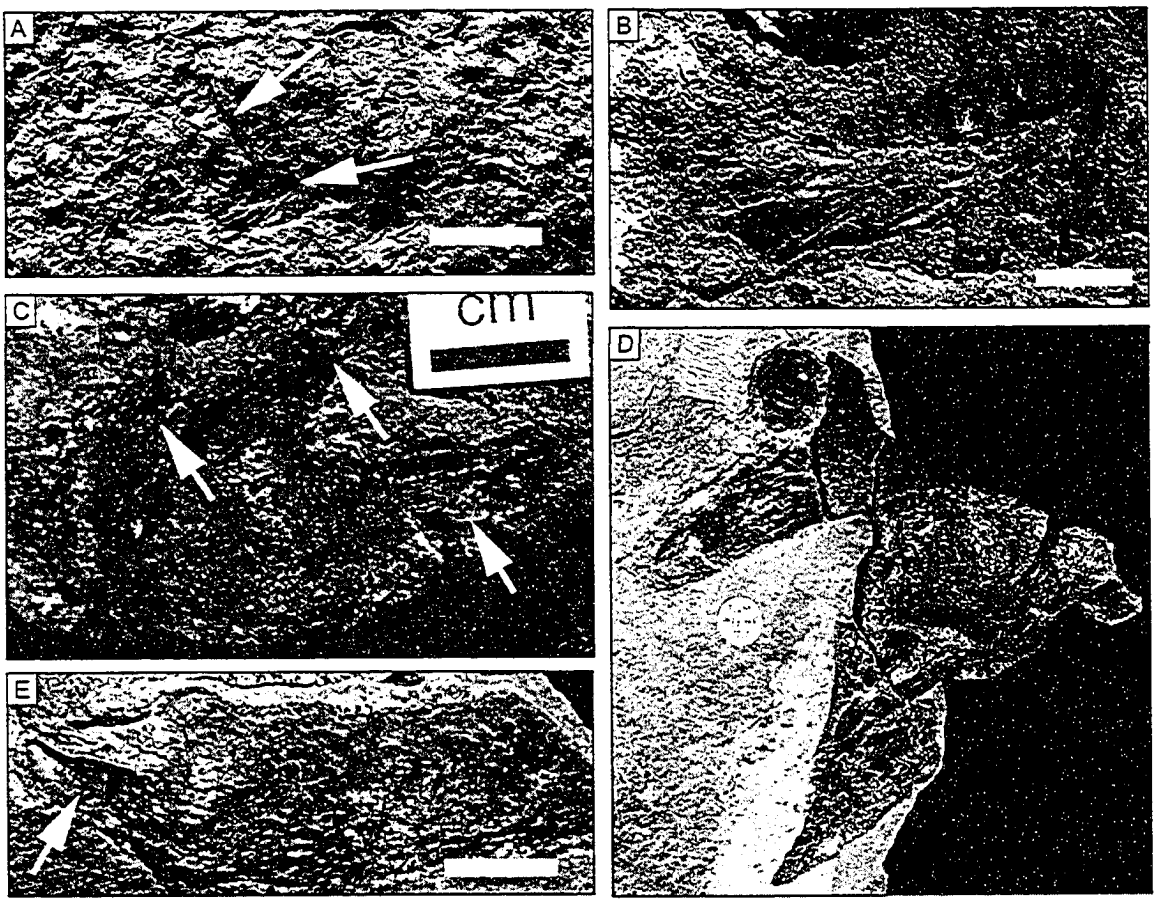



Figure 83: Examples of tetrapod material from Hebert beds. A) Basal lag of channel body 5 containing elongate rhizoconcretions (upper center, arrowed) and a microsaur jaw (lower centre, arrowed), FGM000GF19, scale = 2 cm diameter, B) Enlargement of microsaur jaw shown in Fig. 83A, scale = 7 mm, FGM000GF19, C) Labyrinthine tooth, FGM000GF104a ; three cusps are arrowed, D) Baphetid pelvic girdle assembly, FGM998GF7.1, Museum tag = 13 mm diameter, E) robust mandible with labyrinthine conical tooth (arrowed), scale = 3 cm, FGM000GF104b.

given systematic treatment here. However, preliminary investigations suggest that three tetrapod families are probably represented, including baphetids, anthracosaurs and microsaurs (Hebert and Calder, 2004).

The skeletal elements were found in a dense accumulation in channel body 274C (Fig. 79). Matrix-supported intraformational conglomerates marking the channel base yielded a microsaur jaw (23 mm long) containing nine teeth (Figs. 83A and B), a labyrinthine tooth (Fig. 83C), and a larger (>8 cm long) unidentified jaw exhibiting a single 1.3 mm long conical tooth (putative baphetid-anthracosaur; Fig. 83E). The rest of the skeletal elements were found in very fine sandstone to siltstone units at a medial level in the IS bedsets. Although limited exposure prevented detailed exploration of bone taphonomy, some of the elements were evidently partially articulated (e.g. pelvic girdle assembly; Fig. 83D) whereas others were isolated. None of the material has undergone significant mechanical fracture (the breakages visible in the figured images being created during extraction). In addition, skeletal elements show little sign of weathering (stage 0/1 on the index of Behrensmeyer, 1978) in that they show no evidence of surface cracking or flaking, or perhaps only minimal mosaic cracking.

### 7.6. Paleoenvironmental and paleoecological interpretation

Davies and Gibling (2003) interpreted the Hebert beds as the alluvial channel deposits of a well-drained alluvial plain. However, analysis of the architecture and sedimentology presented here permits more precise interpretation. In addition, new paleontological data allow inferences to be made concerning the enigmatic nature of Pennsylvanian dryland ecosystems.

### 7.6.1. Facies interpretation of Hebert beds

Based on bedset form and sedimentary structures, three types of architectural elements (Miall, 1996) are identified in these channel bodies. Sandy bedform sheets predominate in the fixed channel bodies. Lateral-accretion macroforms are present in all channel bodies, but predominate in the meandering channel bodies. These are represented by IS and IHS bedsets that dip away from channel margins, with flow-directional sedimentary structures (where measurable) oriented approximately along-strike of the inclined surfaces. Mud-dominated, abandoned channel fills occur in channel bodies 274B and C.

The architecture and probable aspect ratios of channel bodies 271, 271.5, 274A differ from that of channel bodies 274B and C, indicating that they originated under different, although genetically related, flow conditions. Based on their low W/T values and the rarity of channel migration features, the first three bodies can be classified as fixed channel bodies representing the deposits of channels that remained stationary on the floodplain (Friend, 1983) of ~4-6 m deep and ~13 m wide. The incised nature of the channel bodies and the scarcity of extensive, genetically related overbank deposits suggest that the channel bodies represent relatively long-lived river channels rather than secondary crevasse splay channels. The predominance of sandy bedforms and accessory nature of lateral accretion barforms implies that the river channels predominantly filled by vertical aggradation of bedforms, with minor contributions from in-channel and bank-attached bars. Stacked storeys within channel body 271.5 and the high density of channel bodies in this interval further suggest that successive river channels tended to reoccupy old drainage pathways. The homogeneous sandstone fill of these bodies indicates that

flows sufficiently vigorous to transport sand throughout the lifetime of the active channels. However, flow strength evidently fluctuated considerably, resulting in the transportation of pebble-sized clasts and the formation of upper-stage plane beds during periods of elevated discharge, and small dunes and ripples in medium-grained sand during periods of subdued discharge. During peak discharge, flow overtopped the channel banks, resulting in the formation of sandy "wings" (Friend *et al.*, 1979). The marked variations in flow strength characteristic of the fixed channel bodies probably reflect seasonal variations in discharge given the paleosol evidence for rainfall seasonality (Smith, 1991).

In contrast, channel bodies 274B and C represent the deposits of meandering channels that laterally migrated by cutbank erosion and associated point bar growth, as indicated by their higher W/T ratios, and the ubiquity of lateral accretion elements. The active channel responsible for 274B was at least 3.5 m deep and 8.3 m wide given the dimensions of the abandonment fill. Based on the thickness and lateral extent of lateral accretion elements (Leeder, 1973), the active channel responsible for channel body 274C was probably at least 1.8 m deep and 19 m wide (dimensions corrected for paleoflow obliquity). Lag deposits along scour surfaces in both channel bodies indicate that occasionally flows were vigorous enough to transport pebble-sized mudstone and carbonate clasts as well as cobble-sized *Archanodon* shell fragments. However, abundant lenses of mudrock and heterolithic channel fill suggest that erratic low-stage flow and ponding was a more common occurrence. Furthermore, raindrop impressions, desiccation cracks and adhesion ripples (which are formed by wind-blown sand across a moist surface) preserved within channel body 274C indicate that water levels were periodically

low enough to expose significant portions of the point bar surface subaerially. However, because these features are absent on the lower part of the point bar surface, it is likely that this channel never became completely dry but retained standing water in the thalweg region for most, if not all, of the year. Matrix-supported intraformational conglomerates at the channel base may suggest that seasonal flow resumption was initially characterized for a short time by concentrated slurry-like conditions.

Several characteristics strongly indicate that collectively the Hebert beds originated in an anastomosing fluvial system composed of multiple co-active channels. Key similarities between the channel bodies described in this study (especially fixed channel bodies) and those of modern anastomosing fluvial systems include their low W/T ratios, lateral stability and a tendency to reoccupy old drainage paths (Smith and Smith, 1980; Nanson and Knighton, 1996; Gibling *et al.*, 1998). An anastomosed interpretation is further supported by the presence of multiple small channels at precisely the same stratigraphic level at numerous intervals in the Joggins Formation and by the presence of anastomosed channels in the overlying Springhill Mines Formation (Rust *et al.*, 1984). The repeated adoption of an anastomosed fluvial morphology may have facilitated maximum sediment transport (Nanson and Knighton, 1996; Nanson and Huang, 1998) into the rapidly subsiding Cumberland Basin.

Although anastomosed fluvial systems are best described from humid climatic settings (e.g. Smith and Smith, 1980), closer analogues for the Hebert beds include the anastomosed drainages of central and northern Australia (Fig. 84), where rainfall seasonality is marked, and channel confinement is facilitated by indurated, sunbaked

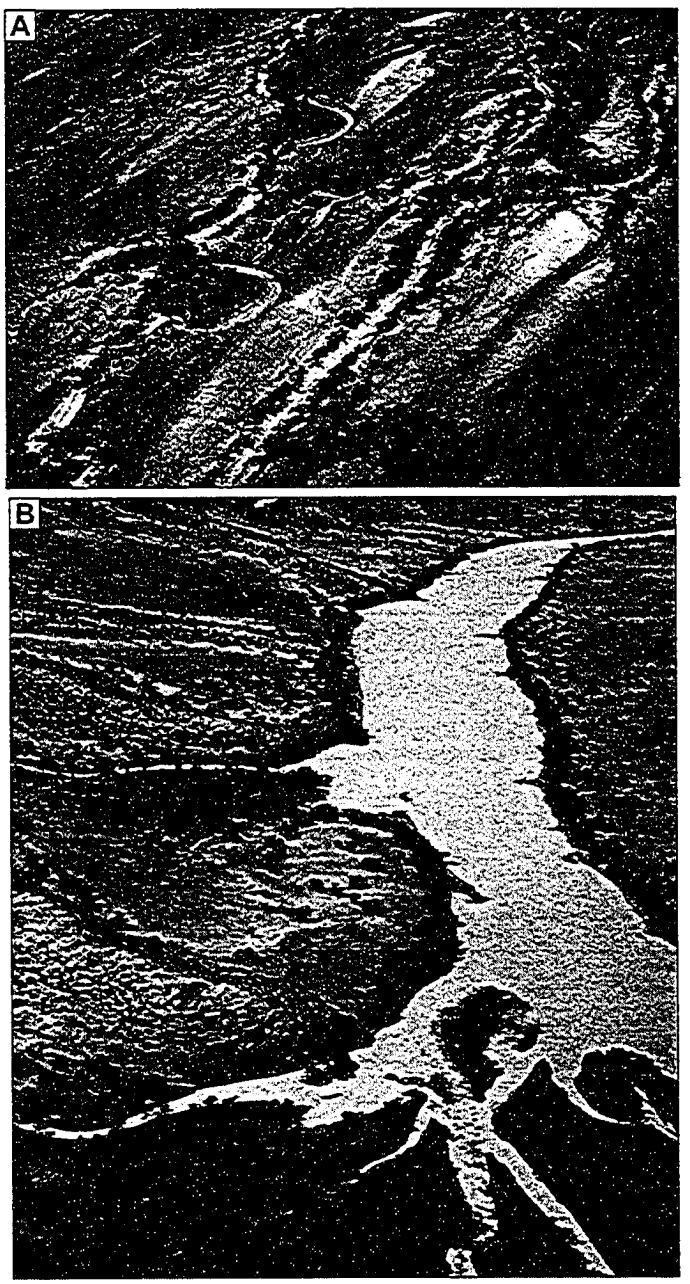



Figure 84: Anastomosed drainage networks of the Channel Country, Queensland, central Australia offer a good analogue for the Hebert beds paleoenvironment, A) river channels are analogous to the fixed channel bodies, and B) waterholes are analogous to channel bodies 274B and C.

floodplain muds and localized vegetated levees (Nanson *et al.*, 1986; Knighton and Nanson, 1994; Gibling *et al.*, 1998). The appropriateness of such Australian analogues is investigated below, but first the paleoenvironment of the fossiliferous meandering channel bodies is further interpreted.

As already noted, these units represent the deposits of sinuous channels that, following the repeated cessation of fluvial through-flow, became perennially ponded to sluggishly flowing water bodies. Given the evidence for seasonality in rainfall (Smith, 1991) and channel discharge, it is highly probable that the perennial ponded bodies on the Joggins alluvial plain acted as ecologically significant sources of water (waterholes sensu Jackson, 1997), especially during seasonal drought. This interpretation is supported by the abundance of fossils in these units.

### 7.6.2. Plant ecology

Facies analysis of fossil plants provides insight into the vegetation ecology of the Hebert beds. Rare *Stigmaria* associated with mudstone beds of the meandering channel bodies demonstrate that a few lycopsid trees grew within and immediately adjacent to channels during sustained periods of ponding. Fielding and Alexander (2001) considered the presence of in-channel trees as an important facies criterion for recognizing seasonally flowing river systems; rare in situ lycopsids therefore provide further evidence for the seasonal nature of the Hebert bed channels. Although lycopsids underwent a relatively rapid life cycle (Phillips and DiMichele, 1992), the existence of large, in-channel trees suggests that, at times, many years must have elapsed without significant channel through-flow, while trees grew to maturity. However, sedimentary facies and other fossil data (below) suggest that it was more normal for rivers to flow seasonally.

Facies-associated allochthonous trunks indicate that the drought-tolerant *Sigillaria* was the dominant lycopsid tree in this riparian niche (Phillips and DiMichele, 1992; Falcon-Lang, 2003).

During more active periods of channel flow, calamites colonized rapidly aggrading channel margins and within-channel bars, as indicated by *in situ* stems rooted in sandstone beds on the edge of channel body 274C, and implied by allochthonous stems preserved on point bar surfaces. Like their extant relative *Equisetum*, calamiteans were adapted to disturbed niches because of their prolific ability to resprout from underground rhizomes (Gastaldo, 1992).

By far the largest volume of plant material in the meandering channel bodies consists of allochthonous leaves, trunks, pith casts and wood (commonly charred) derived from cordaite trees, together with indeterminate gymnosperm rhizoconcretions. Facies analysis of these remains throughout the WDF facies association suggests that they were transported from ecologically stressed, fire-prone gymnosperm vegetation that occupied well drained floodbasins between the fluvial channels (Falcon-Lang, 1999, 2003), some distance from the alluvial waterholes. The discovery of gymnosperm roots preserved in carbonate concretions confirms that these plants were indeed growing in seasonally dry, carbonate-accumulating soils.

### 7.6.3. Bivalve ecology

The occurrence of the unionoid bivalve *Archanodon* sheds light on the aquatic ecology of the Hebert bed seasonal drainages and waterholes. Four Devonian-Pennsylvanian species of this bivalve have been previously described, all of which occur

in similar facies associations despite their disjunct temporal distribution (Weir, 1969; Chamberlain, 2004).

The first species, *Archanodon catskillensis* Vanuxem, is common in Middle to Upper Devonian successions in eastern USA, associated with the deposits of meandering alluvial channels, crevasse splays, floodbasin mudstones (Friedman and Chamberlain, 1995) and ephemeral carbonate lakes (Demicco *et al.*, 1987). Burrows, some containing *A. catskillensis* in life position, occur in point bar, levee and proximal splay deposits (Thoms and Berg, 1985; Bridge *et al.*, 1986) and indicate that organisms were freshwater infaunal suspension feeders (Friedman and Chamberlain, 1995). Diminutive *A. catskillensis* specimens associated with leperditiid and beyrichiid ostracods have led to speculation that some forms may have tolerated brackish water (Knox and Gordon, 1999), but supporting facies evidence is equivocal (Friedman and Lundin, 2001; Knox, 2001).

No facies data exist to ascertain the mode of life of a second species, *A. rhenana* Beushausen, from Middle Devonian units of Germany (Thoms and Berg, 1985). However, a third species, *A. jukesi* Forbes, found in Upper Devonian-Mississippian strata of the British Isles, is associated with coarse-grained, fresh-to-brackish fluvial channel deposits and ephemeral carbonate lake facies (Howse, 1878; Holland, 1981; Turner *et al.*, 1997).

The fourth species, *A. westoni* Whiteaves, is endemic to Joggins, and prior to this study was known only from two specimens discovered in the nineteenth century (Whiteaves, 1893; Chamberlain, 2004). Almost all Joggins specimens found in more recent times occur in the Hebert beds (Hebert and Calder, 2004), and although many are

fluvially reworked (disarticulated fragments), some are in life position or parautochthonous, demonstrating that these bivalves lived in river point bars like their Devonian ancestors. Their thick, smooth, elongate valves suggest that they were adapted to periodic high-energy conditions, and were infaunal suspension feeders (Eagar, 1948).

Little is known of the ecology of extant unionid bivalves in seasonally dry river channels (McMichael, 1952). Limited observations indicate that they exhibit a filter-feeding strategy during periods of bankfull channel flow, but at times of low flow burrow into the muddy channel floor where they remain dormant (aestivate) until flow is resumed in the following wet season (McMichael, 1952; Tevesz and Carter, 1980). A similar mode of life is envisaged for *Archanodon* at Joggins as Hebert bed drainages periodically oscillated between actively flowing alluvial channels and ponded waterholes. Modern unionids can survive in a dormant state for only a few months (McMichael, 1952) before they die of their own toxicity; following death their shells spring open and become filled with sediment. The sandstone-cast nature of the single *Archanodon* specimen in life position therefore suggests that, at times, the length of the droughts must have exceeded the upper tolerance limit of these organisms.

Under favorable conditions, the mantle of modern unionid bivalves continuously secretes shell material, but during ecological disturbance, it contracts, resulting in the formation of a growth band. In seasonal tropical settings, primary bands develop during the summer drought, with secondary bands recording minor environmental fluctuations (Tevesz and Carter, 1980). Given the tropical paleolatitude of Joggins, primary growth bands in *Archanodon* specimens provide further evidence for rainfall seasonality, and

indicate that these large bivalves typically lived for around 8-10 seasons, like their long-lived extant relatives (Strayer, 1999).

The temporally disjunct nature of *Archanodon* populations, its four species sporadically occurring in the Devonian-Pennsylvanian interval, may provide additional ecological information. Dryland alluvial deposits are preserved infrequently in the geological record, more typically being sites of net erosion than deposition. Temporally disjunct *Archanodon* species therefore may indicate that populations were centered in a seasonal continental-interior setting where long-term preservation potential was low.

### 7.6.4. Gastropod ecology

The presence of the pulmonate land snail, *Dendropupa vetusta*, provides insight into one part of the terrestrial ecology of the Hebert beds waterhole. *Dendropupa* specimens were first found in the PDF facies association at Joggins, located within the hollow lycopsid trunks (Dawson, 1860, 1880; Solem and Yochelson, 1979). However, subsequently this species has been found more widely in the WDF facies association, where it predominates in coarse-grained channel lags and as clusters of multiple individuals in mudstone beds associated with fossil plant detritus (Hebert and Calder, 2004). Comparison with extant related taxa suggests that *Dendropupa* was a grazing detritivore (Dawson, 1860), an interpretation supported by the facies data presented here. Rather than representing allochthonous hydrodynamic concentrations, the most parsimonious explanation for the clusters of multiple gastropods is that they represent life assemblages, preserved when populations grazing on plant debris within the waterhole were buried by the resumption of fluvial flow. Many extant, related viviparid gastropods can resist drought for long periods (>10 months) by burrowing into drying mud, sealing

their operculum and aestivating (Withers *et al.*, 1997). Given its occurrence in a dryland setting, *Dendropupa* may have had a similar capacity.

### 7.6.5. Vertebrate ecology

The vertebrate skeletal fragments in channel body 274C provide information about a second facet of the terrestrial ecology of the Hebert beds waterhole. Hebert bed baphetids and anthracosaurs were probably aquatic or amphibious, broad-snouted tetrapods that fed on fish, and, based on skeletal dimensions, were up to 2 m in length. In contrast, Hebert bed microsaurs were salamander-like insectivores, up to 20-30 cm long (Milner, 1987; Milner and Lindsay, 1998).

The absence of well-developed weathering features (stage 0/1) suggests that the Hebert bed vertebrate remains were subject to a relatively short period of subaerial weathering after death (probably <4 years based on modern weathering rates; Behrensmeyer 1978). This may suggest that animals died near the waterhole, or at least were rapidly transported into it. Vertebrate remains are commonly associated with modern and ancient waterhole deposits because animals are attracted to standing water bodies during severe drought, where they starve to death as local food resources are depleted (Conybeare and Haynes, 1984).

Although some skeletal remains are evidently allochthonous (i.e. disarticulated jaws in the channel lag deposits), other remains are probably parautochthonous. This is especially true of the partially articulated pelvic girdle remains that occur in siltstone or very fine sandstone units deposited during ponded to sluggishly flowing conditions. The Hebert bed vertebrate remains therefore probably fall somewhere in the middle of the taphonomic continuum of Behrensmeyer (1988) of fluvial-hosted vertebrate assemblages,

material having undergone either little or some transport in the seasonally active Joggins dryland rivers.

### 7.7. MODERN ANALOGUES

The remainder of this paper is devoted to developing and discussing modern analogues for the Joggins waterhole deposit and its biota. From a purely sedimentological perspective, the anastomosed drainage networks of the semi-arid Channel Country, Queensland, central Australia, offer one analogue in which summer storm-driven floods alternate with winter droughts when flow ceases (Rust, 1981). Perennial waterholes (0.1-2 km in length) are common, forming within the deepest channel reaches at points of channel constriction, confluence, or within remnant scours during low-stage flow (Knighton and Nanson, 1994, 2000). They are normally stagnant water bodies, but experience gentle flow (typically <1 m $s^{-1}$) for a few weeks each year when they become connected to active channels (Fig. 84; Nanson *et al.*, 1986; Knighton and Nanson, 1994, 2000). Specific facies characteristics shared with channel bodies 274B and C of the Hebert beds include the presence of rain prints, adhesion ripples, desiccation cracks, lateral accretionary bar-forms, the predominance of suspension deposits, and W/T ratios substantially greater than normal active channels (Knighton and Nanson, 1994; Gibling *et al.*, 1998; Knighton and Nanson, 2000).

Despite this general facies correspondence, paleosol data for the Joggins section (Smith, 1991 and summary in Chapter 10) suggest a considerably more humid climate than that of the Channel Country, where rainfall ranges from 120 to 150 mm per year (Gibling *et al.*, 1998). Consequently, this analogue is probably inappropriate for the biological component of the Hebert beds. However, seasonally flowing rivers with

perennial waterholes are also characteristic of more humid parts of Australia. These regions include the Burdekin River of Queensland (Fielding *et al.*, 1999) and rivers of the northern Australian coast (e.g. Knighton and Nanson, 1993; Wende and Nanson, 1998), where rainfall is in the range of 700-1500 mm per year but strongly seasonal (Williams, 1983).

Like the Hebert beds, these seasonally humid systems exhibit relatively low-diversity plant communities with vegetation biomass being dominated by ecologically stressed seed-bearing trees. Another similarity is that along waterhole levee to floodplain transects, a pronounced vegetation gradient exists in many places. For example, at Magela Creek, northern Australia, hydrophilic palms and mangroves proximal to the waterhole give way to fire-prone sedges, grasses and paperbark on the dry floodbasin (Williams, 1983). A further feature of all Australian seasonal rivers also seen in the Hebert beds is the colonization of channel bases by trees (Williams, 1983; Gibling *et al.*, 1998; Fielding and Alexander, 2001).

Other biological similarities to the Hebert beds include the presence of common large infaunal unionid bivalves in the Australian waterholes, in particular the widespread genus *Velesunio* (Williams, 1983; Gibling *et al.*, 1998). Like *Archanodon*, these related organisms are active suspension feeders during times of channel through-flow, but remain dormant in the muddy channel floors during drought (McMichael, 1952; Gibling *et al.*, 1998). Their relatively thin valves, in contrast to *Archanodon*, may be a consequence of the low levels of dissolved carbonate in many Australian watercourses (Bayly and Williams, 1973; Tevesz and Carter, 1980). Also present around the Channel Country waterholes and in more humid regions are abundant viviparid gastropods such as

Notopala, which may have an analogous ecology to *Dendropupa*. This extant gastropod, like its Pennsylvanian relative, is dominantly a deposit feeder, grazing on vegetable detritus and algae within seasonal alluvial channels (Gibling *et al.*, 1998).

Finally, Australian waterholes also contain common, but relatively low-diversity tetrapod faunas including frogs, lizards, tortoises and crocodiles. Many of these organisms have evolved significant tolerance of drought (for example, the moaning frog can lose up to a quarter of its body weight through water loss during daily foraging, and still survive) or have developed behavioral strategies such as burrowing and aestivation that limit water loss (Williams, 1983). Given the close environmental correspondence to Australian waterholes, tetrapods of the Hebert beds may have possessed similar adaptive traits.

It will be clear that the seasonal drainages of the Hebert beds bear a genuinely close similarity to those of present-day northern and central Australia, especially in terms of sedimentology and biology. This is emphasized by two general ecological similarities: both systems exhibit high degrees of endemicity (especially amongst the invertebrate fauna) and possess relatively low species richness. Such features are considered highly characteristic of ecologically stressed biomes (Williams, 1983) and this implies that the striking ecological convergence of these two temporally and geographically disjunct regions is probably related to the strong environmental forcing exerted by their common setting.

In conclusion, analysis of the Hebert beds assemblage and comparison with the modern Australian analogues sheds new light on the nature of the enigmatic tropical drylands (summerwet biome) of Pennsylvanian times (Fig. 85). In the future, study will

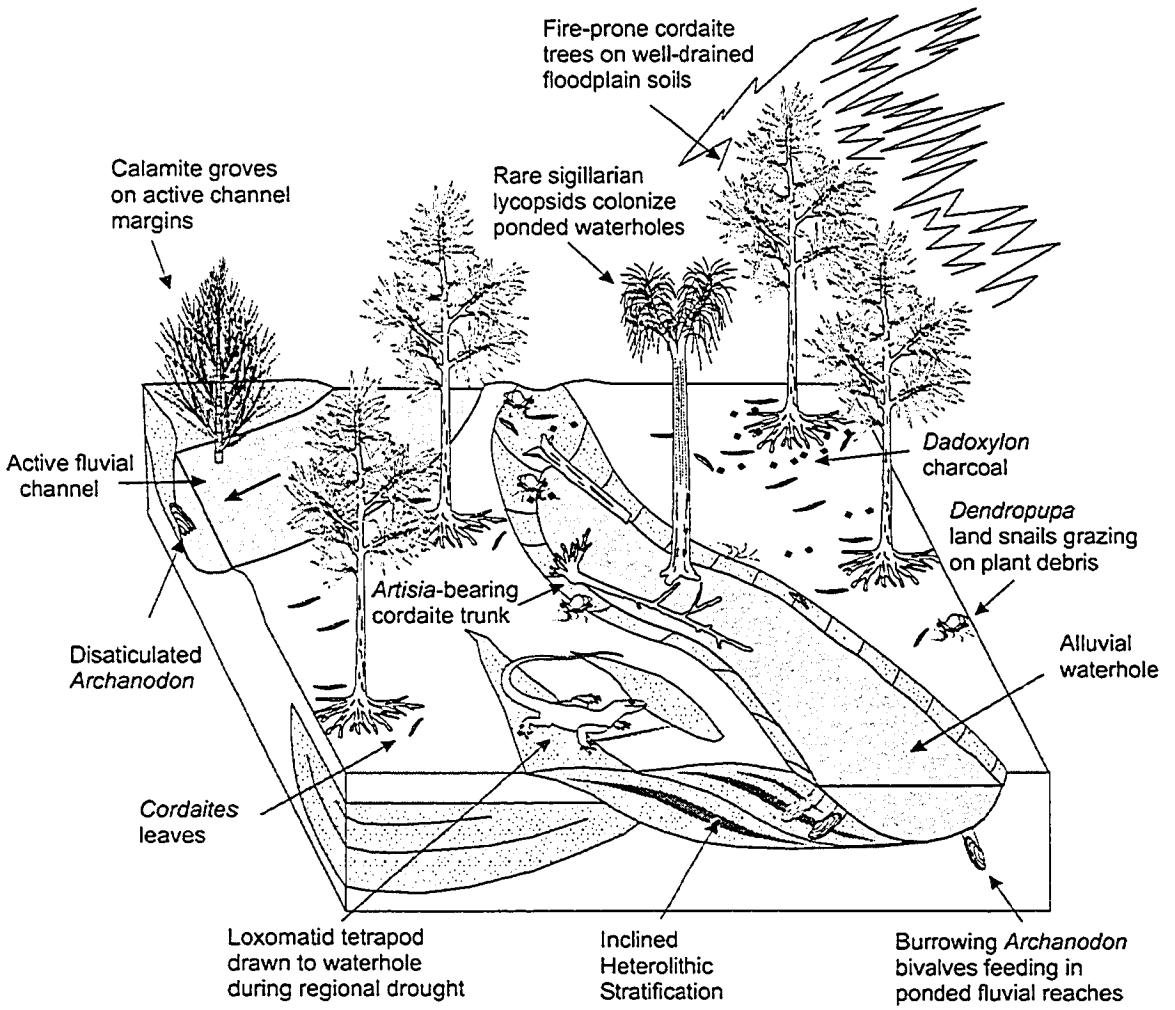



Figure 85: Paleoenvironmental synthesis summarizing the main components of the Hebert beds environment and ecosystem. Note: it is not envisaged that the river depicted in the top left (which is representative of the fixed channel bodies) was actively flowing at a time when the channel in the lower right was ponded and partially dry (meandering channel bodies). The two channels depict alternate periods of flow and ponding.

focus on channel bodies with similar facies characters to the Hebert beds at Joggins in an attempt to locate more of these important assemblages.

## 7.8. CONCLUSIONS

1. An early Pennsylvanian channel complex containing an unusual fossil assemblage has been described at Joggins, Nova Scotia; this unit is informally termed the Hebert beds. Channel architecture and facies analysis suggest that the unit represents a waterhole preserved in seasonally dry alluvial plain deposit.

2. The Joggins waterhole fossil assemblage, which includes fossil plants, gigantic freshwater unionoid bivalves, terrestrial gastropods and semi-terrestrial tetrapods, is significant because it sheds light on the composition and ecology of the enigmatic Pennsylvanian summer-wet biome.

3. Results demonstrate that major differences existed between the ecology of Pennsylvanian continental drylands and the better known peat-forming wetland realm, the former being dominated by low-diversity, ecologically stressed ecosystems.

## 7.9. ACKNOWLEDGEMENTS

This paper would not have been possible were it not for the fossil discoveries of B. Hebert. We thank A. Milner for assisting with tetrapod identification. H.F.L. acknowledges the receipt of a Killam Fellowship at Dalhousie University, a NERC Fellowship at the University of Bristol (NER/I/S/2001/00738), and a Paleontology grant from the Nova Scotia Museum of Natural History (2001). M.R.G. acknowledges funding from the Natural Sciences and Engineering Research Council of Canada, Imperial Oil, and the American Chemical Society (Petroleum Research Fund). M.C.R. acknowledges grants from the American Association of Petroleum Geologists, the Geological Society of America (GSA), and the Coal Geology Division of GSA (Medlin Award). J.H.C. acknowledges receipt of a Paleontology grant from the Nova Scotia Museum of Natural History (1999). This paper greatly benefited from the scientific and editorial reviews of R. Gastaldo, H. Pfefferkorn and A. Crame.

# CHAPTER 8: STRATIGRAPHY AND SEDIMENTOLOGY OF EARLY PENNSYLVANIAN RED BEDS AT LOWER COVE, NOVA SCOTIA, CANADA: THE LITTLE RIVER FORMATION WITH REDEFINITION OF THE JOGGINS FORMATION

*John H. Calder, Michael C. Rygel, R.J. Ryan, Howard J. Falcon-Lang, & Brian L. Hebert*

## 8.1. ABSTRACT

The coastal cliffs along the eastern shore of Chignecto Bay, Nova Scotia contain one of the finest Carboniferous sections in the world. In 1843, Sir William Logan measured the entire section, as the first project of the Geological Survey of Canada, and defined eight stratigraphic divisions. Here we present a detailed bed-by-bed re-measurement of part of this section, which corresponds almost exactly with Logan's Division 5. The strata are exposed in the wave-cut platform and low-relief bluffs of a two kilometer long section at Lower Cove, near Joggins, north and south of Little River. This 635.8-m-thick succession was previously included within the basal part of the Joggins Formation, and overlies the Boss Point Formation. However, the studied strata are lithologically distinct from bracketing units, and in this paper, are recognized as a new formation: the Little River Formation. This newly proposed formation is bounded by regionally important surfaces and is traceable inland for 30 km from its Lower Cove type section. Facies analysis indicates that it represents the deposits of a well-drained alluvial plain dissected by shallow, flashy rivers. It is clearly distinguishable from the underlying Boss Point Formation (Logan's Division 6) in terms of its much smaller sandstone bodies, and from the overlying Joggins Formation (Logan's Division 4) by the absence of coal seams and bivalve-bearing limestone beds. Palynological assemblages indicate that the

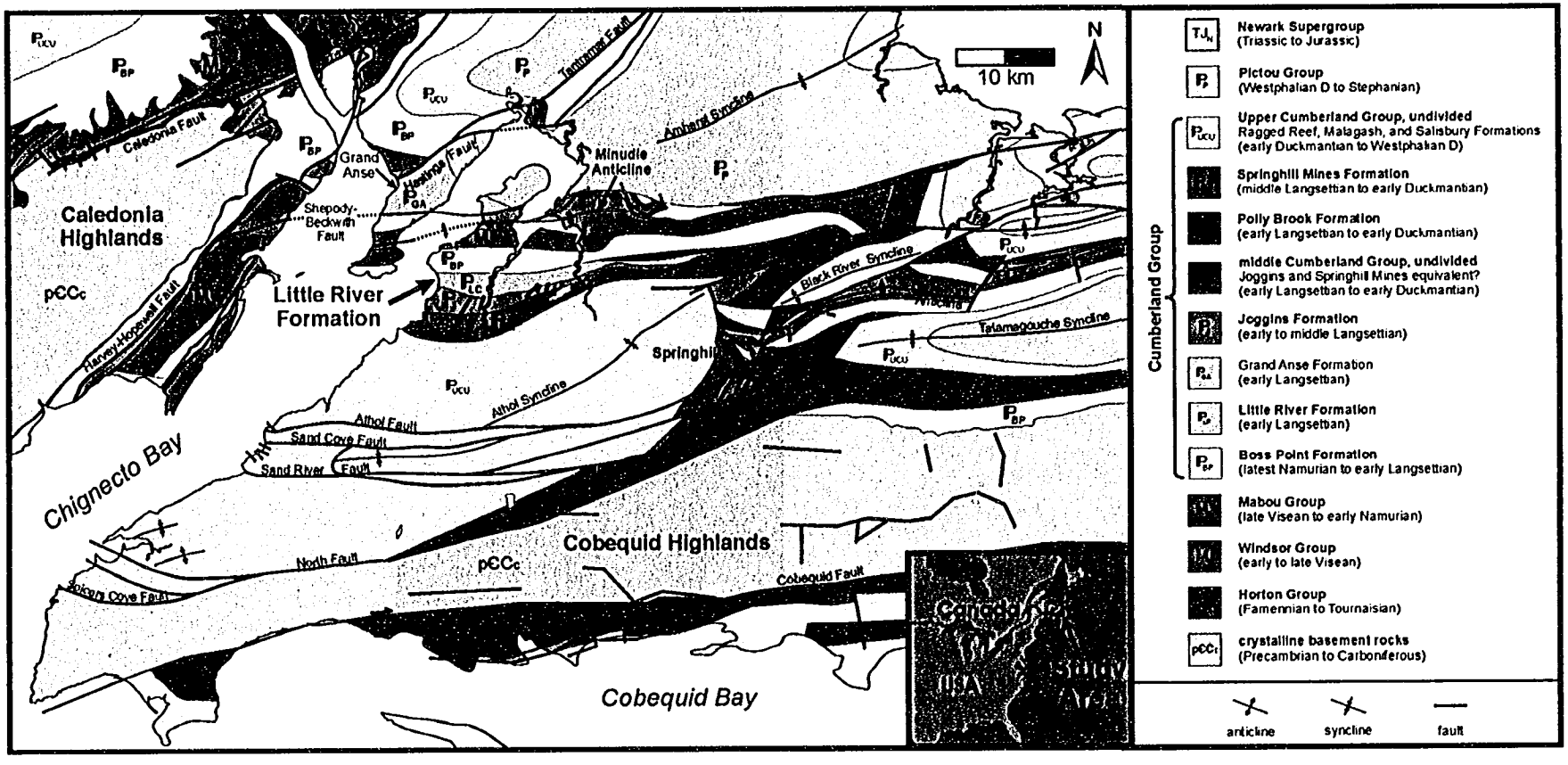
Little River Formation is of probable late Namurian to basal Westphalian age (basal Langsettian), and likely time-equivalent to the informal Grand-Anse Formation of southeast New Brunswick.

## 8.2. INTRODUCTION

The coastal cliffs along the eastern shore of Chignecto Bay, Nova Scotia, Atlantic Canada have long been considered to be one of the world's classic Carboniferous sections (Fig. 86; Lyell, 1871; Gibling, 1987). The seminal work that defined the stratigraphy of these strata is that of Sir William Logan, who undertook measurement of the section as one of the first field projects of the Geological Survey of Canada (Logan, 1845; Rygel and Shipley, Chapter 2). In this paper, we examine in detail, for the first time since that work, the 636-m-thick section of low topographic relief that intervenes between underlying prominent, thick sandstone bodies of the Boss Point Formation, valued source of grindstones in the nineteenth century, and the cliff section of the Joggins Formation, the coal measure succession where the seminal paleontological discoveries of Sir William Dawson and Sir Charles Lyell (Falcon-Lang and Calder, 2004).

The strata described herein are exposed in the wave-cut platform and bluffs in the two kilometer long redbed section north and south of the mouth of Little River, near the village of Lower Cove, Nova Scotia. This stratal interval, measuring 636 m in thickness, almost exactly corresponds with Division 5 of Logan (1845). Our newly measured section log (Appendix 5), recorded in the field at 1:100, and digitally transcribed subsequently by Andrew Henry, adjoins a similar log of the overlying Joggins Formation measured simultaneously by Sarah Davies, University of Leicester, and Martin Gibling,

Figure 86: Geologic map of the Cumberland Basin showing the location of the Little River Formation (based on Ryan *et al.*, 1990; Ryan *et al.*, 1990; Keppie, 2000; New Brunswick Department of Natural Resources and Energy, 2000; St. Peter, 2001).


10 km
N
Caledonia Fault
Caledonia Highlands
Grand Anse
Hastings Fault
Shepody-Beckwith Fault
Minudie Anticline
Amherst Syncline
Tantramar Fault
Little River Formation
Harvey-Hopewell Fault
Springhill
Black River Syncline
Tatamagouche Syncline
Athol Syncline
Athol Fault
Sand Cove Fault
Sand River Fault
Chignecto Bay
North Fault
Advocate Cove Fault
Cobequid Highlands
Cobequid Fault
Cobequid Bay
Cumberland Group
Newark Supergroup (Triassic to Jurassic)
Pictou Group (Westphalian D to Stephanian)
Upper Cumberland Group, undivided Ragged Reef, Malagash, and Salisbury Formations (early Duckmantian to Westphalian D)
Springhill Mines Formation (middle Langsettian to early Duckmantian)
Polly Brook Formation (early Langsettian to early Duckmantian)
middle Cumberland Group, undivided Joggins and Springhill Mines equivalent? (early Langsettian to early Duckmantian)
Joggins Formation (early to middle Langsettian)
Grand Anse Formation (early Langsettian)
Little River Formation (early Langsettian)
Boss Point Formation (latest Namurian to early Langsettian)
Mabou Group (late Visean to early Namurian)
Windsor Group (early to late Visean)
Horton Group (Famennian to Tournaisian)
crystalline basement rocks (Precambrian to Carboniferous)
anticline
syncline
fault

Dalhousie University (Davies *et al.*, submitted). Together, these papers provide a continuous reference log of the Joggins section from South Reef at the upper contact of the Boss Point Formation, to the contact of the Joggins Formation with the overlying Springhill Mines Formation, north of MacCarrons Creek. This is the first comprehensive log of the "classic" Joggins section to have been completed since that of Logan (1845).

The section of red beds described in this paper provides a clear basis for the division and redefinition of stratigraphic units in this classic section, in particular the stratigraphic relationship of the Boss Point and Joggins Formations and coeval units exposed across the bay in New Brunswick. Furthermore, the Little River red beds are key to understanding the evolution of the landscape, setting the stage for the environment recorded in the overlying classic Joggins section.

## 8.3. Geologic Setting

The Lower Cove section is situated in the western Cumberland Basin, which during Carboniferous times, was an active depocenter within the regional Maritimes Basin. Highland massifs lay to the south (Cobequid Highlands) and west (Caledonia Highlands) of the Cumberland Basin (Fig. 86). The western part of the basin (Athol Syncline) experienced subsidence rates unsurpassed in contemporaneous coal basins of Europe and North America (Calder, 1994; Davies and Gibling, 2003). Contributing to this subsidence history was the halokinetic withdrawal of thick Mississippian salt deposits (Waldron and Rygel, Chapter 9). The age of coastal exposures of the Carboniferous-fill spans the Viséan through early Westphalian (Duckmantian). During this time interval, the basin was positioned close to the equator, east of the rising

Appalachian mountain belt and midway between the Appalachian and Western European foreland basin complex (Calder, 1998).

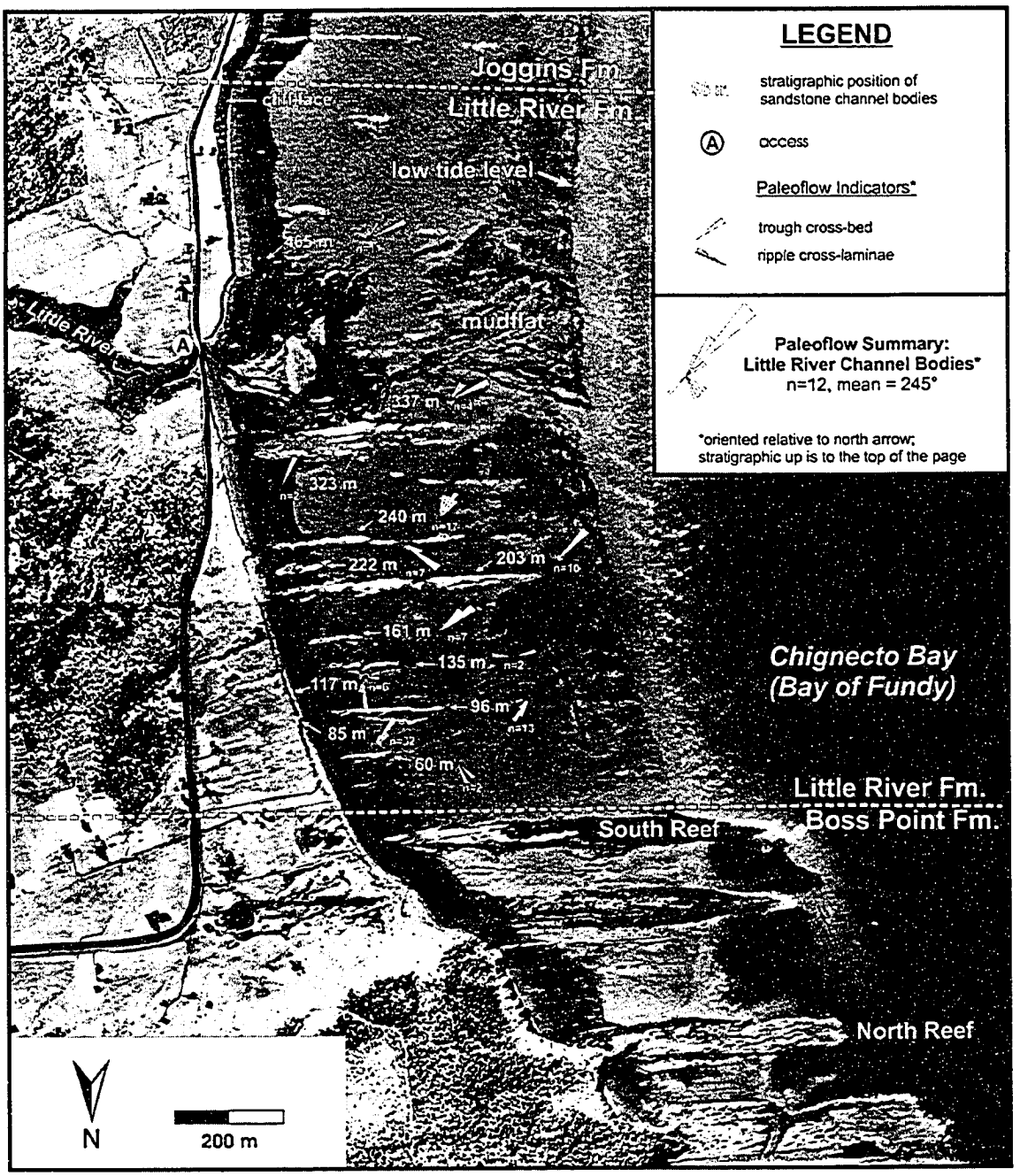
### 8.4. Stratigraphic History

The first stratigraphic account of the Carboniferous section at Joggins, and for the Maritimes Basin in general, was the pioneering work of Brown and Smith (1829). Their stratigraphic framework, and subsequent modifications (Gesner, 1836, 1843; Lyell, 1843; Dawson, 1878), underscored the geologic parallels between once-contiguous Nova Scotia and the British Isles (Calder, 1998).

The Carboniferous strata exposed along the eastern shore of Chignecto Bay were first measured by William Logan during the summer of 1843 (Logan, 1845; reprinted in Poole, 1908). Logan measured ~15 km of virtually continuous coastal section from Minudie south to Shulie, a succession that by his calculation, totaled 4442.4 m (14,570 ft, 11 in). Incredibly, this feat was achieved during a five-day stop en route from Halifax to the Gaspé Peninsula (Rygel and Shipley, Chapter 2) as a precursor to the search for coal-bearing strata in Lower Canada, and comprised the first field project of the fledgling Geological Survey of Canada.

Logan subdivided his section into eight lithologically distinct divisions, numbered from youngest (1) to oldest (8). The redbeds of Lower Cove were assigned to Division 5, and the overlying coal measures of the Joggins and Springhill Mines Formations to Divisions 4 and 3 respectively. The sandstone-dominated strata of the underlying Boss Point Formation were assigned to Division 6. Logan placed the lower contact of Division 5 at the top of "South Reef" (Fig. 87), which we consider to represent the uppermost sandstone body of the Boss Point Formation. He placed the upper contact 5 ft, 6 in (1.65

Figure 87: Labeled air-photograph showing the position of prominent sandstone channel bodies in the intertidal zone, formation boundaries, and paleoflow information. The image is a mosaic created from air-photographs A18580-125 and 18580-121(both 1:15,840), available from the Nova Scotia Department of Housing and Municipal Affairs, Land Information Services Division.


LEGEND
stratigraphic position of sandstone channel bodies
access
Paleoflow Indicators*
trough cross-bed
ripple cross-laminae
Paleoflow Summary:
Little River Channel Bodies*
n=12, mean = 245°
*oriented relative to north arrow; stratigraphic up is to the top of the page
Joggins Fm.
Little River Fm.
low tide level
mudflat
Little River
A
365 m
337 m
323 m
240 m
222 m
203 m
161 m
135 m
117 m
96 m
85 m
60 m
Chignecto Bay
(Bay of Fundy)
Little River Fm.
Boss Point Fm.
South Reef
North Reef
N
200 m

m) below the stratigraphically lowest coal (No. 45) of Division 4, a bed that we propose herein as the basal datum of the revised Joggins Formation (see below).

Logan's "Recapitulation" of Division 5 reads as follows: "dominated by red shale, reddish grey sandstone with occasional "drift plants" and "concretionary limestone", and minor greenish grey sandstone, totalling 2082 ft 0 in". The thickness of the Little River redbeds (634.6 m) obtained by Logan agrees remarkably closely with the thickness of 635.8 m measured in this study (a mere 1.2 m difference). Despite minor modifications and combinations over the years, Logan's (1845) measurements and subdivisions form the basis for all later stratigraphic studies of the Carboniferous strata of the Cumberland Basin, including the present paper.

### 8.5. Relationship to other units within the Cumberland Basin

The stratigraphic relationship of the Lower Cove red beds to other units within the basin (other than those in direct contact in the coastal exposures) has long been enigmatic. Brown and Smith (1829) did not distinguish the Lower Cove beds from their "Millstone Grit" and overlying "Coal Measures" (Fig. 88). Dawson (1855) originally assigned Divisions 5-8 to the "Lower or Older Coal-Formation", broadly analogous to the Lower Carboniferous, but later reconsidered and correlated these strata with the "Millstone-grit Series" (Dawson, 1868). Grouping of Logan's Divisions into more broadly recognized lithostratigraphic units represented an attempt to correlate these stratal packages beyond the confines of the basin, but required an understanding of the localized sedimentation patterns within the tectonically active Cumberland Basin.

During the first half of the twentieth century W.A. Bell (1912; 1914; 1927; 1938; 1943) studied the paleontology and regional stratigraphy of the Carboniferous of Nova

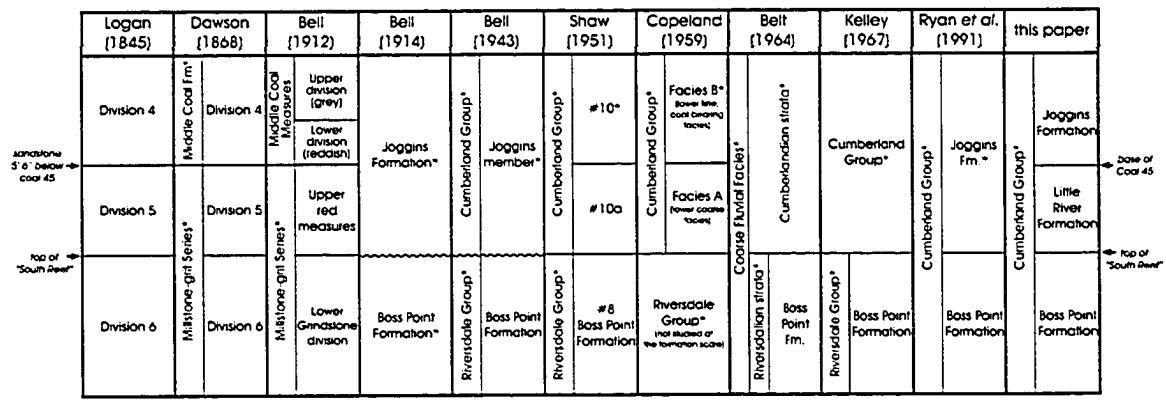



Figure 88: Summary of stratigraphic nomenclature employed historically in reference to the Little River and Joggins Formations.

Scotia. Well aware of the lithostratigraphic complexities of the Cumberland Basin, Bell felt that the basin fill could be more naturally subdivided based on the presence of unconformities as indicated by the floral and faunal record. Bell's regional stratigraphy, grounded in his steadfast belief in unconformity-bound groups, became the definitive work of the twentieth century, but his combined use of bio- and lithostratigraphic definitions has proven problematic in usage. Influential advocates of a purely lithostratigraphic approach to the regional stratigraphy of the Maritimes Basin have been Belt (1964; 1965) and Kelley (1967), whose arguments were addressed, at least in part, by Ryan *et al.* (1991).

In his first round of stratigraphic revisions, Bell (1912; 1914; 1938) grouped Divisions 3-5 of Logan and the basal part of Division 2 into his "Joggins Formation". His grouping of the Lower Cove redbeds (Division 5) with the overlying coal-bearing strata (Division 3-4) was based, in part, on the lack of contrary (or indeed any) megafloral evidence recorded within the redbeds. Bell correlated the contact between coal-bearing strata and conglomerate at Spicer's Cove (Fig. 86) on the south limb of the Athol Syncline (Fletcher, 1908) with the contact between Divisions 5 and 6 at Lower Cove (Bell, 1914, 1927). This correlation, later shown to be incorrect (Ryan *et al.*, 1990; Ryan *et al.*, 1990), contributed to the impracticality of mapping his Shulie and Joggins formational groupings inland (Bell, 1938). Consequently, Bell later advocated their abandonment in favor of an undivided Cumberland Series (1938), and later Cumberland Group (1943; 1958), comprising Divisions 1-5, with Divisions 6-7 assigned to his Riversdale Group.

In the mid-twentieth century, efforts were renewed to map the basinfill. Central to this work was the goal of establishing stratigraphic relationships inland with the economically important coal measures of Springhill. In the course of this work, Shaw (1951; 1951) recognized the red beds of Lower Cove as a lithologically distinct subunit (10a) of his "coal-bearing facies" and considered the redbeds to be coeval with basin-margin conglomerates (his map unit 9, the Polly Brook Formation of later authors) near Springhill (Fig. 86). Copeland (1959) concurred, but grouped the Lower Cove redbeds with the basin-margin conglomerates (his Facies A).

Bell, Shaw and Copeland drew strength in this direct correlation of the Lower Cove redbeds and basin margin conglomerates from their belief that the coal-bearing strata of Spicer's Cove were correlative with the Joggins coals and were underlain by conglomerates exposed at the south of Spicer's Cove. Palynostratigraphic studies (Hacquebard and Donaldson, 1964; Dolby, 1991) have demonstrated that the Spicer's Cove section is younger than that of Lower Cove, a conclusion supported in the megafloral record (R.H. Wagner, personal communication 2000). Furthermore, a growing body of evidence further suggested that the contact between the Lower Cove redbeds and the underlying Boss Point Formation was likely conformable (Hacquebard, 1972; Howie and Barss, 1975).

Later in the century, a subsequent round of mapping and stratigraphic investigations in the Cumberland Basin was undertaken by the Nova Scotia Department of Natural Resources (Ryan *et al.*, 1990; Ryan *et al.*, 1990; Ryan *et al.*, 1991; Calder, 1995). The lithostratigraphic distinctiveness and regionally mappable boundaries of the Lower Cove red beds were acknowledged by Ryan *et al.* (1990) on their geological map,

but this unit was nonetheless included with the coal-bearing strata of Division 4 and the basal 51 m of Division 3 in their revised and reinstated Joggins Formation (Ryan *et al.*, 1990; Ryan *et al.*, 1991). Members were not formally defined within this 1433-m-thick unit, although the informal term "Little River Bridge member" was used by Ryan *et al.* (Ryan *et al.*, 1991) and Ryan and Boehner (1994; their Figs. 2-13) in reference to the Lower Cove red beds.

## 8.6. Little River Formation

### 8.6.1. Definition

Here we formally propose elevating the Lower Cove redbeds to the status of Formation, and propose the name Little River Formation for these beds. Our proposed unit is defined purely on the basis of lithostratigraphy, being a non-coal-bearing red bed-dominated succession positioned beneath the coal-bearing strata of the Joggins Formation. The formation is named after Little River, the mouth of which crosses the type section where it enters Chignecto Bay at Lower Cove. For the sake of clarity, it is important to note that this newly proposed unit bears no relationship to the now historically obsolete "Little River Group" of southwest New Brunswick (Dawson, 1868), despite these strata being approximately time-equivalent.

### 8.6.2. Justification

The Little River Formation comprises a lithologically distinctive and regionally mapable unit. It is separated from the overlying Joggins Formation on the basis that it lacks both coal and bivalve-bearing limestone beds, the two defining hallmarks of the overlying strata (Ryan *et al.*, 1991). It is also lithologically distinct from the underlying Boss Point Formation, which is characterized by thick, multistorey, well-sorted grey

sandstones, features absent from the Little River Formation. Similarly, although it is considered to be, in part, coeval with the Polly Brook Formation, it is lithologically distinct from that polymictic conglomerate succession. Both base and top of the Little River Formation are regionally important surfaces.

### 8.6.3. Type locality

The type section comprises outcrops within the intertidal zone and alonglow-relief coastal bluffs on the eastern shore of Chignecto Bay, at Lower Cove, near Joggins, Cumberland County, Nova Scotia. The section begins at the top (southern edge) of the South Reef of the Boss Point Formation (UTM Coordinates 5066450N, 388000E; NAD 83 datum), and extends 1500 m southwards to a point 500 m south of the mouth of Little River (5063200N, 388400E). The top of the section coincides with the base of the lowest coal bed (Coal 45 of Logan, 1845) of the Joggins Formation, near the start of the continuous cliff section (Fig. 87).

### 8.6.4. Reference localities

Strata of the Little River Formation are known to occur inland on four stream sections east of the type section (see Ryan *et al.*, 1990). These include, from west to east, (1) exposures on a small tributary to the Maccan River north of the village of Maccan, (2) along Baird Brook at Chignecto, (3) near the contact with the underlying Polly Brook Formation on Saint George's Brook east of Chignecto, and (4) on Styles Brook south of Stanley.

### 8.6.5. Boundaries

The basal contact of the Little River Formation is placed at the top of the highest multistorey sandstone bed of the Boss Point Formation, which at the type section is the

top of the South Reef, almost exactly coinciding with the base of Division 5 (Logan, 1845). Inland, to the east, the base of the formation progressively onlaps against polymictic conglomerates of the Polly Brook Formation (Ryan *et al.*, 1990; Ryan *et al.*, 1991). The upper contact of the formation is placed at the base of the stratigraphically lowest coal bed (Coal 45 of Logan, 1845), which coincides with the base of the revised Joggins Formation (Davies *et al.*, submitted).

### 8.6.6. Thickness and distribution

The type section near Little River, constituting a re-measurement of Division 5 of Logan (1845), is 635.8 m in thickness. The formation can be traced 30 km to the east along the north limb of the Athol Syncline to Styles Brook (Ryan *et al.*, 1990), where it eventually pinches out between the underlying Polly Brook Formation and overlying Joggins and Springhill Mines Formations (Fig. 86). The Little River beds exhibit many similarities with fault-bound strata exposed across Chignecto Bay to the west on Maringouin Peninsula, New Brunswick, assigned to the informal Grande Anse Formation (St. Peter and Johnson, personal communication 2004).

### 8.6.7. Correlation

Inland, the Little River Formation is inferred to be laterally equivalent to the Polly Brook Formation near the southern and eastern edges of the Athol Syncline (Fig. 89; Ryan *et al.*, 1990; Calder, 1991, 1994; Waldron and Rygel, Chapter 9). Although it is probable that the Grand Anse Formation in southeast New Brunswick may represent a facies of the Little River Formation, their unequivocal correlation is problematic due to uncertainties in the stratigraphic relationship of the Grand Anse strata with neighboring geologic units: the lower contact of the Grand Anse section is in faulted contact with the

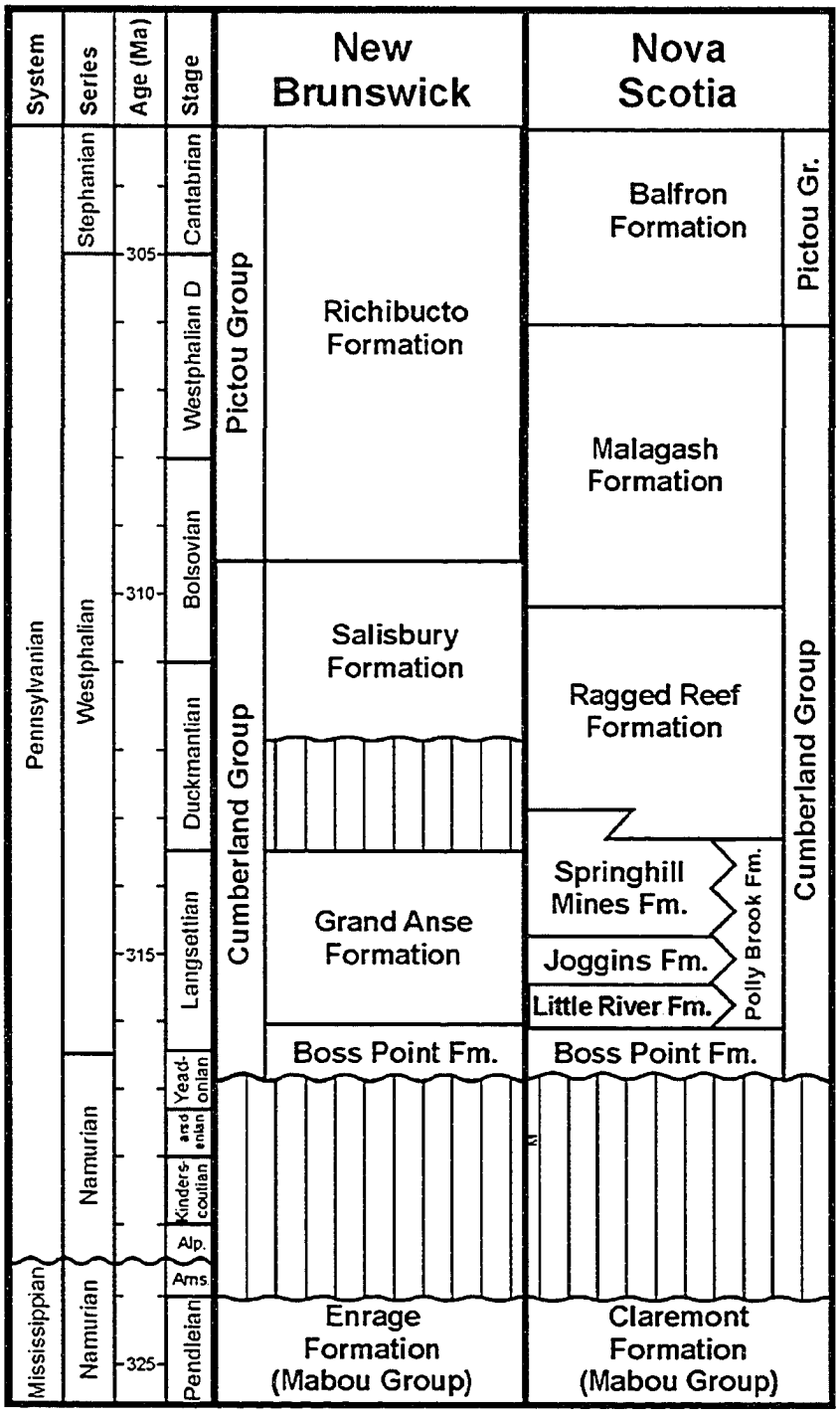



Figure 89: Stratigraphic units of the Joggins coastal section and their relationship to basin-fill units inland and in New Brunswick. Modified from Ryan *et al.* (1990), Calder (1995) and St. Peter (2001).

Boss Point Formation, and the upper contact is in faulted contact with the Mississippian Windsor Group.

### 8.6.8. Age

Age determination of the Little River Formation is problematic, due to its sparse paleontological record, and in particular, the complete absence of key age-diagnostic marine index fossils (Calder, 1998). Furthermore, although palynology offers an alternative means to date strata, difficulties exist in disentangling evolutionary signatures from paleoecological effects. With these uncertainties in mind, comprehensive palynostratigraphic studies of the type section place the Little River Formation within the upper Namurian (Kinderscoutian) to basal Westphalian (basal Langsettian) according to Dolby (1991; 2003), or entirely within the upper Namurian (Marsdenian to Yeadonian) according to John Utting (personal communication 2004).

On the basis of the occurrence of *Cananoropolis mehtae,* which until recently was known only from strata in the informal "Coal Mine Point member" of the Joggins Formation (Ryan *et al.*, 1991), redbeds comprising the Grand Anse section on Cape Maringuoin, New Brunswick have been assigned a late Langsettian age (Dolby 1999). Subsequent sampling of the formation at Lower Cove, however, yielded a solitary specimen of *C. mehtae* (Dolby, 2003), suggesting that it may be less useful as a local index taxon than previously assumed, and therefore giving cause to reconsider the late Langsettian age for the Grand Anse Formation.

## 8.7. SEDIMENTOLOGY OF THE LITTLE RIVER FORMATION

### 8.7.1. Major sandstone channel bodies

Twelve major (>2-m-thick) and accessible channel bodies crop out on the wave cut platform as prominent "reefs", and vary in width from 31 to 534 m. Channel bodies have been assigned numerical values (Fig. 87), which correspond to the stratigraphic position in meters of the top of their uppermost bed in reference to the measured section. Channel bodies are described using the bounding surface and lithofacies terminology of Miall (1996). Smaller channel bodies (<2-m-thick) also occur in the section, but are dealt which separately below.

8.7.1.1. Channel Body Geometry.

The lateral exposure of Little River channel bodies varies depending on their size and position on the shoreline. Five fully exposed channel bodies are 2.4 to 6.0 m thick and have width:thickness (W/T) ratios ranging between 6 and 43 when measured perpendicular to paleoflow. Seven incompletely exposed channel bodies are 3.1 to 10.0 m thick and have minimum W:T ratios of 13.6 to 147.0 when measured perpendicular to paleoflow.

The architecture of these sandstone channel bodies is defined by the fifth-order (channel body-) bounding surfaces, which both separate them from the underlying mudrocks and compartmentalize them into vertically stacked, or abutting storeys. The basal storey(s) of many channel bodies comprises an obviously erosional fifth-order surface, which forms one or more concave-up channel bases. These U-shaped forms are 3.1 to 7 m thick with W/T ratios between 5 and 25. Where concave-up surfaces flatten, they pass into the relatively bedding-parallel, fifth-order(?) surface that defines the base

of the overlying, more tabular storey. These uppermost tabular storeys are 1 to 4 m thick with W/T ratios greater than 35, and are similar to the thick sandstone "wings" of Friend *et al.* (1979). In summary, the composite sandstone channel bodies described are amalgamations of U-shaped incised storeys with overlying, more laterally extensive storeys.

Internally, storeys contain numerous third- and fourth-order bounding surfaces (macroform growth increment and macroform bounding, respectively) that separate the sandy fill into channel elements and sandy bedforms. Individual channel elements are generally 1.5 to 6.0 m thick and have a narrow, u-shape in cross-section (W/T ratio <10). Inclined stratification within sandy bedforms is variably oriented with dips ranging from perpendicular to oblique to the channel margin. Third- and fourth-order surfaces divide the basal part of most storeys into stacked packages of crudely stratified intraformational conglomerate (Gh) overlain by trough, planar, or low-angle cross-bedded sandstone (St, Sp and Sl, respectively). The upper portions of these channel bodies, and the entirety of others (e.g. channel body at 465 m), contain varying proportions of horizontally, low-angle, and/or ripple cross-laminated sandstone (Sh, Sl, and Sr respectively). These intervals commonly contain third-order bounding surfaces, which are expressed as either low angle or channel element bounding erosional surfaces.

A shallow erosional scour atop the channel body at 96 m (see Appendix 5) contains an assemblage of lithofacies unique within the Little River Formation. The 2.45 m-deep and 20-m-wide scour is incised into a 3 m-thick package of trough to low angle cross-bedded sandstone and intraformational conglomerate. The basal 0.70 m of the scour is filled with two sets of planar cross bedded sandstone that are overlain by ~15 cm

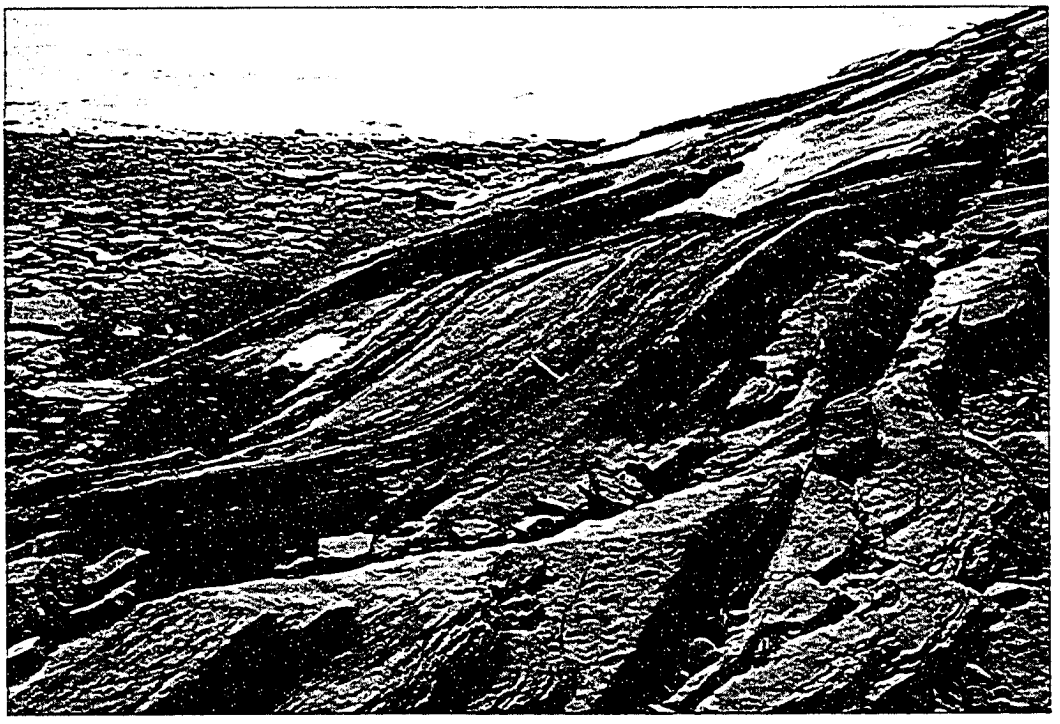


Figure 90: Large, sigmoidal bedform at 96 m of the measured section (Appendix 5).

of horizontally laminated sandstone. A "sigmoidal" erosional surface (Fig. 90) cuts down from the channel margin, truncating these basal units. The erosion surface is draped by a form-concordant, sigmoidal blanket of ripple cross-laminated sandstone that gradually becomes flat lying and passes upward into a sheet that extends beyond the margin of the scour and caps the entire channel body.

8.7.1.2. Sediment composition.

Channel bodies generally are composed of quartz- and calcite-cemented, very fine- to medium-grained feldspathic arenites. Sandstones additionally contain abundant sand-sized clay particles with bright clay fabric, which may represent mud aggregates (Gierlowski-Kordesch and Gibling, 2002; Müller *et al.*, 2004; Gardiner and Gibling, 2005). Erosion surfaces are lined locally with crudely stratified intraformational conglomerate (Gh) containing medium to coarse-grained sandstone (Ss), which is either interspersed as a matrix or co-occurs within separate lenses. Lag deposits are clast-supported and contain pebble sized rip-up clasts of red and green mudstone with rare granule-sized quartz clasts (channel body at 90 m). Locally abundant calcareous rip-up clasts are composed of concentric layers of finely crystalline calcite developed around a core of sparry calcite.

Although no root tissue was observed, these clasts are otherwise identical to the calcareous rhizoconcretions described by Falcon-Lang *et al.* (2004) from redbeds in the overlying Joggins Formation.

8.7.1.3. Paleoflow.

The orientation of trough cross-beds and ripples in the channel bodies are plotted as rose diagrams (10° petals) on the measured section (Appendix 5) and outcrop map

(Fig. 87). Planar cross-beds and primary current lineations were locally abundant, but these structures are relatively unreliable indicators of paleoflow, and omitted from the analysis. Measurements were grouped by structure type within individual channel bodies to allow for comparison between different scales of structures and for intrachannel variation. Because the axes of troughs and ripples are linear features, they need not be corrected for the ≤25° dip at the Little River type section (Potter and Pettijohn, 1977).

Where ripples and trough cross-beds were measurable within the same channel body (n=3), their mean orientation varied by 1° to 19° (mean: 7.7°). Given this similarity, these structures were treated as equally reliable and used to calculate a mean paleoflow direction for each channel body (Fig. 87). The twelve Little River channel bodies shown a southwestern trend (mean = 245°, r=0.6). Of the four bodies that deviate from this trend, three exhibit paleoflow to the northwest with the remaining one to the northeast.

8.7.1.4. Comparison with bracketing formations.

Channel bodies of the Little River Formation are an order of magnitude smaller than those of the underlying Boss Point Formation and exhibit considerable differences in alluvial lithofacies and paleoflow direction. Browne and Plint (1994) describe the Boss Point Formation as being characterized by 20- to 90-m-thick braidplain sandstone packages, which are underlain by sixth-order bounding surfaces and extend several hundred meters across the intertidal zone. These bodies are composed dominantly of trough cross-bedded sandstone and have individual channel elements up to 35 m thick. Furthermore, the 245° (southwesterly) trend of the Little River Formation channel bodies

differs from the southeasterly trend of the underlying Boss Point Formation by 70° (Browne and Plint, 1994).

Little River Formation channel bodies also differ from those of the overlying Joggins Formation in terms of both geometry and internal architecture. Redbeds in both formations contain channel bodies between 5- and 10-m-thick, but the examples in the Joggins Formation contain significant amounts of interstratified mudrock, are contained within small incised valleys, and are not capped by laterally extensive wings (Davies and Gibling, 2003). Although some Joggins Formation channel bodies (e.g. Coal Mine Point) are similar in size and geometry to those in the Little River Formation, these bodies are single storey and contain well developed lateral accretion surfaces (Davies and Gibling, 2003). Paleoflow directions within the Little River and Joggins Formations are variable, but large channel bodies in both tend to have a southerly or southwesterly flow orientation.

### 8.7.2. Mudrock-dominated intervals

8.7.2.1. Mudrocks.

The Little River Formation is mudrock-rich, which contributes to its low relief in the type section. Mudrocks, comprising claystone to silty claystone, invariably are red in color. Ubiquitous drab-haloed root compressions are characteristic of the formation; calcareous rhizoconcretions and amalgamated (dm-scale) carbonate nodules occur locally. Discrete, thin (cm-scale), dark grey, organic-rich mudrock intervals, may occur at some horizons, and may persist laterally for tens of meters, but true coal beds are absent.

8.7.2.2. Paleosols.

Mudrocks within the Little River Formation contain three types of paleosols, which are described here using standard terminology (Retallack, 2001; Soil Survey Staff, 2003). By far the most common type comprises intervals containing drab-haloed root compressions, locally associated with standing vegetation. These weakly developed mineral paleosols lack horizons and represent very weakly developed Entisols. Their common occurrence indicates pervasive pedogenesis throughout the accretion of the Little River Formation. Smith (1991) studied similar, but better developed, paleosols in the overlying Joggins Formation and interpreted them as paleo-Alfisols formed under warm, oxidizing conditions. In contrast with these Joggins Formation paleosols, however, Early Permian red beds of north-central Texas contain Alfisols with pedogenic carbonate horizons (DiMichele *et al.*, in press). Other paleosols exhibit surficial horizons <10 cm thick that are composed of green or grey mudstone with variable amounts of organic material and rooting. The most organic-rich of these horizons consist of incipient histic epipedons (surface horizons) capping weakly developed Entisols.

A distinctive aspect of the paleosols of the Little River Formation that contrasts with those of the Joggins Formation is the development of calcic (Bk) horizons. These horizons contain discontinuous carbonate-cemented nodules (<20 cm thick) that reach Machette's (1985) Stage III of carbonate accumulation. Such pedogenic carbonate development indicates xeric conditions and a semi-arid to arid climate with seasonal drying and incomplete leaching (Soil Survey Staff, 2003; DiMichele *et al.*, in press). Paleosols with vertically oriented calcareous rhizoconcretions are similar to paleosols described from the Early Permian of north-central Texas interpreted by DiMichele *et al.*

(in press) as Alfisols, whereas more extensively cemented pedogenic carbonate was considered indicative of Inceptisols. Clay mineralogy and petrographic studies of the Little River paleosols at Lower Cove will be required to refine these preliminary interpretations.

8.7.2.3. Small channel bodies.

Small (<2 m thick), U-shaped (W/T <5) channel bodies occur throughout the Little River Formation, hosted within the mudrock-dominated intervals. These features have convex-down bases and flat tops; mounded tops occur locally. Channel bodies commonly occur in stacked groups where individual channel bodies are obliquely offset from one another. Small channel bodies are either isolated within mudrock or pass laterally into thin (<1 m thick) sheet sandstones. Channel fill consists of varying proportions of horizontally, low-angle, and/or ripple cross-laminated sandstone (Sh, Sl, and Sr respectively), or more rarely may largely contain laminated, grey/green mudstone.

8.7.2.4. Sheet sandstone bodies.

Thin (<1 m thick) sheet sandstones are commonly interbedded with red mudrocks of the Little River Formation. These beds typically extend for several tens of meters, their complete extent being unknown due to limited exposure at the coastal section. Internally, sheet sandstones are often massive with localized areas of horizontal or ripple cross-laminated sandstone (Sh and Sr, respectively). The presence of drab haloed root compression and occasional calamitean plants in growth position suggests that these beds experienced some pedogenic overprinting. A few beds near the top of the section are very strongly cemented by calcite, a phenomena that may reflect pedogenic accumulation of calcite at or near the water table.

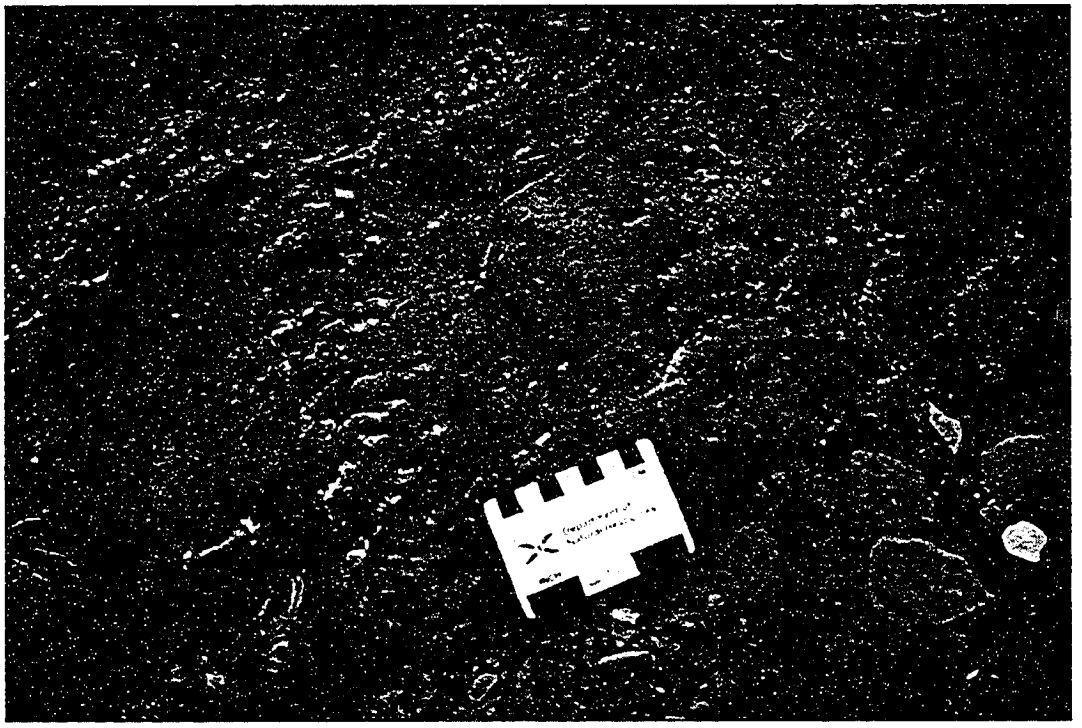


Figure 91: *Diplichnites* trail, ascribed to the huge detritivorous arthropod *Arthropleura*, from ~335 m of the measured section (Appendix 5).

## 8.8. PALEONTOLOGY

In spite of 150 years of investigation of the rich terrestrial fossil record of the Joggins Formation (Falcon-Lang and Calder, 2004), no floral or faunal records exist from the red beds of the Little River Formation. The first records that have emerged in the course of this study likely afford but a glimpse of the total biodiversity of this unit.

### 8.8.1. Fauna

8.8.1.1. Invertebrates.

Aggregations of the land snail *Dendropupa vetusta* occur concentrated on discrete drab horizons (98 m, Appendix 5). These aggregations represent surface litter accumulations (Hebert and Calder, 2004) that are consistent with their detritivorous autoecology (Solem and Yochelson, 1979). The Little River occurrences predate those of the Joggins Formation and so push back in time the first appearance of pulmonate gastropods in the fossil record. The presence of the largest known terrestrial detritivore, the large millipede-like *Arthropleura,* is betrayed by a 23-cm-wide *Diplichnites* trackway (Fig. 91; 335 m, Appendix 5). The polychaete worm *Spirorbis* is abundant in a single, small, grey mud-filled channel at 352 m in the measured section, where the epifauna densely adhere to cordaitalean trunks (see below).

8.8.1.2. Vertebrates.

The solitary record as yet obtained from the Little River Formation is an occurrence of large tetrapod footprints (96.5 m, Appendix 5) provisionally assigned to the ichnogenus *Pseudobradypus*. The possible affinity of this ichnotaxon with the baphetid stem tetrapods and its occurrence in stratigraphic proximity to the land snail *Dendropupa*

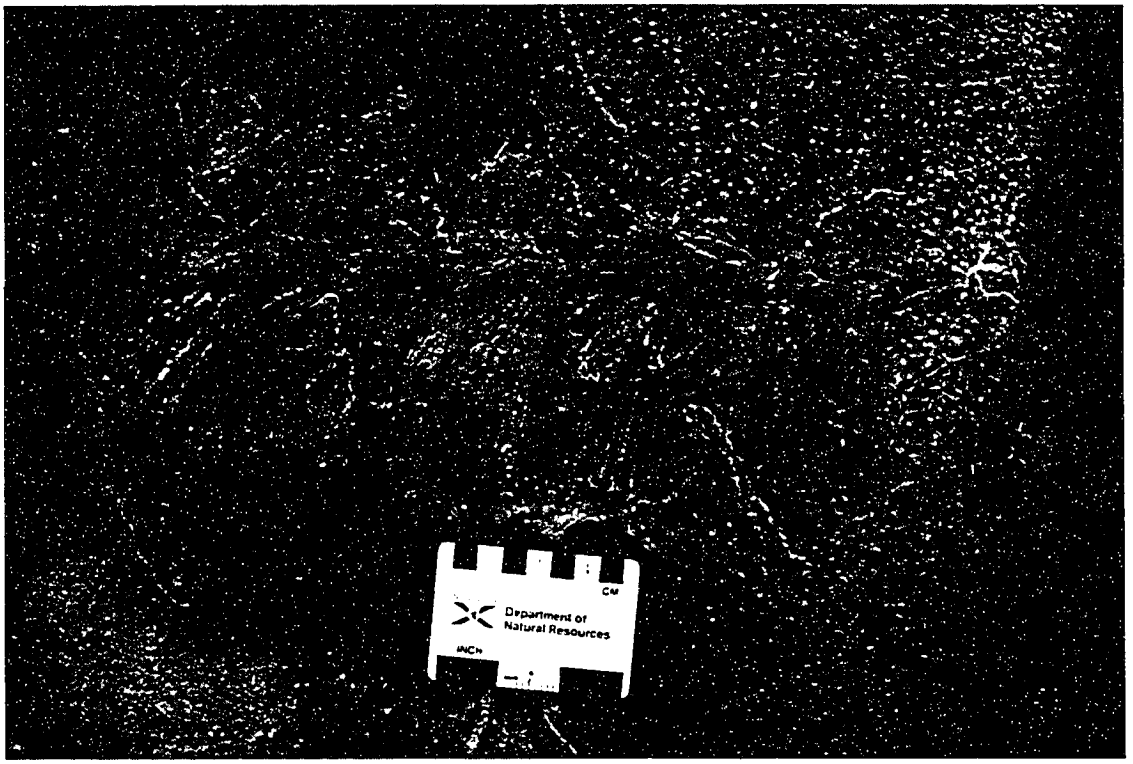



Figure 92: Enigmatic "hinterland" plant similar to *Rhacopteris busseana* Stur, from the Little River Formation.

recall their association in the Hebert sandstone of the Joggins Formation (Falcon-Lang *et al.*, 2004; Hebert and Calder, 2004).

### 8.8.2. Flora

8.8.2.1. Adpressed plant assemblages.

By far the most abundant megafloral impressions are sphenopsid stems (*Calamites cisti* and less commonly *C. suckowi*), which occur throughout the section as prostrate axes in channel lag deposits, and less commonly in growth position. Unfragmented *Cordaites* leaves, up to 22 cm in length, are common locally in red mudrock beds and channel sandstone bodies. Less commonly recorded are medullosan pteridosperm axes, rare foliage (*Alethopteris sp.*) and seeds (*Trigonocarpus cf. parkinsoni*). Lycopsid remains are very rare indeed, represented only by leaf compressions (*Cyperites* sp.) at 220 m in the measured section, and at 241 m, by trunk compressions (*Lepidodendron* sensu latu and *Sigillaria* cf. *rugosa*). Stigmarian rootstocks are completely absent. An enigmatic plant (Fig. 92) found in the measured section is similar to *Rhacopteris busseana* Stur (R.H. Wagner, personal communication 2004), and may represent a rarely encountered dryland or hinterland floral element.

8.8.2.2. Anatomically preserved woods.

Multiple channel sandstone units, in particular those at 96 m and 240 m in the measured section, contain allochthonous charred blocks of wood (up to 17 mm diameter), and more rarely calcite-permineralized trunk fragments. These anatomically preserved woods are present both in channel lags and in cross-bedded intervals higher in the channel bodies. In addition, a single small mud-filled channel, hosted in a mudrock-

dominated interval at 352 in the measured section, contains a further four calcite-permineralized trunks, 18-24 cm in diameter.

Scanning electron microscopy and thin section analysis shows all specimens comprise pycnoxylic coniferopsid wood of *Dadoxylon*-type. The best preserved examples are assigned to *D. recentium*, a wood characterized by biseriate, alternate, bordered tracheid pitting (Fig. 93A), cupressoid pits per cross-field (Fig. 93B and C), and low rays (Fig. 93D). In the Joggins Formation, *Dadoxylon recentium* wood has been recorded in biological attachment to septate axes of *Mesoxylon* type (Falcon-Lang 2003), indicating that at least some of the charred wood in the Little River Formation is cordaitalean. However, some of the calcite-permineralized woods in the Little River Formation are attached to non-septate axes (up to 3-4 cm diameter, up to 45 cm long). At present it is unclear whether the absence of pith septa is a biological or taphonomic feature, but in either case, the most likely affinity of these woods is cordaitalean (Falcon-Lang, 2005).

## 8.9. Depositional Environment of the Little River Formation

### 8.9.1. Facies interpretation

Major channel sandstone bodies of the Little River Formation represent the deposits of alluvial drainage channels with characteristics typical of braided streams. These channels were 2.6 to 11 m deep, and evolved from relatively narrow, incised, South Saskatchewan-like rivers to late-stage, shallow, Platte-like rivers (Smith, 1970; Cant and Walker, 1978). These deposits contrast markedly with similar sized channel bodies within redbeds of the overlying Joggins Formation, which were deposited by

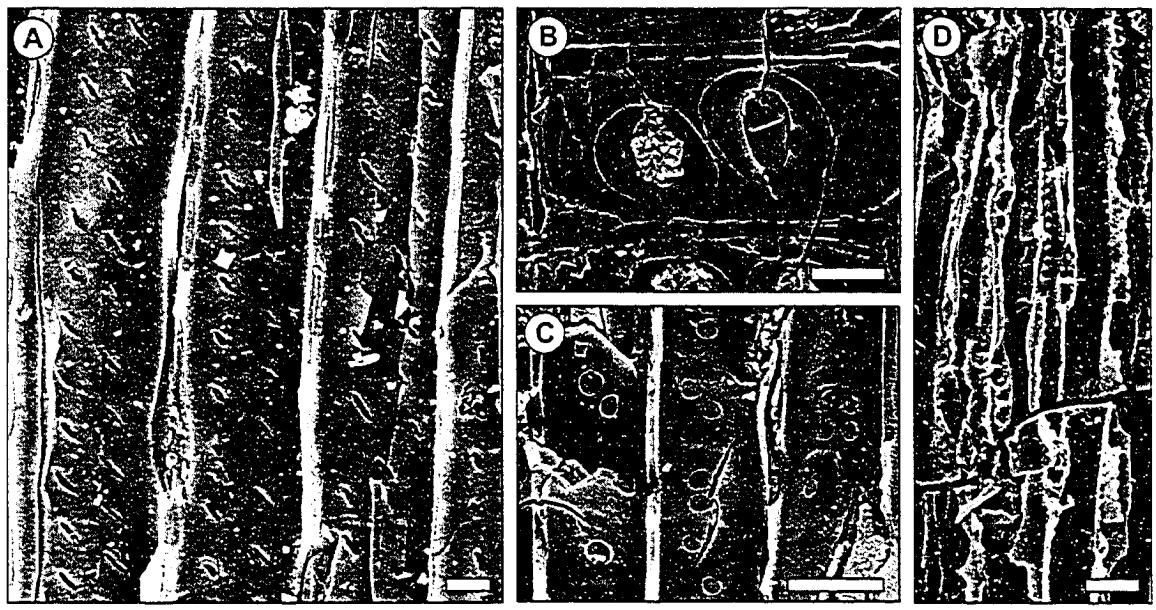



Figure 93: Scanning electron micrographs of *Dadoxylon recentium* wood charcoal from 240 m (A-C) and 352 m (D) of the measured section. A) Alternate, biseriate tracheid pitting, scale: 10 μm, radial view. B) Cupressoid cross-field pits, scale: 10 μm, radial view. C) 1-2(-4) cupressoid cross-field pits, scale: 40 μm, radial view. D) Uniseriate rays (1-8 cells high), scale: 40 μm, tangential view.

sinuous, mixed-load rivers confined within shallow valleys (Davies and Gibling, 2003). The channel forms of the Little River Formation facilitated aggradation, whereas sediment bypass and cannibalization typified the Joggins paleochannels. The flashy flow and rapid aggradation of the Little River Formation drainage channels are indicated by a sigmoidal barform preserved at 95 m, which may represent a transitional antidune (Fig. 90), and by sandy wings, which record periods of maximum discharge when flow topped levees (Friend *et al.*, 1979). Sand-size clay grains, associated with this and other channel complexes, may represent mud aggregates or finely ground intraformational mud clasts reworked from floodplain deposits, indurated by drying (Gardiner and Gibling, 2005).

The presence of petrocalcic paleosol horizons indicates pronounced rainfall seasonality and greater soil longevity than in the overlying Joggins Formation, which is characterized by weakly developed, immature paleosols (Smith, 1991). Local gleyed horizons represent wetting or ponding on the floodplain, which may have been facilitated by induration of the desiccated mudrocks. Alternatively, the single *Spirorbis*-rich grey mudstone bed hints of cryptic transgressive events. Although the ecological amplitude of this fauna is poorly known, it is locally associated with brackish facies in the overlying Joggins Formation (Skilliter, 2001; Tibert and Dewey, 2005). Although the redbeds generally reflect oxidizing, well-drained conditions with sufficient sediment input to prevent extensive pedogenesis, drab haloed root compressions indicate that neither moisture deficit nor disturbance prevented plant life.

The reproductive and growth strategies of the most common plant groups show adaptation consistent with the sedimentological record of periodic moisture deficit and aggrading sediment. The persistence of calamiteans, perhaps the most ecologically

resilient of the Late Palaeozoic plant groups (Calder *et al.*, in press; DiMichele *et al.*, in press), was aided by their prolific vegetative propagation by underground rhizomes (Gastaldo, 1992). Medullosan pteridosperms and cordaitaleans were assisted through dry periods not conducive to reproduction by the seed habit, and a substantial root system, which perhaps allowed them to tap deep groundwater sources (Falcon-Lang and Bashforth, 2004). Although not ubiquitous, the sparse record of lycopsids in the upper two-thirds of the section indicates that standing water was available for their reproduction (Phillips and DiMichele, 1992), at least temporarily or in restricted areas of the landscape.

Stratigraphic relationships indicate that the red beds of the Little River Formation were largely coeval with the extrabasinal conglomerates of the Polly Brook Formation at the southern basin margin, which represent extensive alluvial fan deposits derived from the Cobequid Highlands massif to the south (Calder, 1991, 1994; Waldron and Rygel, 2005, Chapter 9). Paleoflow indicators within the Little River Formation at Lower Cove, however, indicate a dominant source to the northeast of the type section, which argues against the Little River Formation as distal deposits of the Polly Brook Formation alluvial fans. The immature, feldspathic composition of certain horizons within the channel sandstone bodies at 90 and 160 m suggests, however, that the Little River Formation may include deposits derived from Polly Brook-like alluvial fans deposited along the Caledonia Highlands of southern New Brunswick. Equivocal support for this hypothesis comes from the Grand Anse strata to the north and east of the type section, which exhibit a coarser, more feldspathic composition than at Lower Cove. As discussed earlier,

however, the age and fault boundaries of the Grand Anse cast some uncertainty on firm correlation of the two units.

### 8.9.2. Discussion: drylands as climate or topographic indicators

The clear evidence of prevailingly dry conditions during deposition of the Little River Formation speak convincingly of climate as an underlying control, although, the stratigraphic relationships within such an active basinal setting also require consideration of topographic factors that may have come into play in imparting the well drained character of these redbeds (see Section 10.4). Evidence supporting a dry or dry seasonal climate includes *in situ* pedogenic carbonate development, absence of coal beds, evidence for flashy paleoflow within channel bodies, and the pervasive reddening of mudrocks and some sandstone bodies. The possibility of topographically related drainage effects comes indirectly from possible relationships with basin margin alluvial fan systems. Although scattered calcareous rhizoliths are present in the Joggins Formation (Davies and Gibling, 2003; Falcon-Lang *et al.*, 2004), no *in situ* source beds are present in that interval, nor within the Joggins Formation. This then raises the possibility of reworking from an upstream source, similar to the Little River Formation redbeds. The absence of bivalve-bearing beds, record of flooding events, suggests that base level was not felt within the Little River environment, with the putative exception of a single *Spirorbis*-rich interval. This further suggests that gradient may have facilitated enhanced drainage and so have been a factor in the development of the redbeds. The general lack of evidence of incision by channel bodies within the Little River Formation, which would be expected if base level was lowered, is problematic, however, in this situation.

In summary, while there is cause for considering topographic factors in draining the Little River drylands, the development of calcareous soils, complete absence of coal beds and supporting sedimentological evidence clearly required a climate regime with pronounced dry intervals. Topographically enhanced drainage may have played a contributing role.

## 8.10. CONCLUSIONS

The 635.8 m section of redbeds at Little River is sedimentologically and stratigraphically distinct from bracketing units within the Cumberland Basin, and so warrants designation as a separate formation, as recognized by Sir William Logan. Additionally, recognition of the Little River Formation better circumscribes the definition of the overlying Joggins Formation as coal-bearing and enhances its utility as a regionally recognizable stratigraphic unit. The fluvial style recorded in the Little River Formation records a dramatic change from that of the underlying Boss Point Formation, although the onset of reddening is presaged in the upper mudrocks of the Boss Point. This dramatic cessation of the Boss Point fluvial systems and their replacement by mud-rich systems is mimicked in other depocenters of the Maritimes Basin (Rehill *et al.*, 1995). The landscape during deposition of the Little River Formation was substantially better drained than that of the succeeding Joggins Formation, including the seasonal dryland environments (Falcon-Lang *et al.*, 2004; Hebert and Calder, 2004). The absence of coal beds, pervasive reddening of mudrocks and sandstones and development of pedogenic carbonate within the Little River Formation all are consistent with xeric conditions and a pronounced dry season, although topographic effects may have contributed to the drainage of the Little River environment. The Little River redbeds then provide limiting

constraints to the interpretations of seasonal drylands in the succeeding Joggins Formation, which in contrast records a gradual shift to wetter conditions with peat formation and flooding events near base level.

## 8.11. ACKNOWLEDGEMENTS

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# CHAPTER 9: ROLE OF EVAPORITE WITHDRAWAL IN THE PRESERVATION OF A UNIQUE COAL-BEARING SUCCESSION: PENNSYLVANIAN JOGGINS FORMATION, NOVA SCOTIA

*John W.F. Waldron and Michael C. Rygel*

## 9.1. ABSTRACT

The Pennsylvanian Joggins and Little River Formations, in the Cumberland Group of Nova Scotia, are widely regarded as the world's best exposure of coal-bearing, Carboniferous strata. This 1.5-km-thick, coal-bearing interval, famous for upright fossil lycopsid trees, is preferentially preserved in the Athol Syncline, in the western Cumberland Basin. New seismic profiles show that the Athol Syncline sits atop a salt weld and that the Joggins and Little River Formations thin on the flanks of adjacent evaporite-cored anticlines. These observations indicate that during deposition of these units, at least 1 km of syndepositional subsidence was facilitated by flow of underlying salt into the adjacent anticlines. In contrast, halokinesis was mainly active during the Mississippian in the eastern Cumberland Basin (Tatamagouche Syncline); minibasins were filled by Mabou Group sediments, whereas the Cumberland Group is thin and lacks significant coals. This basinwide comparison shows that much of the subsidence responsible for the preservation of the coal-bearing Joggins Formation was the result of salt withdrawal at depth.

## 9.2. INTRODUCTION

The Joggins section is a 4.5-km-thick section of Carboniferous rocks exposed in a gently dipping coastal section along the Bay of Fundy in northwestern Nova Scotia (Fig. 2). Widely regarded as the world's best coal-bearing Pennsylvanian exposure, the Little

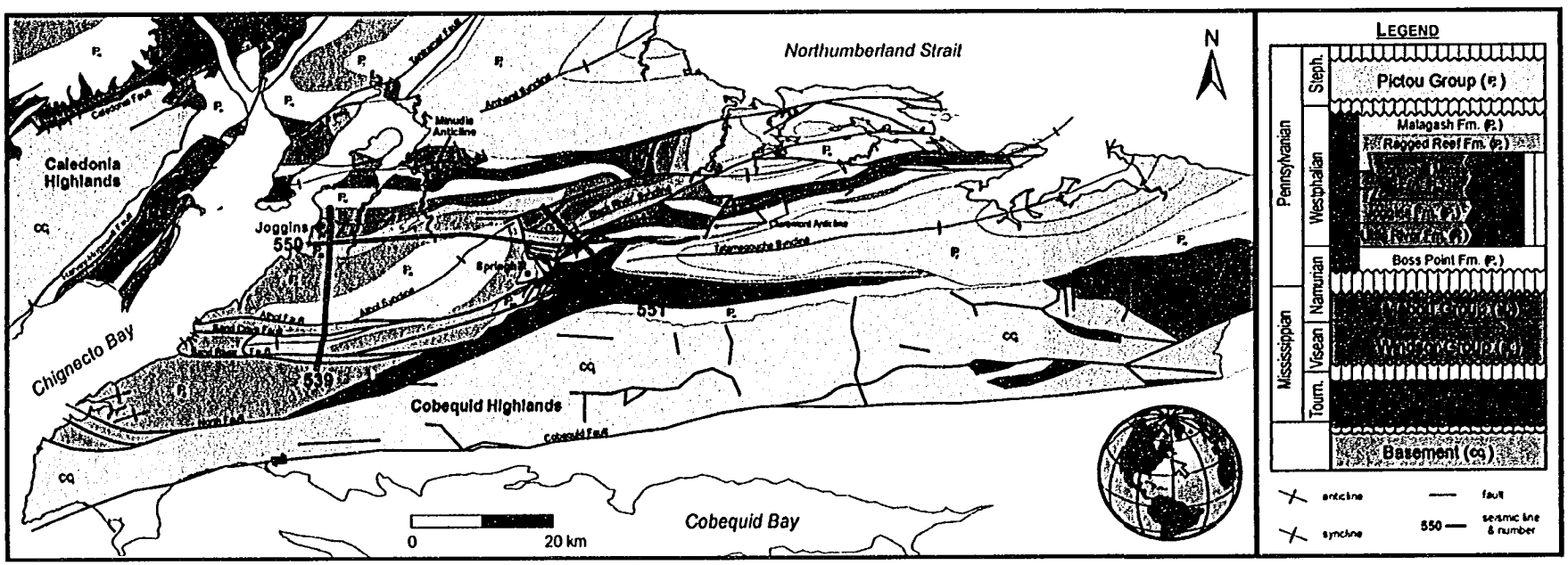
River and Joggins Formations comprise a 1550.3 m thickness of fine grained alluvial strata. Within this interval the 915.5-m-thick Joggins Formation contains at least 76 coal seams (0.05 to 1.5 m thick) and 63 forested horizons with standing lycopsids 5–6 m tall (Davies *et al.*, submitted). Hailed by Charles Lyell (1842) as "the most wonderful phenomenon perhaps that I have ever seen," the Joggins section is mentioned in his *Principles of Geology* (Lyell, 1871) and Darwin's (1859) *On the Origin of Species*. This remarkable section, proposed as a UNESCO World Heritage Site (Falcon-Lang and Calder, 2004), profoundly influenced the young science of geology by serving as a proving ground for the principles of Uniformitarianism, *in situ* botanical origin of coal, and incompleteness of the fossil record.

Despite these contributions, relatively little is known about the basin dynamics responsible for the preservation of this window into the Carboniferous world. This paper demonstrates that the localized rapid subsidence necessary for preservation of the Joggins Formation was created by the withdrawal of underlying Mississippian-aged evaporites.

## 9.3 Regional Geology

The Joggins and Little River Formations lie in the Cumberland Basin of Nova Scotia (Fig. 94), a depocenter within the Paleozoic Maritimes Basin (Fig. 9), which is interpreted as either a basin dominated by strike-slip motion, a rift, or a transtensional combination of the two (Bradley, 1982; Gibling, 1995; Pascucci *et al.*, 2000; Waldron, 2004). Fluvial to lacustrine clastic sedimentary rocks comprise the majority of the 12-km-thick Maritimes Basin fill, but repeated marine incursions during the Mississippian are recorded by carbonates and evaporites of the Windsor Group. The Cumberland Basin lies near the southwest corner of the Maritimes Basin and contains a 7–9 km stratal

Figure 94: Geologic map of the Cumberland Basin (Ryan and Boehner, 1990; Ryan *et al.*, 1990, 1990; Ryan *et al.*, 1990; Keppie, 2000; New Brunswick Department of Natural Resources and Energy, 2000; St. Peter, 2001). Red, numbered lines show seismic profiles discussed in this paper, unmarked Pennsylvanian units on the New Brunswick side of the basin are colored to reflect the correlation with coeval units in Nova Scotia. This figure is presented in a larger format in the rear of the thesis.


Northumberland Strait
N
Caledonia Highlands
Chignecto Bay
Cobequid Highlands
Cobequid Bay
Joggins
550
551
539
Minudie Anticline
Springhill
0
20 km
LEGEND
Pennsylvanian
Steph.
Westphalian
Namurian
Mississippian
Visean
Tourn.
Pictou Group (P)
Malagash Fm. (P)
Ragged Reef Fm. (P)
Boss Point Fm. (P)
Basement (cg)
anticline
syncline
fault
550
seismic line & number

succession comprising the Mississippian Windsor and Mabou Groups and the overlying Pennsylvanian Cumberland and Pictou Groups (Fig. 94). The floor of the basin is unexposed, but observations elsewhere in the region indicate that Devonian to Mississippian clastic rocks (Horton Group) and/or volcanic rocks (Fountain Lake Group) may be present. Although the majority of the basin is bounded by a complex network of faults (Fig. 94), the Cumberland Group locally onlaps basement to the southeast and northwest.

The dominant structural features within the Cumberland Basin are the Minudie and Claremont Anticlines, and the adjacent Athol and Tatamagouche Synclines (Fig. 94). Anticlines are cored by Windsor Group evaporites and conglomeratic redbeds of the Mabou Group. In the western Cumberland Basin (Athol Syncline; Fig. 94), the overlying 4.2-km-thick Pennsylvanian Cumberland Group consists of sandstone-shale cycles of the Boss Point Formation, fine-grained redbeds of the Little River Formation, a 2.2-km-thick coal-bearing interval (Joggins and Springhill Mines Formations) capped by conglomerates and redbeds (Polly Brook, Ragged Reef, and Malagash Formations). Farther east (Tatamagouche Syncline; Fig. 94), thick coal-bearing units are absent and the remaining Cumberland Group thins to <450 m. These units are overlain with angular unconformity by Pictou Group red beds.

Intra-Pennsylvanian halokinesis is well known within the Maritimes Basin (Calder, 1998) and has been inferred within the Cumberland Basin (Carter, 1987; Boehner, 1992; Calder, 1994), where it was linked to extensional detachments (Lynch and Keller, 1998). However, detailed inferences on the timing and kinematics of salt movement have been limited by the lack of outcrop and quality of previous seismic data.

## 9.4. JOGGINS SECTION

At their type section, the Joggins and Little River Formations form the medial coal-bearing portion of the 4.2-km-thick Cumberland Group. This 1550.3-m-thick package was deposited over a ~1.5 m.y. in the early Langsettian (Dolby, 1991; Menning *et al.*, 2000). With sedimentation rates of ~1 mm/yr (compaction effects neglected), these formations experienced one of the highest average sedimentation rates among coal-bearing Carboniferous units (McCabe, 1991).

Wetland deposits (including 76 coal seams, 71 of which are <50 cm thick) make up 56.4% of the Joggins Formation and become the dominant facies in the upper 500 m. The absence of pronounced sequence boundaries and deep-water deposits, as well as the rheotrophic (groundwater-fed) nature of the precursor peats suggests that the sediment surface remained close to relative base level throughout deposition of the Joggins Formation (Davies and Gibling, 2003). With subsidence and sedimentation rates almost perfectly balanced near the threshold for peat accumulation (Haszeldine, 1989), conditions were optimal for lycopsid entombment during deposition of the Joggins Formation. Calder (1994) showed that conditions favorable for peat accumulation migrated to the east over time, during deposition of the Joggins and Springhill Mines Formations.

## 9.5. SEISMIC DATA

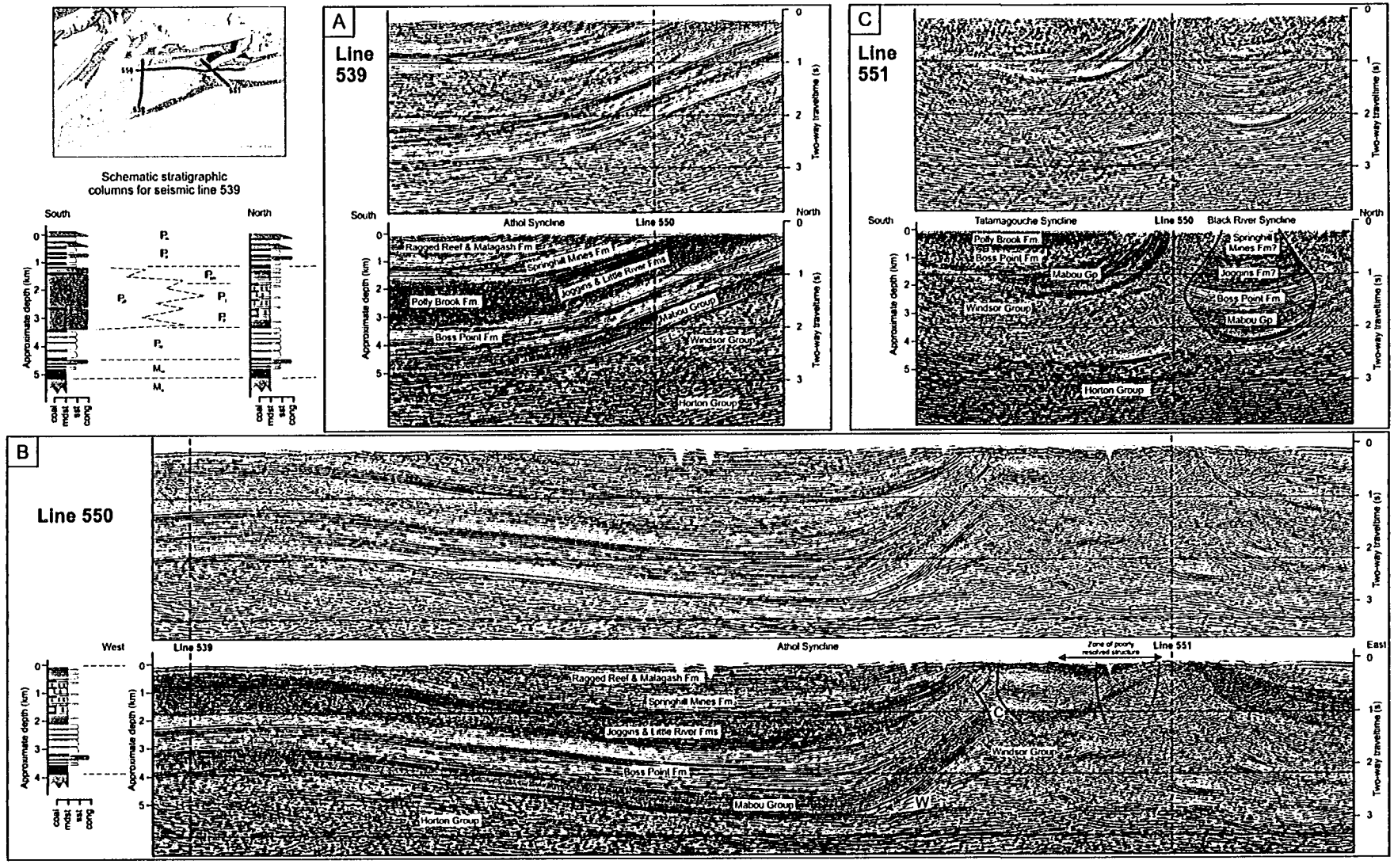
Two-dimensional seismic reflection profiles were collected by Devon Canada along a network of lines in the Cumberland Basin in 2002 (Fig. 94). The profiles are of much higher quality than previous data sets and allow reflectors to be traced to the surface and identified by using existing geologic maps.

### 9.5.1. Athol Syncline

Dip line 539 (Fig. 95A; plus foldout) is 1–6 km inland from the Joggins section, approximately perpendicular to strike. Stratigraphic boundaries can be projected from the coast into the profile with an accuracy of ±50 m, allowing seismic velocities to be estimated in the absence of drilling. The base of the Little River Formation is a reflector that can be traced (Fig. 95 A) from the surface to a depth of ~1.5 s TWT (two-way travel time) beneath the Athol syncline. Beneath it, the measured stratigraphic thickness (1,074 m) and dip (22°) of the Boss Point Formation were used to identify the base of the Cumberland Group, which projects to the surface ~2.4 km beyond the north end of line 539. A similar calculation allowed identification of the conformably underlying Mabou Group. Higher units in the Cumberland Group were picked from their mapped positions at the surface. The coal-bearing units (Joggins and Springhill Mines Formations) are marked by a diachronous zone of strong coherent reflectivity that marks the changing locus of coal deposition within the basin (Calder and Bromley, 2005). Traced downdip, the coal-bearing units lose coherence and pass into a lens of diffuse reflectivity interpreted as the Polly Brook Formation, an alluvial-fan conglomerate that interdigitates with the coal-bearing units in outcrop (Ryan *et al.*, 1991; Calder, 1994).

By tying line 539 to line 550, the units identified along the coast can be traced east towards the closure of the SW-plunging Athol Syncline (Fig. 94) and the adjacent

Figure 95: Seismic lines. Each panel shows stacked, migrated seismic data in uninterpreted and interpreted form. Locations of lines shown in inset and Figure 94. Vertical dashed lines show ties between profiles. Schematic stratigraphic columns show inferred thicknesses of units, based on an average velocity of 3.8 $km \cdot s^{-1}$ (for clastic rocks, 5 $km \cdot s^{-1}$ used for salt). A) Line 539—dip line across Athol syncline. Stratigraphic columns at left are based on inland and coastal sections. B) Line 550—approximate strike line on north limb of Athol syncline, showing thinning of Cumberland Group (especially the Joggins and Little River Formations) onto Claremont Anticline. C) Line 551—dip line across Tatamagouche and Black River Synclines. This figure is presented in a larger format in the rear of the thesis.


Schematic stratigraphic columns for seismic line 539
South
North
A
Line 539
Athol Syncline
Line 550
Ragged Reef & Malagash Fm
Springhill Mines Fm
Joggins & Little River Fms
Polly Brook Fm
Boss Point Fm
Mabou Group
Windsor Group
Horton Group
Two-way traveltime (s)
Approximate depth (km)
C
Line 551
Tatamagouche Syncline
Black River Syncline
Springhill Mines Fm?
Joggins Fm?
Mabou Gp
B
Line 550
West
East
Line 539
Athol Syncline
Line 551
Zone of poorly resolved structure
coal
mdst
sst
cong

Claremont Anticline (Figs. 95A and B). Strong out-of-plane dips (not corrected by the migration of the two-dimensional data) cause some reflections to appear at different TWTs at the tie-point, but reflections are easily correlated by their distinctive character. To the east, strata of the Cumberland and Mabou Groups slope upward and converge (Fig. 95B). Convergence is most conspicuous in the Joggins and Little River Formations, which are reduced to less than one third of their thickness (confirming observations by Copeland, 1959). The Cumberland Group is cut by a near-vertical zone of complex structure (labeled "C" in Fig. 95B) in the Claremont Anticline near Springhill. Windsor Group evaporites occur as surficial karst features in this structure, along with variably oriented regions of Cumberland Group strata, interpreted as fault-bounded blocks in current geologic maps (see compilation in Ryan *et al.*, 1991; Calder, 1995). At depth, zone C appears continuous with a triangular region of discontinuous reflectivity that underlies the Mabou Group, and clearly pinches out to the west at the location labeled "W." Zone C is interpreted as largely filled by Windsor Group evaporites, and pinch-out W is inferred to represent a "salt weld" (Jackson and Cramez, 1989) created by evaporite withdrawal. The eastward convergence of reflections in the overlying succession indicates that deposition of the Joggins and Little River Formations was accompanied by salt flow into the adjacent anticlines and at least 1 km of differential subsidence in the Athol Syncline.

Beneath the inferred weld, subhorizontal diffuse reflections at 3.0–3.6 s TWT are interpreted to represent deeper units of the Windsor, Horton, and/or Fountain Lake Groups. Though poorly imaged, these units appear to continue beneath the evaporite-filled structure at Springhill.

### 9.5.2. Tatamagouche Syncline and Black River Minibasin

Profiles across the Tatamagouche and Black River Synclines were also interpreted by using mapped stratigraphic boundaries. In contrast to the Athol Syncline, the Mabou Group–Cumberland Group contact in the southeast part of line 550 (Fig. 95C) is a distinct angular unconformity. The Mabou Group thickens considerably and shows internal, nonparallel reflectors that converge downdip to the southeast. This configuration is interpreted as a minibasin that syndepositionally subsided into the evaporite-bearing Windsor Group, similar to minibasins deposited above evaporites in offshore settings (Jackson *et al.*, 1995).

The unit beneath the minibasin is interpreted as Windsor Group. It shows complex internal structure marked by converging bundles of discontinuous reflectors, indicating that halokinesis began soon after deposition of thick lower Windsor evaporites, with upper Windsor strata filling additional minibasins. Diffuse subhorizontal reflections at ~3 s TWT probably represent the basal Windsor and/or Horton and Fountain Lake Groups beneath the evaporites.

In the northwest part of line 551 (Fig. 95C), in the Black River Syncline, a second minibasin extends from the surface to ~2.2 s TWT. The Mabou stratigraphy can be identified from its seismic character, and its upper unconformable contact is clear. However, in this minibasin, a thick overlying Cumberland Group indicates that evaporite withdrawal continued through the Early Pennsylvanian.

## 9.6. Discussion

### 9.6.1. Basin evolution

Rapid subsidence during deposition of the Joggins Formation has long been attributed primarily to basin-bounding faults (Browne and Plint, 1994; Davies and Gibling, 2003), although Calder (1994) speculated that salt withdrawal may have played a role. Lines 550 and 551 show striking intra-basinal contrasts in subsidence history and dramatic thinning of stratal units against salt-cored anticlines, strong indicators of evaporite involvement (Rowan *et al.*, 2003). The general continuity of sub-Windsor reflections at ~3 s TWT suggests that the dramatic thickness changes across the basin resulted from evaporite flow. It is possible that the process may have been initiated and localized by motion along basement and/or basin-bounding faults (Bradley, 1982; Howie, 1986) or by the resulting progradation of alluvial fans near the basin margin (e.g. models of Gemmer *et al.*, 2004).

The amount of differential subsidence can be used to place lower limits on the original thickness of evaporites. The Tatamagouche Syncline minibasin records at least 0.9 km of differential subsidence during deposition of the Mabou Group. The contrasting depth of the Boss Point Formation in the Black River syncline indicates an additional 1.6 km of differential subsidence during deposition of the Cumberland Group and thus, the removal of at least 2.5 km of evaporites.

There is no indication of differential subsidence during Mabou Group deposition beneath the Athol Syncline. Halokinesis and minibasin development began during deposition of the Cumberland Group as indicated in line 550 by an evaporite weld at depth, the great thickness of coal-bearing Cumberland Group, and the lateral thickness

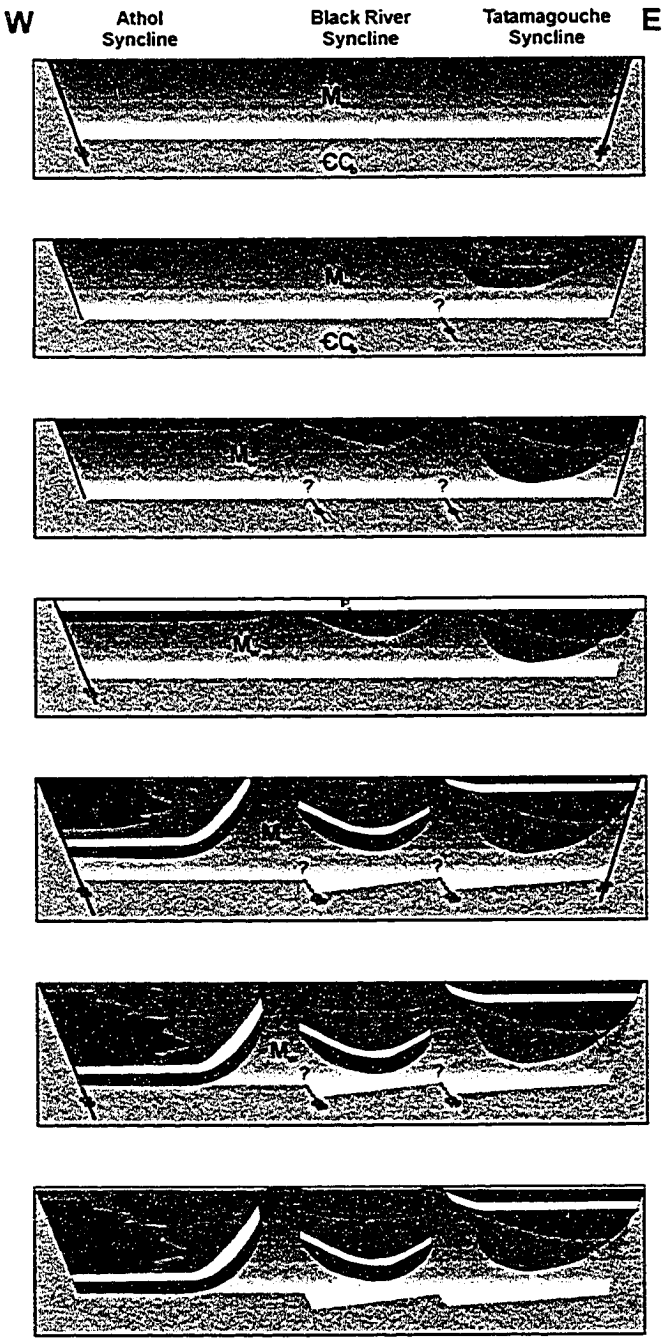
and facies changes shown by the Cumberland Group (especially the Joggins and Little River Formations). These features indicate that the Athol Syncline also has the character of a minibasin, albeit significantly larger than those in the east. Comparing the depths to the Boss Point Formation in lines 539 and 551 indicates that salt withdrawal was accompanied by at least 3.3 km of differential subsidence in the Athol Syncline. This amount requires a much larger thickness of Windsor Group than has been previously envisaged for this area (Boehner, 1992).

Figure 96 shows inferred Cumberland Basin evolution in cartoon form. Within the Cumberland Group, the Joggins and Little River Formations show the most obvious evidence for evaporite-controlled differential subsidence. The amount of halokinetic subsidence occurring during deposition of these formations was at least 1 km (the amount of differential thickness variation within the formation), and perhaps the entire 1.5 km thickness of the unit.

### 9.6.2. Subsidence in the Athol Syncline

Interpretation of the Athol Syncline as a "terrestrial minibasin" provides a viable mechanism to explain the limited extent and high rate of subsidence recorded by the Joggins and Little River Formations. The overall rate of subsidence (>1 mm/yr) compares well with values of 0.4 mm/yr to 7 mm/yr for minibasins in the Gulf of Mexico (Rowan, 1995; McBride *et al.*, 1998) and with numerical models of evaporite flow (Poliakov *et al.*, 1996). Although the conglomerates of the Polly Brook Formation indicate early Westphalian fault motion along the southern basin margin, the sedimentology of the Joggins and Little River Formations suggests a basin that subsided steadily rather than by

Figure 96: Cartoon showing possible basin history. Colors and patterns as in Figure 94. Not to scale.




**middle to late Visean**
Deposition of up to 3 km of Windsor Group evaporites.

**late Visean**
Possible salt movement accompanied by deposition of Windsor clastics in the eastern Cumberland Basin.

**latest Visean to earliest Namurian**
Clastics of the Mabou Group form minibasins in the eastern part of the basin.

**late Namurian**
Widespread depositon of the Boss Point Formation; episodic downdrop along the basin-bounding faults but some localized onlap of the highlands.

**early Langsettian**
Major halokinesis in the western part of the basin perhaps localized atop basement faults or initiated by loading via the Polly Brook alluvial fans; also some movement along basin-bounding faults.

**late Langsettian to early Duckmantian**
Probably continued halokinesis, but this level is now eroded away; continued motion along the basin bounding faults created Polly Brook alluvial fans.

**post Duckmantian**
Continued passive diapirism kept salt near the sediment surface; subsidence slows and becomes more homogeneous across the basin. Possible post-Carboniferous halokineis in the Tatamagouche area.

major episodic down-dropping. This interpretation stands in contrast to that proposed for the underlying Boss Point Formation, wherein alternating braidplain and lacustrine cycles have been linked to intermittent motion along the bounding faults (Browne and Plint, 1994).

The Joggins lycopsid casts, commonly 5–6 m tall, and reportedly up to 12 m tall (Lyell, 1842), are among the tallest known. Lycopsids had a soft pith supported by a rigid periderm, and entombment must have occurred within a few decades after smothering of the stigmarian roots (Gastaldo *et al.*, 2004; Calder *et al.*, in press). However, Joggins lycopsids are generally entombed by stacked packages of heterolithic strata that make burial by a single catastrophic flood or earthquake unlikely (Calder *et al.*, in press). If complete burial is assumed to have occurred within 100 yr, entombment of the Joggins lycopsids required frequent sedimentation rates of >50 mm/yr and perhaps as high as 120 mm/yr.

Early peat compaction has been suggested as a mechanism for preserving erect tree fossils (Gastaldo *et al.*, 1991). However, most ($n = 59$) forested horizons at Joggins occur in association with thin, organic-rich horizons or mineral soils; the few ($n = 4$) coal seams found below lycopsids are thin (≤10 cm) and would have generated only a few tens of centimeters of accommodation as they compacted. Gastaldo *et al.* (2004) also considered the role of eustasy, in a study of 4.5-m-tall lycopsids in the Mary Lee Coal Zone of the southeastern United States, and suggested that eustasy alone could not have generated the necessary rapid accommodation, instead invoking coseismic subsidence.

Therefore, it is likely that salt withdrawal contributed significantly to the generation of accommodation over relatively short time scales. Although time-averaged

vertical movement rates in Quaternary diapirs range only up to 18 mm/yr (Frumkin, 1996), brittle deformation of sedimentary cover above flowing evaporites is common (Vendeville and Jackson, 1992; Poliakov *et al.*, 1996). In southwestern Tajikistan, salt withdrawal causes hundreds of low-magnitude earthquakes ($M < 5.2$) per decade (Leith and Simpson, 1986). Therefore, rapid development of accommodation at Joggins was probably the result of salt withdrawal combined with episodic brittle deformation, dissolution, and/or episodic changes in base level. Subsidence that was episodic on a scale of decades but "geologically continuous" provides a mechanism to explain the ubiquitous fossil forests and thin coals of the Joggins Formation.

## 9.7. Conclusions

The Joggins section, one of the world's most remarkable and influential Carboniferous outcrops, is preserved within a minibasin created by the withdrawal of evaporites into adjacent diapiric structures. In this minibasin, the Cumberland Group is 4.2 km thick and contains 2.2 km of coal-bearing strata (Joggins and Springhill Mines Formations); equivalent units in the Tatamagouche Syncline are thinner (<500 m) and lack coal-bearing units. Halokinesis provided sustained rapid subsidence, optimal conditions for peat accumulation and lycopsid entombment, and may have driven the eastward migration of the depositional "coal window" (Calder, 1994). Subsidence may have been episodic at a time scale of years to decades, thus enabling the repeated preservation of remarkable standing lycopsid casts 5–6 m tall. The subsidence history indicates the initial presence of several kilometers of evaporites in the Cumberland Basin, a much thicker Mississippian succession than previously envisaged.

## 9.8. ACKNOWLEDGEMENTS

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# CHAPTER 10: DISCUSSION AND CONCLUSIONS

This thesis provides the first detailed insight into the spatially and temporally variable subsidence within the Cumberland Basin and characterizes the impact of rapid subsidence and sediment accumulation on floodplain sedimentation during deposition of the Joggins Formation. With a new understanding of basin dynamics and processes now in place, it is worth reviewing the broader tectonic, paleogeographic, and paleoclimatic implications for the Cumberland Basin.

## 10.1. Tectonics of the Cumberland Basin

Excluding the northern margin of the Cobequid Highlands east of Springhill, the Cumberland Basin is separated from the adjacent Cobequid and Caledonia Highlands by the North and Harvey-Hopewell Faults, respectively (Figure 12). These basin-bounding faults have a complex history of motion and are generally considered to have been active in the Namurian through early Westphalian (Webb, 1963; Browne and Plint, 1994; Davies and Gibling, 2003). Bradley (1982), Browne (1991), and Reed et al. (1993) suggested that the western Cumberland Basin formed in response to dextral transpression, but this interpretation is based on the assumption that Late Carboniferous(?) movement along the Cobequid and Harvey-Hopewell Faults was representative of the sense of motion during the Westphalian. This interpretation was supported by the observation that Langsettian dextral transpression took place in southern New Brunswick (Plint and van de Poll, 1984; Nance, 1987). In view of the kinematic and temporal uncertainties that surround interpretation of these faults, the application of structural data from elsewhere in the basin has resulted in the strike-slip model being adopted as an explanation for the basin as a whole.

Mapping of the southwestern portion of the Cumberland Basin by Ryan et al. (1990) showed that the Pennsylvanian basin fill did not onlap the western margin of the Cobequids as indicated by previous studies (Salas, 1986; Reed *et al.*, 1993), but was separated from the highlands and undivided Devonian-Mississippian strata by the North Fault zone (Keppie, 1976; Ryan and Boehner, 1994). This term was used to designate a network of known and assumed faults (which includes the Spicer's Cove fault) along the northern margin of the Cobequids. The relationship, nature, and history of the North Fault is poorly constrained, but proprietary seismic lines suggest that it is steeply dipping and may have a component of thrust motion (Ryan and Boehner, 1994). Recognition of this fault network has important implications for the Carboniferous basin fill because it implies that the southern margin of the basin was not as intimately coupled to motion along the Cobequid Fault as previously assumed, which calls the dextral transpression model into question.

Within the Cumberland Basin, both Calder (1994) and Martel (1987) described distinct depocenters positioned atop fault-bounded basement blocks. The dramatic stratigraphic changes described in Chapter 9 suggest that the importance of these basement blocks have been underestimated. The salt tectonic history emphasizes the role that salt tectonics played in influencing sedimentation patterns within the basins, but the thickness, heterogeneity, and timing of salt movement probably were, to a certain degree, basement controlled.

Caution should be used in interpreting the origin and tectonics of the Cumberland Basin in terms of a single, basin-wide process (i.e. dextral transpression). Although the Cumberland Basin represents a series of adjacent, interconnected depocenters, these areas

may have experienced markedly different subsidence patterns and tectonic influences and may have less in common than previously assumed. Although the designation of the Cumberland "Basin" is a reasonable and logical designation, the temporal and stratigraphic contrasts between its basement-controlled depocenters is analogous to the sub-basins and polycyclic history of the regional Maritimes Basin as a whole.

Devon Canada seismic lines in other parts of the basin suggest that the Carboniferous history of the Cumberland Basin is more complex than previously recognized (research in progress by the author and J.Waldron). With proper documentation, previously unrecognized phases of Mississippian extension and Pennsylvanian thrusting have the potential to fundamentally reshape our tectonic understanding of this structurally complex area.

### 10.2. Paleogeography of the Cumberland Basin

The wealth of paleoflow information (Chapter 6) combined with recognition of syndepositional diapirism (Chapter 9) and the presence of brackish water ostracods (Tibert and Dewey, 2005) adds to our understanding of the paleogeography of the Joggins floodplain. The largest channel bodies in the Joggins Formation were clearly sourced to the northwest of the Joggins floodplain, either in the Caledonia Highlands or in the New Brunswick platform. Given the relatively small size of the Caledonia highlands relative to the volume of early Pennsylvanian sediment, the latter source area seems most likely. Additionally, Joggins' position near the center of the basin and the relative proximity of the Polly Brook alluvial fans (Line 539 in Figure 95) make it probable that Joggins was situated near the confluence of drainages from the opposing highlands, perhaps near the axial drainage proposed by Calder (1994). The lack of

paleoflow data from Joggins-equivalent strata elsewhere in the Cumberland Basin makes it difficult to interpret regional drainage patterns, but the convergence of the adjacent highlands and thrusting at Tynemouth Creek (Plint and van de Poll, 1982) suggest that the basin was closed to the south and that the Joggins rivers exited the basin to the north.

Although diapirism was active in the Minudie, Springhill, and Black River areas during deposition of the Joggins Formation and probably created areas of elevated relief, gaps up to several tens of kilometers in width would probably have allowed drainages to exit the basin with little or no disruption. The diapirs are shown as slightly higher topographic areas in Figure 77, the humid-seasonal climate would have actively dissolved salt and any surface expression of the diapir would probably have been subtle. Having said that, Browne (1991) documented paleoflow divergence across the Minudie Anticline in the older Mabou Group and Boss Point Formation, an observation he initially explained as divergence around a paleotopographic high and later as an artifact of strike-slip rotation along a bend in the Harvey-Hopewell Fault zone. Whatever the case, diapirs do not appear to have isolated the Athol Syncline or regionally deflected drainages into this area during the Langsettian. The position of a "mid-Euramerican sea" to the north and east (Calder, 1998; Ziegler *et al.*, 2002) and the regional pattern of northeastern paleoflow directions during the Pennsylvanian (Gibling *et al.*, 1992) indicate that the Cumberland Basin probably drained and was transgressed via a northerly passage into an open seaway.

The relatively fine-grained nature of the Joggins Formation and the lack of large channels capable of acting as bypass conduits to open-water environments indicates that a great deal of sandy and coarse-grained material was trapped in upstream areas, perhaps

as alluvial fans at the base of the Caledonia Highlands, a process that may also have been enhanced by withdrawal of underlying salt.

### 10.3. Facies Relationships

Chapter 6 highlights the one of the most fundamental questions about the Joggins Formation: Do the three facies associations have a Waltherian relationship or do they record spatially and temporally disjunct floodplain conditions? Disjunct relationships could have been caused by very rapid base-level changes or by climate change. The Waltherian relationship (namely, that the three associations were lateral equivalents within the basin and that all three were present locally at any given point in time) is the preferred relationship set out in Chapter 6, but this cannot be proven without additional exposures of the Joggins Formation. This Waltherian approach could also be applied at the formation scale, where the redbeds of the Little River Formation are the updip equivalents of the Joggins Formation. Although the relationship between the Joggins and Little River Formations remains enigmatic, the Waltherian approach is the preferred interpretation for the facies associations within the Joggins Formation because: 1) the largest active channels occur in the poorly drained intervals (indicating gaining streams and an updip suite of smaller channels), 2) all three types of channel body occur in both poorly and well drained settings, implying geomorphic continuity across facies associations, and 3) there is direct evidence for base level change whereas the climatic record is difficult, if not impossible to distinguish.

## 10.4. PALEOCLIMATE

Paleobotanical information (primarily bands within woody material and the abundance of charcoal) suggests that the Joggins Formation, particularly the well drained facies association, formed under a humid, but probably seasonal climate (Falcon-Lang, 2000, 2003, 2003). The ubiquity of redbeds in the Little River Formation suggests that it also formed under a seasonal, and perhaps drier, climate. Paleosols of these two units are generally cumulative and immature alfisols to entisols and did not have enough residence time on the floodplain to develop marked horizonation or other strong indicators of paleoclimate, although Smith (1991) suggested a humid climate.

Depth to carbonate horizons in soils has been used to characterize rainfall and climate (Retallack, 2001); the few scattered carbonate nodules in the Joggins Formation do not represent a significant enough accumulation to allow this type of study. Unfortunately the few paleosols in the Little River Formation with subsurface accumulations of carbonate are too poorly exposed (and possibly preserved) to provide useful information about precipitation. Calcretes are present in redbeds of the coeval Tynemouth Creek and New Glasgow Formations (Plint and van de Poll, 1982; Chandler, 1998), suggesting that, at times, climatic conditions were suitable for carbonate accumulation if soils were given sufficient time to develop. Chandler (1998) documented a depth to carbonate value of ~1 m for what appears to be a completely preserved paleosol in the New Glasgow Formation, a value that suggests an annual rainfall of between 300 and 950 mm/yr (Retallack, 2001), although the scatter in the dataset is great.

The conditions under which different soil types and catenas form crudely brackets the amount of annual precipitation that the Joggins and Little River Formations received. The presence of calcareous horizons and absence of coal in the Little River Formation may record climatic conditions similar to those recorded by the New Glasgow Formation (between 300 to 950 mm/yr). These values probably represent minimum values for the Joggins Formation, where the paucity of calcareous horizons either reflects a climate unsuitable for carbonate accumulation or the brief lifetime of the soils - Retallack (2001) noted that it commonly takes about 1,000 years for significant accumulations of carbonate to form in soils. Given the Waltherian approach that is favored in this thesis, it is worth noting that even under modest precipitation values (250-1300 mm/yr), soils with carbonate and gypsum can form in well drained areas while thin, high-ash peats form in adjacent coastal or lacustrine areas (Retallack, 2001).

Precipitation values for the Joggins floodplain (both poorly drained and well drained sediments) more likely fell between 1300 and 2500 mm/yr. This range reflects precipitation amounts where rheotrophic mires could expand to include inland, terrestrial surfaces; beyond these values mires can become independent of groundwater and develop into ombrotrophic (domed) forms (Retallack, 2001). The situation at Joggins was probably similar to that of the modern Mississippi Delta (1,110 to 1,700 mm of precipitation/yr; Scott *et al.*, 2000), where the difference between the poorly drained (peat-accumulating) and well drained swamps (non-peat accumulating) reflects local drainage (Roberts *et al.*, 1983). Under these conditions, the well drained swamp has similar organic production to the poorly drained swamp and may be under water for several months of the year, but the presence of oxidizing conditions for part of the year

result in the nearly complete destruction of plant material and the formation of iron oxide nodules. Although these comparisons to modern soils do not pinpoint exact amounts of precipitation, they provide a maximum range and demonstrate that well drained and poorly drained conditions could have formed under identical climate conditions.

The latter scenario implies a degree of wet-dry seasonality, an interpretation suggested by previous authors and supported by several observations presented in this thesis. The abundance of redbeds and ubiquity of upper flow regime structures in the Little River Formation attests to strong flow pulses followed by rapid drops in water level. Within the Joggins formation, the presence of muddy interbeds within channel fills suggests that flow cessation occurred on a regular basis. Additionally, the "waterhole" model proposed for the Hebert beds implies that, at least seasonally, water became scarce on the well drained floodplain. The presence of scattered carbonate nodules within paleosol horizons probably formed during the dry season; however, rapid sedimentation rates within the basin prevented the carbonate from forming indurated calcretes.

Although the Waltherian (relative base level) approach is favored as the dominant control on facies distribution, it probably did not act independently of climate – despite the difficulty in determining the climatic signature. In actuality, the two probably acted together to form a situation wherein wetlands generally occurred in relatively low-lying (downdip?) areas that received a significant amount of groundwater input. Under more arid conditions this belt probably narrowed to the coastal zone and under humid conditions it probably expanded across much of the floodplain. Correlation with inland cores or detailed paleopedological studies may offer the only hope to resolve this complex issue.

## 10.5. CONCLUSIONS

1) The Pennsylvanian Joggins Formation was deposited in the Cumberland Basin of Nova Scotia, a fault-bounded depocenter within the regional Maritimes Basin. Famous for its upright fossil lycopsid trees, the coastal exposure of this unit is widely regarded as the world's best exposure of coal-bearing Carboniferous strata. The newly redefined Joggins Formation comprises just a small part of the 4,441-m-thick "Joggins section," which was measured by Sir William Logan during a 5 day period in June of 1842.

2) Seven types of vegetation-induced sedimentary structures (VISS) record hydrodynamic and decay-related interactions between *in situ* plants and the alluvial sediment that entombed them. These structures represent local sediment accumulations that could easily be mistaken for small channels, and are the most prominent and distinctive sedimentary structures in the Joggins Formation. The paucity of descriptions of VISS in the rock record suggests that these features may have been overlooked or misinterpreted in the past, and could provide important information about the distribution of land plants during the initial stages of terrestrial colonization.

3) Vegetation-induced sedimentary structures developed in the low-energy swamps of the Mississippian Horton Group provide an interesting contrast to the erosion-dominated forms described from the Pennsylvanian Joggins Formation. Recognition of these structures focused our attention on cryptic stump casts formed after *Protostigmaria*, the lobed base of the cormose lycopsid *Lepidodendropsis*. In

addition to providing compelling evidence that *Lepidodendropsis* inhabited coastal wetlands, this study also confirms that VISS can increase understanding about early vegetative colonization of the terrestrial realm, an event that profoundly impacted landscape stabilization, channel planform, mud storage in floodplains, carbon sequestration and atmospheric composition (Algeo *et al.*, 1995).

4) The 82 channel bodies of the Joggins formation were classified as fixed, meandering, and multistorey types, with each type present in coastal wetland and interior dryland facies associations. These channel bodies represent an anastomosed network of small fixed and meandering channels that acted as tributaries and distributaries to larger, meandering trunk rivers. A few multistorey channel bodies formed during periods of low accommodation are present in the section, but it is unclear whether these features represent paleovalleys formed by sea level fall (Type 1 paleovalleys) or by other factors such as tectonism or climate change (Type 2 paleovalleys). Graphical plotting and statistical analysis of completely exposed channel bodies show that thickness values for each type are distinct, as are W/T values for fixed and meandering channel bodies; incomplete lateral exposure of multistorey bodies prevented similar W/T analysis. Conversely, paleochannel depth and width/depth determined for channel bodies of all types are statistically similar, apart from a small group of unusually deep meandering channels in the coastal wetlands. Although forcing factors such as tectonism and eustasy probably influenced the Joggins channel bodies, the differences in fluvial form probably represent much of the original geomorphic variability of the original drainage network. Comparison with the underlying Boss

Point Formation shows that both the style and magnitude of basin subsidence can profoundly impact channel body architecture.

5) The fluvial deposits between 270 and 274 m in the Joggins Formation (a unit informally termed the "Hebert beds") represent a "waterhole" preserved within a seasonally dry alluvial plain deposit. This interval contains an unusual suite of fossil plants, unionoid bivalves, terrestrial gastropods, and tetrapods – a low-diversity assemblage indicating that the ecosystem was more ecologically stressed than that of coeval peat-forming wetlands.

6) Channel bodies of the Little River Formation represent a transition in fluvial style between the braidplain deposits of the underlying Boss Point Formation and the predominantly single storey, fixed and meandering channel bodies of the Joggins Formation. These channel bodies record an initial, confined phase with characteristics of the South Saskatchewan River facies model, and a broader abandonment phase with characteristics of the Platte River facies model.

7) During the Early Pennsylvanian, the Athol Syncline portion of the Cumberland Basin was undergoing rapid subsidence that was largely generated by the withdrawal of the underlying Windsor Group evaporites. This localized style of syndepositional subsidence indicates that the Athol Syncline is a large minibasin, similar to those described from the deepwater Gulf of Mexico. Although salt tectonics has long been a known process in the Cumberland Basin, this is the first study to confidently date

salt motion and to link it to the deposition of the coal-bearing facies of the Joggins Formation.

## REFERENCES CITED


AHLBERG, P.E., and MILNER, A.R., 1994, The origin and diversification of early tetrapods: Nature, v. 368, p. 507-514.

ALCOCK, E.J., 1948, The father of Canadian geology: The Earth Science Digest, v. 2, p. 5-10.

ALEXANDER, J., 1992, Nature and origin of a laterally extensive alluvial sandstone body in the Middle Jurassic Scalby Formation: Journal of the Geological Society, v. 149, p. 431-441.

ALGEO, T.J., and SCHECKLER, S.E., 1998, Terrestrial-marine teleconnections in the Devonian: links between the evolution of land plants, weathering processes, and marine anoxic events: Philosophical Transactions of the Royal Society of London, Series B, v. 353, p. 113-130.

ALGEO, T.J., BERNER, R.A., MAYNARD, J.B., and SCHECKLER, S.E., 1995, Late Devonian oceanic anoxic events and biotic crises: "Rooted" in the evolution of vascular land plants? GSA Today, v. 5, p. 45, 64-66.

ALLEN, J.R.L., 1965, The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales: Proceedings of Yorkshire Geological Society, v. 35, p. 139-185.

ALLEN, J.R.L., 1978, Studies in fluviatile sedimentation: An exploratory quantitative model for the architecture of avulsion-controlled alluvial suites: Sedimentary Geology, v. 21, p. 129-147.

ALLEN, J.R.L., 1982, Sedimentary Structures: Their Character and Physical Basis, v. 2: Amsterdam, Elsevier, 663 p.

ANDREWS, H.N., 1940, On the stelar anatomy of the pteridosperms with particular reference to the secondary wood: Annals of the Missouri Botanical Garden, v. 27, p. 51-118.

ARCHER, A.W., CALDER, J.H., GIBLING, M.R., NAYLOR, R.D., REID, D.R., and WIGHTMAN, W.G., 1995, Invertebrate trace fossils and agglutinated foraminifera as indicators of marine influence within the classic Carboniferous section at Joggins, Nova Scotia, Canada: Canadian Journal of Earth Sciences, v. 32, p. 2027-2039.

ARDIES, G.W., DALRYMPLE, R.W., and ZAITLIN, B.A., 2002, Controls on the geometry of incised valleys in the Basal Quartz unit (Lower Cretaceous), Western Canada Sedimentary Basin: Journal of Sedimentary Research, v. 72, p. 602-618.

ARTHAUD, F., and MATTE, P., 1977, Late Paleozoic strike-slip faulting in southern Europe and northern Africa: result of a right-lateral shear zone between the Appalachians and the Urals: Geological Society of America Bulletin, v. 88, p. 1305-1320.

ASLAN, A., and AUTIN, W.J., 1999, Evolution of the Holocene Mississippi River floodplain, Ferriday, Louisiana: insights on the origin of fine-grained floodplains: Journal of Sedimentary Research, v. 69, p. 800-815.

AVERY, T.E., and BURKHART, H.E., 1983, Forest Measurements: McGraw-Hill Series in Forest Resources: New York, McGraw-Hill, 331 p.

AXELSSON, V., 1967, The Laitaure Delta, a study of deltaic morphology and processes: Geografiska Annaler, v. 49A, p. 1-127.

BAGNOLD, R.A., 1941, The Physics of Blown Sand and Desert Dunes: London, Methuen, 265 p.

BAILEY, E., 1952, Geological Survey of Great Britain: London, Murby, 278 p.

BAROIS, I., DUBROEUCQ, D., ROJAS, P., and LAVELLE, P., 1998, Andosol-forming processes linked with soil fauna under the perennial grass *Mulhembergia macroura*: Geoderma, v. 86, p. 241-260.

BARR, S.M., RAESIDE, R.P., MILLER, B.V., and WHITE, C.E., 1995, Terrane evolution and accretion in Cape Breton Island, Nova Scotia: *in* Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada, Special Paper 41, p. 391-407.

BARTHEL, K.W., 1966, Concentric marks: current indicators: Journal of Sedimentary Petrology, v. 34, p. 1156-1162.

BATEMAN, R.M., 1991, Palaeobiological and phylogenetic implications of anatomically-preserved archaeocalamites from the Dinantian of Oxroad Bay and Loch Humphrey Burn, southern Scotland: Palaeontographica Abteilung B, v. 223, p. 1-59.

BAYLY, I.A.E., and WILLIAMS, W.D., 1973, Inland Waters and their Ecology: Camberwell, Australia, Longman, 316 p.

BECKETT, H., 1845, On a fossil forest in the Parkfield Colliery near Wolverhampton: Quarterly Journal of the Geological Society of London, v. 1, p. 41-43.

BEERBOWER, R., 1985, Early development of continental ecosystems: *in* Tiffney, B.H., ed., Geological Factors and the Evolution of Plants: New Haven, Yale University Press, p. 47-91.

BEHRENSMEYER, A.K., 1978, Taphonomic and ecologic information from bone weathering: Paleobiology, v. 4, p. 150-162.

BEHRENSMEYER, A.K., 1988, Vertebrate preservation in fluvial channels: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 63, p. 183-199.

BEHRENSMEYER, A.K., DAMUTH, W.A., DIMICHELE, W.A., POTTS, R., SUES, H.-D., and WINGS, S.L. eds.), 1992, Terrestrial Ecosystems through Time: Chicago, University of Chicago Press, 568 p.

BELL, J.S., and HOWIE, R.D., 1990, Paleozoic Geology: *in* Keen, M.J., and Williams, G.L., eds., Geology of the Continental Margin of Eastern Canada: Geological Society of America, Geology of Canada No. 2, p. 141-165.

BELL, W.A., 1912, Joggins Carboniferous section of Nova Scotia: Geological Survey of Canada, Summary Report for 1911, p. 328-333.

BELL, W.A., 1914, Joggins Carboniferous section, Nova Scotia: Geological Survey of Canada, Summary Report for 1912, p. 360-371.

BELL, W.A., 1927, Outline of Carboniferous stratigraphy and geological history of the Maritime Provinces of Canada: Transactions of the Royal Society of Canada, Section 4, p. 75-108.

BELL, W.A., 1929, Horton-Windsor District, Nova Scotia: Geological Survey of Canada, Memoir 155, 268 p.

BELL, W.A., 1938, Springhill map sheet with marginal notes: Geological Survey of Canada, Map 337A.

BELL, W.A., 1943, Carboniferous rocks and fossil floras of northern Nova Scotia: Geological Survey of Canada, Memoir 238, 276 p.

BELL, W.A., 1958, Possibilities for the occurrence of petroleum reservoirs in Nova Scotia: Nova Scotia Department of Mines, Miscellaneous Publication ME 1958-2, 177 p.

BELL, W.A., 1960, Mississippian Horton Group of Type Windsor-Horton District, Nova Scotia: Geological Survey of Canada, Memoir 314, 112 p.

BELT, E.S., 1964, Revision of Nova Scotia middle Carboniferous units: American Journal of Science, v. 262, p. 653-673.

BELT, E.S., 1965, Stratigraphy and paleogeography of Mabou Group and related Middle Carboniferous Facies, Nova Scotia, Canada: Geological Society of America Bulletin, v. 76, p. 777-802.

BESLY, B.M., 1988, Paleogeographic implications of late Westphalian to early Permian red-beds, central England: *in* Besley, B.M., and Kelling, G., eds., Sedimentation in a Synorogenic Complex: the Upper Carboniferous of Northwest Europe: London, Blackie, p. 200-222.

BLESS, M.J.M., BOUCKAERT, J., and PAPROTH, E., 1987, Fossil assemblages and depositional environments: limits to stratigraphical correlations: *in* Miller, J., Adams, A.E., and Wright, V.P., eds., European Dinantian Environments: Chichester, United Kingdom, John Wiley & Sons, p. 61-73.

BOCHET, E., POESEN, J., and RUBIO, J.L., 2000, Mound development as an interaction of individual plants with soil, water erosion and sedimentation processes on slopes: Earth Surface Processes and Landforms, v. 25, p. 847-867.

BOEHNER, R.C., 1992, An overview of the role of Windsor Group evaporites in the structural development of Carboniferous basins in Nova Scotia: Halifax, Nova Scotia Department of Natural Resources, Report ME 1992-1, p. 39-56.

BRADLEY, D.C., 1982, Subsidence in Late Paleozoic basins in the northern Appalachians: Tectonics, v. 1, p. 107-123.

BRIDGE, J.S., 1985, Paleochannel patterns inferred from alluvial deposits: A critical evaluation: Journal of Sedimenatary Petrology, v. 55, p. 579-589.

BRIDGE, J.S., and LEEDER, M.R., 1979, A simulation model of alluvial stratigraphy: Sedimentology, v. 26, p. 617-644.

BRIDGE, J.S., and MACKEY, S.D., 1993, A theoretical study of fluvial sandstone body dimensions: *in* Flint, S.S., and Bryant, I.D., eds., The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues: International Association of Sedimentologists, Special Publication 15, p. 213-236.

BRIDGE, J.S., GORDON, E.A., and TITUS, R.C., 1986, Non-marine bivalves and associated burrows in the Catskill magnafacies (Upper Devonian) of New York State: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 55, p. 65-77.

BRISTOW, C.S., 1999, Gradual avulsion, river metamorphosis and reworking by underfit streams: a modern example from the Brahmaputra River in Bangladesh and a possible ancient example in the Spanish Pyrenees: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 221-230.

BROMLEY, R.G., 1990, Trace Fossils: Boston, Unwin Hyman, 280 p.

BROWN, R., and SMITH, R., 1829, Geology and mineralogy: *in* Haliburton, T.C., ed., A Historical and Statistical Account of Nova Scotia, v. 2: Halifax, Joseph Howe, Section 3, p. 414-453.

BROWNE, G.H., 1991, The sedimentology of the Boss Point Formation (Pennsylvanian), eastern New Brunswick and northern Nova Scotia [unpublished Ph.D. Dissertation; in two volumes thesis]: University of Western Ontario, London, Ontario, 552 p.

BROWNE, G.H., and PLINT, A.G., 1994, Alternating braidplain and lacustrine deposition in a strike-slip setting: the Pennsylvanian Boss Point Formation of the Cumberland Basin, Maritime Canada: Journal of Sedimentary Research, v. B64, p. 40-59.

BUATOIS, L.A., MANGANO, M.G., ALISSA-ABDULRAHMAN, and CARR, T.R., 2002, Sequence stratigraphic and sedimentologic significance of biogenic structures from a late Paleozoic marginal- to open-marine reservoir, Morrow Sandstone, subsurface of Southwest Kansas, USA: Sedimentary Geology, v. 152, p. 99-132.

BUOL, S.W., MCCRACKEN, R.J., and HOLE, F.D., 1973, Soil Genesis and Classification: Ames, Iowa, Iowa State University Press, 360 p.

CALDER, J.H., 1985, Coal in Nova Scotia: Halifax, Nova Scotia Department of Mines and Energy, 79 p.

CALDER, J.H., 1991, Controls on Westphalian peat accumulation: the Springhill Coalfield, Nova Scotia [unpublished Ph.D. thesis]: Dalhousie University, Halifax, 310 p.

CALDER, J.H., 1994, The impact of climate change, tectonism and hydrology on the formation of Carboniferous tropical intermontane mires: the Springhill coalfield,

Cumberland Basin, Nova Scotia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 106, p. 323-351.

CALDER, J.H., 1995, Geological map of the Springhill Coalfield, Cumberland County, Nova Scotia [parts of 21H09A and D]: Nova Scotia Department of Natural Resources, 1:10 000.

CALDER, J.H., 1998, The Carboniferous evolution of Nova Scotia: *in* Blundell, D.J., and Scott, A.C., eds., Lyell, the Past is the Key to the Present: London, Geological Society, Special Publication 143, p. 261-302.

CALDER, J.H., 2003, 'Coal Age Galapagos': Joggins & the lions of nineteenth century geology: Abstracts with Programs - Geological Society of America, v. 35, p. 11.

CALDER, J.H., and GIBLING, M.R., 1994, The Euramerican Coal Province: controls on Late Paleozoic peat accumulation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 106, p. 1-21.

CALDER, J.H., and BROMLEY, D.S., 2005, Seismic stratigraphy of the Athol Syncline, Cumberland Basin: Implications for coal and coalbed methane exploration: Halifax, Nova Scotia Department of Mines and Energy, Report, in press.

CALDER, J.H., RYGEL, M.C., HEBERT, B.L., and FALCON-LANG, H.J., submitted, Sedimentology and stratigraphy of Pennsylvanian red beds near Joggins, Nova Scotia: The proposed Little River Formation with redefinition of the Joggins Formation: Atlantic Geology.

CALDER, J.H., GIBLING, M.R., EBLE, C.F., SCOTT, A.C., and MACNEIL, D.J., 1996, The Westphalian D fossil lepidodendrid forest at Table Head, Sydney Basin, Nova Scotia: Sedimentary, paleoecology and floral response to changing edaphic conditions: International Journal of Coal Geology, v. 31, p. 277-313.

CALDER, J.H., GIBLING, M.R., SCOTT, A.C., DAVIES, S.J., and HEBERT, B.L., in press, Paleoecology and sedimentology of a fossil lycopsid forest succession in the classic Pennsylvanian section at Joggins, Nova Scotia: *in* Greb, S.F., and DiMichele, W.A., eds., Wetlands through Time: Geological Society of America, Special Paper.

CALDER, J.H., BOEHNER, R.C., BROWN, D.E., GIBLING, M.R., MUKHOPADHYAY, P.K., RYAN, R.J., and SKILLITER, D.M., 1998, Horton Bluffs coastal section (Stop 2): Nova Scotia Department of Natural Resources, Open File Report ME 1998-5, p. 25-35.

CAMERON, B., VAN DOMMELEN, R., WHITE, P.D., DOMANSKI, D., ROGERS, D., and JONES, J.R., 1992, Vertebrate fossils from the middle member of the Early Carboniferous Horton Bluff Formation: *in* MacDonald, D.R., and Mills, K.A., eds., Program and Summaries; Sixteenth Annual Open House and Review of Activities: Halifax, Nova Scotia Department of Mines and Energy, Report ME 1992-4, p. 48.

CANT, D.J., and WALKER, R.G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625-648.

CANTRILL, D.J., and NICHOLS, G.J., 1996, Taxonomy and palaeoecology of Early Cretaceous (Late Albian) angiosperm leaves from Alexander Island Antartica: Review of Palaeobotany and Palynology, v. 92, p. 1-28.

CARR, P.A., 1968, Stratigraphy and spore assemblages, Moncton map-area, New Brunswick: Geologic Survey of Canada, Paper 67-29, p. 47.

CARROLL, R.L., 1988, Vertebrate Paleontology and Evolution: New York, Freeman, 689 p.

CARROLL, R.L., 2002, Early land vertebrates: Nature, v. 418, p. 35-36.

CARROLL, R.L., BELT, E.S., DINELEY, D.L., BAIRD, D., and MCGREGOR, D.C., 1972, Vertebrate paleontology of eastern Canada: XXIV International Geological Congress, Montreal, Excursion A59, Guidebook, p. 64-80.

CARTER, D.C., 1987, A three-dimensional view of the Pugwsh Salt Deposit, Cumburland County, Nova Scotia: Nova Scotia Department of Mines and Energy Report of Activities, 87-1, p. 133-139.

CARTER, D.C., 2003, 3-D seismic geomorphology: Insights into fluvial reservoir deposition and performance, Widuri field, Java Sea: American Association of Petroleum Geologist Bulletin, v. 87, p. 909-934.

CARTER, D.C., and PICKERILL, R.K., 1985, Lithostratigraphy of the Late Devonian-Early Carboniferous Horton Group of the Moncton Subbasin, southern New Brunswick: Maritime Sediments and Atlantic Geology, v. 21, p. 11-24.

CARTER, D.C., and PICKERILL, R.K., 1985, Algal swamp, marginal and shallow evaporitic lacustrine lithofacies from the late Devonian-early Carboniferous Albert Formation, southeastern New Brunswick, Canada: Maritime Sediments and Atlantic Geology, v. 21, p. 69-86.

CASTRO, I.P., 1971, Wake characteristics of two-dimensional perforated plates normal to an air-stream: Journal of Fluid Mechanics, v. 46, p. 599-609.

CECIL, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: Geology, v. 18, p. 533-536.

CECIL, C.B., STANTON, R.W., NEUZIL, S.G., DULONG, F.T., RUPPERT, L.L., and PIERCE, B., 1985, Paleoclimate controls on Late Paleozoic sedimentation and peat formation in the central Appalachian basin: International Journal of Coal Geology, v. 5, p. 195-230.

CHALONER, W.G., and LACEY, W.S., 1973, The distribution of Late Paleozoic floras: *in* Hughes, N.F., ed., Organisms and Continents through Time: London, Palaeontological Association, Special Paper 12, p. 271-289.

CHALONER, W.G., and SHEERIN, A., 1979, Devonian macrofloras: *in* House, M.R., Scrutton, C.T., and Bassett, M.G., eds., The Devonian System: London, Palaeontological Association, Special Papers in Palaeontology 23, p. 145-161.

CHAMBERLAIN, J.A., JR., 2004, Two Catskill freshwater clams, *Archanodon* (Devonian) and *Margaritifera* (Recent): What they tell us about the origin of unionoid bivalves: Northeastern Geology and Environmental Sciences, v. 26, p. 5-21.

CHANDLER, F.W., 1998, Geology of and climatic indicators in the Westphalian A New Glasgow Formation, Nova Scotia, Canada: implications for the genesis of coal and of sandstone-hosted lead deposits: Atlantic Geology, v. 34, p. 39-56.

CHAPMAN, H.H., and MEYER, W.H., 1949, Forest Mensuration: New York, McGraw-Hill, 522 p.

CHRISTIE, N., 1995, Sir William Logan's geological empire and the 'humbug' of economic utility: Canadian Historical Review, v. 75, p. 161-204.

CLACK, J.A., 2002, An early tetrapod from Romer's Gap: Nature, v. 418, p. 72-76.

CLEMMENSEN, L.B., 1986, Storm-generated eolian sand shadows and their sedimentary structures, Vejers strand, Denmark: Journal of Sedimentary Petrology, v. 56, p. 520-527.

COATES, M.I., and CLACK, J.A., 1995, Romer's gap: Tetrapod original and terrestriality: Bulletin du Museum National d'Historie Naturelle, v. 17, p. 373-388.

COATES, M.I., RUTA, M., and MILNER, A.R., 2000, Early tetrapod evolution: Trends in Ecology & Evolution, v. 15, p. 327-328.

COLEMAN, J.M., GAGLIANO, S.M., and WEBB, J.E., 1964, Minor sedimentary structures in a prograding distributary: Marine Geology, v. 1, p. 240-258.

CONYBEARE, A., and HAYNES, G., 1984, Observations on elephant mortality and bones in waterholes: Quaternary Research, v. 22, p. 189-200.

COOKE, R.U., WARREN, A., and GOUDIE, A.S., 1993, Desert Geomorphology: London, UCL Press, 526 p.

COPELAND, M.J., 1959, Coalfields, West Half Cumberland County, Nova Scotia: Geological Survey of Canada, Memoir 298, 89 p.

COTTER, E., 1978, The evolution of fluvial style, with special reference to the Central Appalachian Paleozoic: *in* Miall, A.D., ed., Fluvial Sedimentology: Calgary, Canadian Society of Petroleum Geologists, Memoir 5, p. 361-383.

CROWLEY, T.J., and BAUM, S.K., 1991, Estimating Carboniferous sea-level fluctuations from Gondwanan ice extent: Geology, v. 19, p. 975-977.

DAESCHLER, E.B., SHUBIN, N.H., THOMSON, K.S., and AMARAL, W.H., 1994, A Devonian tetrapod from North America: Science, v. 265, p. 639-642.

DALRYMPLE, R.W., BOYD, R., and ZAITLIN, B.A., 1994, History of research, types and internal organisation of incised-valley systems: Introduction to the volume: *in* Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-valley Systems: Origin and Sedimentary Sequences: Society for Sedimentary Geology, Special Publication 51, p. 3-10.

DARWIN, C., 1859, The Origin of Species by Means of Natural Selection: London, Murray, 513 p.

DAVIES, S.J., and GIBLING, M.R., 2003, Architecture of coastal and alluvial deposits in an extensional basin: the Carboniferous Joggins Formation of eastern Canada: Sedimentology, v. 50, p. 415-439.

DAVIES, S.J., GIBLING, M.R., RYGEL, M.C., CALDER, J.H., and SKILLITER, D.M., submitted, The Joggins Formation: stratigraphic framework and sedimentological log of the historic fossil cliffs: Atlantic Geology.

DAWSON, J.W., 1854, On the coal measures of the South Joggins, Nova Scotia: Quarterly Journal of the Geological Society of London, v. 10, p. 1-42.

DAWSON, J.W., 1855, Acadian Geology. An Account of the Geological Structure and Mineral Resources of Nova Scotia, and Portions of the Neighboring Provinces of British America: Edinburgh, Oliver and Boyd, 388 p.

DAWSON, J.W., 1860, On a terrestrial mollusk, a millipede, and new reptiles, from the Coal Formation of Nova Scotia: Quarterly Journal of the Geological Society of London, v. 16, p. 268-277.

DAWSON, J.W., 1863, Air-Breathers of the Coal Period: A Descriptive Account of the Remains of Land Animals found in the Coal Formation of Nova Scotia with Remarks on their Bearing on Theories of the Formation of Coal and of the Origin of the Species: Montreal, Dawson Brothers, 81 p.

DAWSON, J.W., 1868, Acadian Geology. The Geological Structure, Organic Remains, and Mineral Resources of Nova Scotia, New Brunswick, and Prince Edward Island: London, Macmillan, 694 p.

DAWSON, J.W., 1878, Acadian Geology. The Geological Structure, Organic Remains, and Mineral Resources of Nova Scotia, New Brunswick, and Prince Edward Island: London, Macmillan, 825 p.

DAWSON, J.W., 1880, Revision of the land snails of the Palaeozoic Era, with descriptions of new species: American Journal of Science, v. 20, p. 403-415.

DAWSON, J.W., 1891, The geology of Nova Scotia, New Brunswick, and Prince Edward Island; or, Acadian geology: London, Macmillan, 694 p.

DAWSON, J.W., 1901, Fifty Years of Work in Canada: London & Edinburgh, Ballantyne, Hanson & Co., 308 p.

DE LA BECHE, H.T., Papers, NMW 84.20G.D. Department of Geology, National Museums & Galleries of Wales, Cardiff, U.K.

DEMICCO, R.V., BRIDGE, J.S., and CLOYD, K.C., 1987, A unique freshwater carbonate from the Upper Devonian Catskill magnafacies of New York State: Journal of Sedimenatary Petrology, v. 57, p. 327-334.

DIMICHELE, W.A., and DEMARIS, P.J., 1987, Structure and dynamics of a Pennsylvanian-age *Lepidodendron* forest: colonizers of a disturbed swamp habitat in the Herrin (No. 6) coal of Illinois: Palaios, v. 2, p. 146-157.

DiMichele, W.A., and Hook, R.H., 1992, Paleozoic terrestrial ecosystems: *in* Behrensmeyer, A.K., Damuth, W.A., DiMichele, W.A., Potts, R., Sues, H.-D., and Wings, S.L., eds., Terrestrial Ecosystems through Time: Chicago, University of Chicago Press, p. 205-325.

DiMichele, W.A., and Aronson, R.B., 1992, The Pennsylvanian-Permian vegetational transition: a terrestrial analogue to the onshore-offshore hypothesis: Evolution, v. 46, p. 807-824.

DiMichele, W.A., and Phillips, T.L., 1994, Palaeobotanical and palaeoecological constraints on models of peat formation in the Late Carboniferous of Euramerica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 106, p. 39-90.

DiMichele, W.A., Eble, C.F., and Chaney, D.S., 1996, A drowned lycopsid forest above the Mahoning coal (Conemaugh Group, Upper Pennsylvanian) in eastern Ohio, U.S.A.: International Journal of Coal Geology, v. 31, p. 249-276.

DiMichele, W.A., Pfefferkorn, H.W., and Gastaldo, R.A., 2001, Response of Late Carboniferous and Early Permian plant communities to climate change: Annual Review of Earth and Planetary Sciences, v. 29, p. 461-487.

DiMichele, W.A., Tabor, N.J., Chaney, D.S., and Nelson, W.J., in press, From wetlands to wet spots: the fate and ecological significance of Carboniferous elements in early Permian coastal plain floras of North-Central Texas: *in* Greb, S.F., and DiMichele, W.A., eds., Wetlands Through Time: Geological Society of America, Special Paper.

Doeglas, D.J., 1962, The structure of sedimentary deposits of braided rivers: Sedimentology, v. 1, p. 167-190.

Dolby, G., 1991, The palynology of the western Cumberland Basin, Nova Scotia: Halifax, Nova Scotia, Nova Scotia Department of Mines and Energy, Open File Report 1991-6, 51 p.

Dolby, G., 2003, Palynological analysis of ten outcrop and core hole samples from Nova Scotia: Halifax, Nova Scotia, Nova Scotia Department of Natural Resources, Open File Report ME 2003-5.

Dolson, J., Muller, D., Evetts, M.J., and Stein, J.A., 1991, Regional paleotopographic trends and production, Muddy Sandstone (Lower Cretaceous), central and northern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 75, p. 409-435.

DORR, J.A., and KAUFFMAN, E.G., 1963, Rippled toroids from the Napoleon Sandstone Member (Mississippian) of southern Michigan: Journal of Sedimentary Petrology, v. 33, p. 751-758.

DRIESE, S.G., MORA, C.I., and ELICK, J.M., 1997, Morphology and taphonomy of root and stump casts of the earliest trees (Middle to Late Devonian), Pennsylvania and New York, U.S.A.: Palaios, v. 12, p. 534-537.

DUFF, P.M., and WALTON, E.K., 1973, Carboniferous sediments at Joggins, Nova Scotia, Seventh International Congress on Carboniferous Stratigraphy and Geology, Compte Rendu, v. 2: Krefeld, Geologisches Landesant Nordrhein-Westphalen, p. 365-379.

EAGAR, R.M.C., 1948, Variations in the shape of shell with respect ot ecological station: a review dealing with Recent Unionidae and certain species of the Anthracosiidae in Upper Carboniferous times: Proceedings of the Royal Society of Edinburgh, Series B, v. 65, p. 130-148.

EBERTH, D.A., 1996, Origin and significance of mud-filled incised valleys (Upper Cretaceous) in southern Alberta, Canada: Sedimentology, v. 43, p. 459-477.

EBERTH, D.A., and MIALL, A.D., 1991, Stratigraphy, sedimentology and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico: Sedimentary Geology, v. 72, p. 225-252.

EDWARDS, M.C., ERIKSSON, K.A., and KIER, R.S., 1983, Paleochannel geometry and flow patterns determined from exhumed Permian point bars in north-central Texas: Journal of Sedimentary Petrology, v. 53, p. 1261-1270.

ELICK, J.M., DRIESE, S.G., and MORA, C.I., 1998, Very large plant and root traces from the Early to Middle Devonian: Implications for early terrestrial ecosystems and atmospheric $p(CO_2)$: Geology, v. 26, p. 143-146.

ELLIOTT, T., 1974, Interdistributary bay sequences and their genesis: Sedimentolgy, v. 21, p. 611-622.

ETHRIDGE, F.G., SKELLY, R.L., and BRISTOW, C.S., 1999, Avulsion and crevassing in the sandy, braided Niobrara River: complex response to base-level rise and aggradation: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 179-191.

FALCON-LANG, H., 1999, Fire ecology of a Late Carboniferous floodplain, Joggins, Nova Scotia: Journal of the Geological Society of London, v. 156, p. 137-148.

FALCON-LANG, H.J., 1999, The Early Carboniferous (Asbian - Brigantian) seasonal tropical climate of northern Britain.: Palaios, v. 14, p. 116-126.

FALCON-LANG, H.J., 1999, Fire ecology of a Late Carboniferous floodplain, Joggins, Nova Scotia: Journal of the Geological Society, v. 156, p. 137-148.

FALCON-LANG, H.J., 2000, Fire ecology of the Carboniferous tropical zone: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 164, p. 339-355.

FALCON-LANG, H.J., 2003, Anatomically-preserved cordaitalean trees from Lower Pennsylvanian (Langsettian) dryland alluvial-plain deposits at Joggins, Nova Scotia: Atlantic Geology, v. 39, p. 259-265.

FALCON-LANG, H.J., 2003, Late Carboniferous tropical dryland vegetation in an alluvial-plain setting, Joggins, Nova Scotia, Canada: Palaios, v. 18, p. 197-211.

FALCON-LANG, H.J., 2003, Response of Late Carboniferous tropical vegetation to transgressive-regressive rhythms at Joggins, Nova Scotia: Journal of the Geological Society, v. 160, p. 643-647.

FALCON-LANG, H.J., 2004, Early Mississippian lycopsid forests in a delta-plain setting at Norton, near Sussex, New Brunswick, Canada: Journal of the Geological Society, v. 161, p. 969-981.

FALCON-LANG, H.J., 2004, Pennsylvanian tropical rain forests responded to glacial-interglacial rhythms: Geology, v. 32, p. 689-692.

FALCON-LANG, H.J., 2005, Small cordaitalean trees in a marine-influenced coastal habitat in the Pennsylvanian Joggins Formation, Nova Scotia: Journal of the Geological Society, v. 162, p. 485-500.

FALCON-LANG, H.J., and SCOTT, A.C., 2000, Upland ecology of some Late Carboniferous cordaitalean trees from Nova Scotia and England: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 156, p. 225-242.

FALCON-LANG, H.J., and CALDER, J.H., 2004, UNESCO World Heritage and the Joggins cliffs of Nova Scotia: Geology Today, v. 20, p. 140-144.

FALCON-LANG, H.J., and BASHFORTH, A.J., 2004, Pennsylvanian uplands were forested by giant cordaitalean trees: Geology, v. 32, p. 417-420.

FALCON-LANG, H.J., and CALDER, J.H., submitted, Sir William Dawson (1820-1899): a very modern palaeobotanist: Atlantic Geology.

FALCON-LANG, H.J., CANTRILL, D.T., and NICHOLS, G.J., 2001, Biodiversity and terrestrial ecology of a mid-Cretaceous, high latitude floodplain, Alexander Island, Antarctica: Journal of the Geological Society of London, v. 158, p. 709-725.

FALCON-LANG, H.J., RYGEL, M.C., GIBLING, M.R., and CALDER, J.H., 2004, An early Pennsylvanian waterhole deposit and its fossil biota in dryland alluvial plain setting, Joggins, Nova Scotia: Journal of the Geological Society, London, v. 161, p. 209-222.

FALCON-LANG, H.J., GIBLING, M.R., RYGEL, M.C., CALDER, J.H., and DAVIES, S.J., 2004, A dance to the music of time: Geoscientist, v. 14, p. 4-9.

FIELDING, C.R., 1984, Upper delta plain lacustrine and fluviolacustrine facies from the Westphalian of the Durham coalfield, NE England: Sedimentology, v. 31, p. 547-567.

FIELDING, C.R., and ALEXANDER, J., 1996, Sedimentology of the upper Burdekin River of north Queensland, Australia - an example of a tropical, variable discharge river: Terra Nova, v. 8, p. 447-457.

FIELDING, C.R., and ALEXANDER, J., 2001, Fossil trees in ancient fluvial channel deposits: evidence of seasonal and longer-term climatic variability: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 170, p. 59-80.

FIELDING, C.R., ALEXANDER, J., and NEWMAN-SUTHERLAND, E.N., 1997, Preservation of *in situ*, arborescent vegetation and fluvial bar reconstruction in the Burdekin River of north Queensland, Australia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 135, p. 123-144.

FIELDING, C.R., ALEXANDER, J., and MCDONALD, R., 1999, Sedimentary facies from ground-penetrating radar surveys of the modern, upper Burdekin River of north Queensland, Australia: consequences of extreme discharge fluctuations: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists Special Publication 28, p. 347-362.

FISK, H.N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: Vicksburg, U.S. Army Corps of Engineers, Mississippi River Commission, 78 p.

FLETCHER, H., 1908, Section of rocks from Shulie to Spicer Cove, Sumberland County, Nova Scotia, in descending order: Proceedings and Transactions of the Nova Scotian Institute of Science, v. 11, p. 500-550.

FRIEDMAN, G.M., and CHAMBERLAIN, J.A., JR., 1995, *Archanadon catskillenesis* (Vanuxem): fresh-water clams from one of the oldest back-swamp fluvial facies (upper Middle Devonian): Northeastern Geology and Environmental Sciences, v. 17, p. 431-443.

FRIEDMAN, G.M., and LUNDIN, R.F., 2001, Ostracods as indicators of brackish water environments in the Catskill Magnafacies (Devonian) of New York state: discussion: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 171, p. 73-79.

FRIEND, P.F., 1983, Towards the field classification of alluvial architecture or sequence: *in* Collinson, J.D., and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 345-354.

FRIEND, P.F., SLATER, M.J., and WILLIAMS, R.C., 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of the Geological Society, v. 136, p. 39-46.

FROEHLICH, W., KLIMEK, K., and STARKEL, L., 1972, The Holocene formation of the Dunajec Valley floor within the Beskid Sadecki in the light of flood transport and sedimentation: Studia Geomorphologica Carpatho-Balcanica, v. 6, p. 63-83.

FRUMKIN, A., 1996, Uplift rates relative to base-levels of a salt diapir (Dead Sea Basin, Isreal) as indicated by cave levels: *in* Alsop, G.I., Blundell, D., and Davison, I., eds., Salt Tectonics: London, Geological Society, Special Publication 100, p. 41-47.

GARDINER, J., and GIBLING, M.R., 2005, Pedogenic mud aggregates in the Joggins cliffs, Nova Scotia, Canada: Unusual preservation of dryland floodplain features: GAC-MAC-CSPG-CSSS Joint Meeting, Halifax, Nova Scotia May 16-18, p. 65.

GASTALDO, R.A., 1986, Implications on the paleoecology of autochthonous lycopsids in clastic sedimentary environments of the Early Pennsylvanian of Alabama: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 53, p. 191-212.

GASTALDO, R.A., 1987, Confirmation of Carboniferous clastic swamp communities: Nature, v. 326, p. 869-871.

GASTALDO, R.A., 1992, Regenerative growth in fossil horsetails following burial by alluvium: Historical Biology, v. 6, p. 203-219.

GASTALDO, R.A., DEMKO, T.M., and LIU, Y., 1991, A mechanism to explain persistent alternation of clastic and peat-accumulating swamps in Carboniferous sequences: Bulletin de la Société Géologique de France, v. 162, p. 299-305.

GASTALDO, R.A., STEVANOVIÇ-WALLS, I.M., and WARE, W.N., 2004, Erect forests are evidence for coseismic base-level changes in Pennsylvanian cyclothems of the Black Warrior Basin, U.S.A.: *in* Pashin, J.C., and Gastaldo, R.A., eds., Sequence Stratigraphy, Paleoclimate, and Tectonics of Coal-Bearing Strata: American Association of Petroleum Geologists, Studies in Geology 51, p. 219-238.

GASTALDO, R.A., DEMKO, T.M., LIU, Y., KEEFER, W.D., and ABSTON, S.L., 1989, Biostratinomic processes for the development of mud-cast logs in Carboniferous and Holocene swamps: Palaios, v. 4, p. 356-365.

GAWTHORPE, R.L., FRASER, A.J., and COLLIER, R.E.L., 1994, Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills: Marine Petroleum Geology, v. 11, p. 642-658.

GEMMER, L., INGS, S.J., MEDVEDEV, S., and BEAUMONT, C., 2004, Salt tectonics driven by differential sediment loading: stability analysis and finite-element experiments: Basin Research, v. 16, p. 199-218.

GENSEL, P.G., and ANDREWS, H.N., 1984, Plant Life in the Devonian: New York, Praeger, 380 p.

GENSEL, P.G., and PIGG, K.B., 2002, Reconstruction of the *Lepidodendropsis/Protostigmaria* plant from the Mississippian Price Formation of Virginia, USA: Botany 2002 (Abstracts), Madison, Wisconsin, p. 27.

GERHARZ, R., 1966, Sandwheels as a windeffect during transitory seasons: Neues Jarbuch fur Geologie und Paläontologie Manatshefte, v. 9, p. 550-553.

GESNER, A., 1836, Remarks on the Geology and Mineralogy of Nova Scotia: Halifax, Nova Scotia, Gossip and Coade, 272 p.

GESNER, A., 1843, A geological map of Nova Scotia, with an accompanying memoir: Proceedings of the Geological Society of London, v. 4, p. 186-190.

GIBLING, M.R., 1987, A classic Carboniferous section; Joggins, Nova Scotia: *in* Roy, D.C., ed.: Geological Society of America, Centennial Field Guide, Northeast Section, p. 409-414.

GIBLING, M.R., 1995, Upper Paleozoic rocks, Nova Scotia: *in* Williams, H., ed., Geology of the Appalachian-Caledonian Orogen in Canada and Greenland: Geological Society of America, The Geology of North America, Geology of Canada, No. 6, p. 493-523.

GIBLING, M.R., submitted, Fluvial channel and valley fills in the geological record: Jounal of Sedimentary Research.

GIBLING, M.R., and RUST, B.R., 1987, Evolution of a mud-rich meander belt in the Carboniferous Morien Group, Nova Scotia, Canada: Canadian Society of Petroleum Geologists Bulletin, v. 35, p. 24-33.

GIBLING, M.R., and RUST, B.R., 1992, Silica-cemented paleosols (ganisters) in the Pennsylvanian Waddens Cove Formation, Nova Scotia, Canada: *in* Wolf, K.H., and Chilingarian, G.V., eds., Diagenesis III: New York, Elsevier, Developments in Sedimentology v. 47, p. 621-655.

GIBLING, M.R., and BIRD, D.J., 1994, Late Carboniferous cyclothems and alluvial paleovalleys in the Sydney Basin, Nova Scotia: Geological Society of America Bulletin, v. 106, p. 105-117.

GIBLING, M.R., NANSON, G.C., and MAROULIS, J.C., 1998, Anastomosing river sedimentation in the Channel Country of central Australia: Sedimentology, v. 45, p. 595-619.

GIBLING, M.R., SAUNDERS, K.I., TIBERT, N.E., and WHITE, J.A., 2004, Sequence sets, high-accommodation events and the coal window in the Carboniferous Sydney Basin, Atlantic Canada, Sequence Stratigraphy, Paleoclimate, and Tectonics of Coal-Bearing Strata: American Association of Petroleum Geologists, Studies in Geology v. 51, p. 1-29.

GIBLING, M.R., TANDON, S.K., SINHA, R., and JAIN, M., in press, Discontinuity-bounded alluvial sequences of the southern Gangetic Plains, India: aggradation and degradation in response to monsoonal strength: Journal of Sedimentary Research.

GIBLING, M.R., CALDER, J.H., RYAN, R.J., VAN DE POLL, H.W., and YEO, G.M., 1992, Late Carboniferous and Early Permian drainage patterns in Atlantic Canada: Canadian Journal of Earth Sciences, v. 29, p. 338-352.

GIERLOWSKI-KORDESCH, E.H., and GIBLING, M.R., 2002, Pedogenic mud aggregates in rift sedimentation: *in* Ashley, G.M., and Renaut, R., eds., Sedimentation in Continental Rifts: Tulsa, Oklahoma, Society for Sedimentary Geology (SEPM), Special Publication 73, p. 195-206.

GILES, P.S., 1981, Major transgressive-regressive cycles in Middle to Late Visean rocks of Nova Scotia, Nova Scotia Department of Mines and Energy, Paper 81-2, 27 p.

GINGRAS, M.K., 2002, Stop 1 (km 168): *in* Armitage, I., Gingras, M., and Keighley, D.G., eds., Field Trip Number Four: Lacustrine Sedimentology, Ichnology, and Sequence Stratigraphy of Early Carboniferous Rift Basins (Albert Fm.); Sussex, New Brunswick: Frederick, New Brunswick, Atlantic Universities Geologic Conference, Guidebook, p. 4-6.

GLOVER, B.W., and POWELL, J.H., 1996, Interaction of climate and tectonics upon alluvial architecture: Late Carboniferous Early-Permian sequences at the southern margin of the Pennine Basin, UK: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 121, p. 13-34.

GOLDRING, W., 1927, The oldest known petrified forest: Science Monthly, v. 24, p. 515-529.

GOLONKA, J., and FORD, D., 2000, Pangean (Late Carboniferous-Middle Jurassic) paleoenvironments and lithofacies: Palaeogeography Palaeoclimatology Palaeoecology, v. 161, p. 1-34.

GONZALEZ-BONORINO, G., and EYLES, N., 1995, Inverse relation between ice extent and the late Paleozoic glacial record of Gondwana: Geology, v. 23, p. 1015-1018.

GORE, A.J.P. (ed.), 1983, Mires: Swamp, Bog, Fen and Moor: Ecosystems of the World, v. A&B: Amsterdam, Elsevier, General Studies 4A, 479 p.

GRADZISKI, R., BARYLA, J., DOKTOR, M., GMUR, D., GRADZINSKI, M., KEDZIOR, A., PASZKOWSKI, M., SOJA, R., ZIELINSKI, T., and ZUREK, S., 2003, Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments: Sedimentary Geology, v. 157, p. 253-276.

GRAEME, D., and DUNKERLY, D.L., 1993, Hydraulic resistance by the Red River Gum, *Eucalyptus camaldulensis*, in ephemeral desert streams: Australian Geographical Studies, v. 31, p. 141-154.

GREGORY, K.J., and GURNELL, A.M., 1988, Vegetation and river channel form and process: *in* Viles, H., ed., Biogeomorphology: New York, Basil Blackwell, p. 11-42.

GREINER, H.R., 1962, Facies and sedimentary environments of the Albert shale, New Brunswick: American Association of Petroleum Geologist Bulletin, v. 46, p. 219-234.

GUCCIONE, M.J., BURFORD, M.F., and KENDALL, J.D., 1999, Pemiscot Bayou, a large distributary of the Mississippi River and a possible failed avulsion: *in* Smith, N.D., and Roger, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 211-220.

HACQUEBARD, P.A., 1972, The Carboniferous of Eastern Canada: Compte Rendu, 7th International Congress on Carboniferous Stratigraphy and Geology, Krefeld, Germany, p. 69-90.

HACQUEBARD, P.A., and DONALDSON, J.R., 1964, Stratigraphy and palynology of the Upper Carboniferous coal measures in the Cumberland Basin of Nova Scotia, Canada: Compte Rendu, 5th International Congress on Carboniferous Stratigraphy and Geology, Paris, p. 1157-1169.

HACQUEBARD, P.A., and DONALDSON, J.R., 1970, Coal metamorphism and hydrocarbon potential in the Upper Paleozoic of the Atlantic Provinces, Canada: Canadian Journal of Earth Sciences, v. 7, p. 1139-1163.

HACQUEBARD, P.A., and CAMERON, A.R., 1989, Distribution and coalification patterns in Canadian bituminous and anthracite coals: International Journal of Coal Geology, v. 13, p. 207-260.

HAMBLIN, A.P., and RUST, B.R., 1989, Tectono-sedimentary analysis of alternate-polarity half-graben basin-fill successions: Late Devonian-Early Carboniferous Horton Group, Cape Breton Island, Nova Scotia: Basin Research, v. 2, p. 239-255.

HARRINGTON, B.J., 1883, Life of Sir William E. Logan: Montreal, Dawson Brothers, 432 p.

HASZELDINE, R.S., 1989, Coal reviewed: depositional controls, modern analogues and ancient climates: *in* Whateley, M.K.G., and Pickering, K.T., eds., Deltas, sites and traps for fossil fuels: Geological Society, Special Publication 41, p. 289-308.

HAYEK, L.C., and BUZAS, M., 1997, Surveying Natural Populations: New York, Columbia University Press, 563 p.

HEBERT, B.L., and CALDER, J.H., 2004, On the discovery of a unique terrestrial faunal assemblage in the classic Pennsylvanian section at Joggins, Nova Scotia: Canadian Journal of Earth Sciences, v. 41, p. 247-254.

HENDRIKS, M., JAMIESON, R.A., WILLETT, S.D., and ZENTILLI, M., 1993, Burial and Exhumation of the Long-Range Inlier and Its Surroundings, Western

Newfoundland - Results of an Apatite Fission-Track Study: Canadian Journal of Earth Sciences, v. 30, p. 1594-1606.

HESP, P.A., 1981, The formation of shadow dunes: Journal of Sedimentary Petrology, v. 51, p. 101-112.

HIRST, J.P.P., 1991, Variations in alluvial architecture across the Oligo-Miocene Huesca fluvial system, Ebro Basin, Spain: *in* Miall, A.D., and Tyler, N., eds., The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and Its Implications for Hydrocarbon Discovery and Recovery: Society for Sedimentary Geology (SEPM), Concepts in Sedimentology and Paleontology 41, p. 111-121.

HOLLAND, C.H. (ed.), 1981, A Geology of Ireland: Edinburgh, Scottish Academic Press, p.

HOLMES, R.B., CARROLL, R.L., and REISZ, R.R., 1998, The first articulated skeleton of *Dendrerpeton acadianum* (Temnospondyli: Dendrerpentonidae) from the Lower Pennsylvanian locality of Joggins, Nova Scotia, and a review of its relationships: Journal of Vertebrate Paleontology, v. 18, p. 64-79.

HOWER, J.C., CALDER, J.H., EBLE, C.F., SCOTT, A.C., ROBERTSON, J.D., and BLANCHARD, L.J., 2000, Metalliferous coals of the Westphalian A Joggins Formation, Cumberland Basin, Nova Scotia, Canada: petrology, geochemistry, and palynology: International Journal of Coal Geology, v. 42, p. 185-206.

HOWIE, R.A., 1986, Windsor Group Salt in the Cumberland Subbasin of Nova Scotia: Geological Survey of Canada, Paper 85-11.

HOWIE, R.D., 1984, Carboniferous evaporites in Atlantic Canada: *in* Geldsetzer, H.H.J., ed., Part 1, Atlantic Coast Basins: Carbondale, Southern Illinois University Press, International Congress on Carboniferous Stratigraphy and Geology, v. 9, no. 3, p. 131-142.

HOWIE, R.D., and BARSS, M.S., 1975, Upper Paleozoic rocks of the Atlantic Provinces, Gulf of St. Lawrence, and adjacent continental shelf: Geological Survey of Canada, Paper 74-30, p. 35-50.

HOWSE, R., 1878, Preliminary notice of the occurrence of *Archanodon* (*Anodonta*) *jukesi* (Forbes) in the Lower Carboniferous rocks of north Northumberland: Natural History Transactions of Northumberland, Durham and Newcastle-on-Tyne, v. 7, p. 173-175.

HUNT, A.P., LUCAS, S.G., CALDER, J.H., VAN ALLEN, H.E.K., GEORGE, E., GIBLING, M.R., HEBERT, B.L., MANSKY, C., and REID, D.R., 2004, Tetrapod footprints from Nova Scotia: the Rosetta stone for Carboniferous tetrapod ichnology: Abstracts with Programs - Geological Society of America, v. 36, p. 66.

JACKSON, J.A., 1997, Glossary of Geology: Alexandria, VA, American Geological Institute, 769 p.

JACKSON, M.P.A., and CRAMEZ, C., 1989, Seismic recognition of salt welds in salt tectonics regimes: Gulf Coast SEPM Tenth Annual Research Conference, Houston, Texas, p. 66-89.

JACKSON, M.P.A., ROBERTS, D.G., and SNELSON, S. eds.), 1995, Salt Tectonics: A Global Perspective, American Association of Petroleum Geologists, Memoir 65, 454 p.

JACKSON, R.G., 1976, Largescale ripples of the lower Wabash River: Sedimentology, v. 23, p. 593-623.

JAHNS, R.H., 1947, Geologic features of the Connecticut Valley, Massachusetts, as related to recent floods: Reston, U.S. Geological Survey, Water-Supply Paper 996, p. 158.

JAIN, S.C., 1981, Maximum clear-water scour around cylindrical piers: Journal of Hydraulic Engineering (American Society of Civil Engineers), v. 107, p. 611-625.

JENNINGS, J.R., 1975, *Protostigmaria*, a new plant organ from the Lower Mississippian of Virginia: Palaeontology, v. 18, p. 19-24.

JENNINGS, J.R., KARRFALT, E.C., and ROTHWELL, G.W., 1983, Structure and affinities of *Protostigmaria eggertiana*: American Journal of Botany, v. 70, p. 963-974.

JOHNSON, D.L., WATSON-STEGNER, D.N., JOHNSON, D.N., and SCHAETZL, R.J., 1987, Proisotropic and proanisotropic processes of pedoturbation: Soil Science, v. 143, p. 278-291.

JORDANOVA, A.A., and JAMES, C.S., 2001, Prediction of bed load transport rates through emergent vegetation, *in* Mason, J.A., Diffendal, R.F., and Joeckel, R.M., eds., Program with Abstracts, 7th International Conference on Fluvial Sedimentology, Conservation and Survey Division, University of Nebraska-Lincoln, p. 146.

KARCZ, I., 1968, Fluviatile obstacle marks from the wadis of the Negev (southern Israel): Journal of Sedimentary Petrology, v. 38, p. 1000-1012.

KARRFALT, E.E., 1977, Substrate penetration by the corm of Isoëtes: American Fern Journal, v. 67, p. 1-4.

KEIGHLEY, D., 2000, A preliminary sequence stratigraphy of the Horton Group, southeast Moncton Basin, southeast New Brunswick: interpretation of the Dawson Settlement Member of the Carboniferous Albert Formation, Shell Albert Mines #4 well: New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, Mineral Resource Report, p. 17-29.

KELLER, E.A., and SWANSON, F.J., 1979, Effects of large organic material on channel form and fluvial processes: Earth Surface Processes, v. 4, p. 361-380.

KELLEY, D.G., 1967, Some aspects of Carboniferous stratigraphy and depositional history in the Atlantic Provinces: *in* Neale, E.R.W., and Williams, H., eds., Collected Papers on Geology of the Atlantic Region: Hugh Lilly Memorial Volume: Geological Association of Canada, Special Paper 4, p. 213-228.

KEPPIE, J.D., 1976, Interpretation of P.P.I Radar Imagery of Nova Scotia: Halifax, Nova Scotia Department of Mines, Paper 76-3, 31 p.

KEPPIE, J.D., 2000, Geological map of the province of Nova Scotia: Nova Scotia Department of Natural Resources, Minerals and Energy Branch, 1:500 000.

KIRSCHBAUM, M.A., and MCCABE, P.J., 1992, Controls on the accumulation of coal and on the development of anastomosed fluvial systems in the Cretaceous Dakota Formation of southern Utah: Sedimentology, v. 39, p. 581-598.

KNIGHT, J.B., BATTEN, R.L., YOCHELSON, E.L., and COX, L.R., 1960, Palaeozoic and Mesozoic Caenogastropoda and Opistobranchia: *in* Moore, R.C., ed., Treatise on Invertebrate Paleontology, Part 1: Geological Society of America, p. 318-319.

KNIGHTON, A.D., and NANSON, G.C., 1993, Anastomosis and the continuum of channel pattern: Earth Surface Processes and Landforms, v. 18, p. 613-625.

KNIGHTON, A.D., and NANSON, G.C., 1994, Waterholes and their significance in the anastomosing channel system of Cooper Creek Australia: Geomorphology, v. 9, p. 311-324.

KNIGHTON, A.D., and NANSON, G.C., 2000, Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia: Geomorphology, v. 35, p. 101-117.

KNOX, L.W., 2001, Ostracodes as indicators of brackish water environments in the Catskill Magnafacies (Devonian) of New York State: reply: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 171, p. 81-83.

KNOX, L.W., and GORDON, E.A., 1999, Ostracodes as indicators of brackish water environments in the Catskill Magnafacies (Devonian) of New York State: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 148, p. 9-22.

KOERFER, L.E., and SCHWARZBACH, M., 1971, Scratch circles in Iceland: Zeitschrift fuer Geomorphologie, v. 15, p. 348-349.

KOSTERS, E.C., and SUTER, J.R., 1993, Facies relationships and systems tracts in the Late Holocene Mississippi delta plain: Journal of Sedimentary Petrology, v. 63, p. 727-733.

KRAUS, M.J., 1996, Avulsion deposits in Lower Eocene alluvial rocks, Bighorn Basin, Wyoming: Journal of Sedimentary Research, v. 66, p. 354-363.

KRAUS, M.J., and GWINN, B., 1997, Facies and facies architecture of Paleogene floodplain deposits, Willwood Formation, Bighorn Basin, Wyoming, USA: Sedimentary Geology, v. 114, p. 33-54.

KRAUS, M.J., and WELLS, T.M., 1999, Recognizing avulsion deposits in the ancient stratigraphic record: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 251-268.

KUKAL, Z., and AL NAQASH, A.B., 1970, Scratch circles on the Pliocene sandstones in central Iraq: Zeitschrift für Geomorphologie, v. 14, p. 329-334.

LAMBE, L.M., 1910, Palaeoniscid fishes from the Albert Shales of New Brunswick, Contributions to Canadian Paleontology, Geological Survey of Canada, p. 1-69.

LANGERFELDT, F., 1935, Untermeerische Scharrkreise im Schlick: Natur und Volk, v. 65, p. 458-461.

LAURIN, M., GIRONDOT, M., and DE RICQLÈS, A., 2000, Early tetrapod evolution: Trends in Ecology & Evolution, v. 15, p. 118-123.

LEEDER, M.R., 1973, Fluviatile fining-upwards cycles and the magnitude of paleochannels: Geological Magazine, v. 112, p. 257-270.

LEEDER, M.R., NAMI, M., SCOTT, A.C., and GARDINER, A., 1984, Studies on the sedimentology, palaeontology and palaeoecology of the Middle Coal Measures (Westphalian B, Upper Carboniferous) at Swillington, Yorkshire, Part 2, Centroclinal cross strata preserved around an *in situ* vertical tree trunk: Transactions of the Leeds Geological Association, v. 10, p. 17-21.

LEITH, W., and SIMPSON, D.W., 1986, Earthquakes related to active salt doming near Kulyab, Tadjikistan, USSR: Geophysical Research Letters, v. 13, p. 1019-1022.

LEONARDI, G., 1983, *Notopus petri*, n. gen., sp.; an amphibian imprint in the Devonian of Parana, Brazil: Geobios, v. 16, p. 233-239.

LI, R.M., and SHEN, H.W., 1973, Effect of tall vegetations on flow and sediment: Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers., v. 99, p. 793-814.

LOGAN, W.E., 1840, On the character of the beds of clay lying immediately below the coal seams of South Wales: Proceedings of the Geological Society of London, v. 3, p. 275-277.

LOGAN, W.E., 1841, Canada and U.S. 1840-1: Unpublished diary, Baldwin Room, Toronto Reference Library, Ontario, Canada.

LOGAN, W.E., 1842, On the character of the beds of clay lying immediately below the coal seams of South Wales: Transactions of the Geological Society of London, series 2, v. 6, p. 491-497.

LOGAN, W.E., 1842, On the coal fields of Pennsylvania and Nova Scotia: Quarterly Journal of the Geological Society of London, p. 707-712.

LOGAN, W.E., 1843, Bay of Chaleur - Bay of Fundy: Logan's Field Notebook, National Archives of Canada, RG45, vol. 158, item 2606.

LOGAN, W.E., 1843, Joggins, Bay of Fundy, Nova Scotia and Gaspe, Quebec, 1843, Logan's Field Notebook, National Archives of Canada, RG45, vol. 158, item 1962.

LOGAN, W.E., 1845, Preliminary Report, Appendix W: Geological Survey, Journals of the Legislative Assembly of the Province of Canada, 1844-5, p. 2-6.

LOGAN, W.E., 1845, Report of Progress for the Year 1843, Appendix W: Geological Survey, Journals of the Legislative Assembly of the Province of Canada, 1844-5, p. 6-14.

LOGAN, W.E., 1845, A section of the Nova Scotia coal measures as developed at Joggins on the Bay of Fundy, in descending order, from the neighbourhood of the west Ragged Reef to Minudie, reduced vertical thickness, Appendix W: Geological Survey, Journals of the Legislative Assembly of the Province of Canada, 1844-5, p. 28-45.

LOGAN, W.E., 1846, On the packing of the ice in the River Saint Lawrence; the occurrence of landslips in the modern deposits of its valley; and the existence of marine shells in them and on the mountain of Montreal: Quarterly Journal of the Geological Society of London, p. 422-432.

LOGAN, W.E., Papers, McGill University Archives, Montreal, Quebec, Canada.

LUKIE, T.D., DALRYMPLE, R.W., ARDIES, G.W., and ZAITLIN, B.A., 2002, Alluvial architecture of the Horsefly unit (Basal Quartz) in southern Alberta and northern Montana: influence of accommodation changes and contemporaneous faulting: Bulletin of Canadian Petroleum Geology, v. 50, p. 73-91.

LYELL, C., 1842, Letter to his sister; July 30: *in* Lyell, K.M., ed., Life, Letters, and Journals of Sir Charles Lyell, Bart (published in 1881), v. 2: London, Murray, 489, p. 64-66.

LYELL, C., 1842, Notebook 103, The letters, journals, and notebooks of Sir Charles Lyell, Lady Lyell, and other members of the family: The private collection of Lord Lyell of Kinnordy: Kirriemuir, Angus, Scotland, p. 142.

LYELL, C., 1843, On the upright fossil-trees found at different levels in the coal strata of Cumberland, Nova Scotia: Quarterly Journal of the Geological Society of London, v. 4, p. 176-178.

LYELL, C., 1843, On the coal-formation of Nova Scotia, and on the age and relative position of the gypsum and accompanying marine limestones: Proceedings of the Geological Society of London, v. 4, p. 184-186.

LYELL, C., 1845, Travels in North America, in the Years 1841-2; With Geological Observations on the United States, Canada, and Nova Scotia, v. 2: London, Murray, 272 p.

LYELL, C., 1852, Letter to Leonard Horner, Esq.: *in* Lyell, K.M., ed., Life, letters, and journals of Sir Charles Lyell, Bart (published in 1881), v. 2: London, Murray, 506, p. 178-184.

LYELL, C., 1862, Principles of Geology: New York, Appleton & Co., 834 p.

LYELL, C., 1871, The Student's Elements of Geology: New York, Harper, 640 p.

LYELL, C., Papers, Gen. 113/3500-01. Special Collections, Edinburgh University Library, Edinburgh, U.K.

LYELL, C., and DAWSON, J.W., 1853, On the remains of a reptile (*Dendrerpeton acadianum* Wyman and Owen), and of a land shell discovered in the interior of an erect fossil tree in the coal measures of Nova Scotia: Quarterly Journal of the Geological Society of London, v. 9, p. 58-63.

LYNCH, G., and KELLER, J.V.A., 1998, Association between detachment faulting and salt diapirs in the Devonian-Carboniferous Maritimes Basin, Atlantic Canada: Bulletin of Canadian Petroleum Geology, v. 46, p. 189-209.

LYONS, P.C., and DARRAH, W.C., 1989, Earliest conifers of North America: upland and/or palaeoclimatic indicators: Palaios, v. 4, p. 480-486.

MACAULEY, G., and BALL, F.D., 1982, Oil Shales of the Albert Formation, New Brunswick: New Brunswick Department of Natural Resources and the Geologic Survey of Canada, Institute of Sedimentary and Petroleum Geology, Open File Report 82-12, p. 173.

MACHETTE, M.N., 1985, Calcic soils of the southwestern United States: *in* Weide, D.L., ed., Soils and Quaternary Geology of the Southwestern United States, v. 203: Boulder, Geological Society of America, 150 203, p. 1-21.

MAKASKE, B., 2001, Anastomosing rivers: a review of their classification, origin and sedimentary products: Earth-Science Reviews, v. 53, p. 149-196.

MAMET, B.L., 1970, Carbonate microfacies of the Windsor Group (Carboniferous), Nova Scotia and New Brunswick: Ottawa, Geological Survey of Canada, Paper 70-21, 120 p.

MAPES, G., and GASTALDO, R.A., 1986, Late Paleozoic non-peat accumulating floras: *in* Broadhead, T.W., ed., Land Plants; Notes for a Short Course, Studies in Geology, v. 15: Knoxville, University of Tennessee, p. 115-131.

MARILLIER, F., KEEN, C.E., STOCKMAL, G.S., QUINLAN, G., WILLIAMS, H., COLMAN-SADD, S.P., and O'BRIEN, S.J., 1989, Crustal structure and surface zonation of the Canadian Appalachians: implications of deep seismic reflection data: Canadian Journal of Earth Sciences, v. 26, p. 305-321.

MARTEL, A.T., 1987, Seismic stratigraphy and hydrocarbon potential of the strike-slip Sackville sub-basin, New Brunswick: *in* Beaumont, C., and Tankard, A.J., eds., Sedimentary Basins and Basin-Forming Mechanisms: Calgary, Canadian Society of Petroleum Geologists, Memoir 12, p. 319-334.

MARTEL, A.T., 1990, Stratigraphy, fluviolacustrine sedimentology and cyclicity of the Late Devonian/Early Carboniferous Horton Bluff Formation, Nova Scotia, Canada [unpublished Ph.D. thesis]: Dalhousie University, Halifax, 297 p.

MARTEL, A.T., and GIBLING, M.R., 1991, Wave-dominated lacustrine facies and tectonically controlled cyclicity in the Lower Carboniferous Horton Bluff Formation, Nova Scotia, Canada: International Association of Sedimentologists, 13, p. 223-243.

MARTEL, A.T., and GIBLING, M.R., 1993, Clastic dykes of the Devono-Carboniferous Horton Bluff Formation, Nova Scotia: storm related structures in shallow lakes: Sedimentary Geology, v. 87, p. 103-119.

MARTEL, A.T., and GIBLING, M.R., 1994, Combined-flow generation of sole structures, including recurved groove casts, associated with Lower Carboniferous lacustrine storm deposits in Nova Scotia, Canada: Journal of Sedimentary Research, v. A64, p. 508-517.

MARTEL, A.T., and GIBLING, M.R., 1996, Stratigraphy and tectonic history of the Upper Devonian to Lower Carboniferous Horton Bluff Formation, Nova Scotia: Atlantic Geology, v. 32, p. 13-38.

MARTEL, A.T., MCGREGOR, D.C., and UTTING, J., 1993, Stratigraphic significance of Upper Devonian and Lower Carboniferous miospores from the type area of the Horton Group, Nova Scotia: Canadian Journal of Earth Sciences, v. 30, p. 1091-1098.

MARTINSEN, O.J., RYSETH, A., HELLAND-HANSEN, W., FLESCHE, H., TORKILDSEN, G., and IDIL, S., 1999, Stratigraphic base level and fluvial architecture: Ericson Sandstone (Campanian), Rock Springs Uplift, SW Wyoming, USA: Sedimentology, v. 46, p. 235-259.

MCBRIDE, B.C., ROWAN, M.G., and WEIMER, P., 1998, The evolution of allochthonous salt systems, northern Green Canyon and Ewing Bank (offshore Lousiana), northern Gulf of Mexico: American Association of Petroleum Geologists Bulletin, v. 82, p. 1013-1036.

MCCABE, P.J., 1991, Tectonic controls on coal accumulation: Bulletin de la Société Géologique de France, v. 162, p. 277-282.

MCCARTHY, T.S., ELLERY, W.N., and STANISTREET, I.G., 1992, Avulsion mechanisms on the Okavango fan, Botswana: the control of fluvial systems by vegetation: Sedimentology, v. 39, p. 779-795.

MCGOWEN, J.H., 1969, Gum Hollow Fan Delta, Nueces Bay, Texas: Mode of development and sediment characteristics [unpublished Ph.D. thesis]: University of Texas at Austin, Austin, 232 p.

MCKEE, E.D., CROSBY, E.J., and BERRYHILL, H.L., 1967, Flood deposits, Bijou Creek, Colorado, June 1965: Journal of Sedimentary Petrology, v. 37, p. 829-851.

MCMICHAEL, D.F., 1952, The shells of rivers and lakes - Part 1: The Australian Museum Magazine, v. 21, p. 348-353.

MELROSE, C.S.A., 2003, Fossilized forests of the Lower Carboniferous Horton Bluff Formation, Nova Scotia [unpublished B.Sc. thesis]: Dalhousie University, Halifax.

MELROSE, C.S.A., and GIBLING, M.R., 2003, Fossilized forests of the Lower Carboniferous Horton Bluff Formation, Nova Scotia: Geological Society of America Abstracts with Programs, v. 35, p. 92.

MELVILLE, B.W., and SUTHERLAND, A.J., 1988, Design method for local scour at bridge piers: Journal of Hydraulic Engineering, v. 114, p. 1210-1226.

MELVILLE, B.W., and DONGOL, D.M., 1992, Bridge pier scour with debris accumulation: Journal of Hydraulic Engineering, v. 118, p. 1306-1310.

MELVILLE, B.W., and COLEMAN, S.E., 2000, Bridge Scour: Highlands Ranch, Colorado, Water Resources Publications, LLC, 550 p.

MENNING, M., WEYER, D., DROZDZEWSKI, G., VAN AMEROM, H.W.J., and WENDT, I., 2000, A Carboniferous time scale 2000: Discussion and use of geological parameters as time indicators from Central and Western Europe: Geologische Jahrbuch, v. A156, p. 3-44.

METZ, R., 1991, Scratch circles from the Towaco Formation (Lower Jurassic), Riker Hill, Roseland, New Jersey: Ichnos, v. 1, p. 233-235.

METZ, R., 1999, Scratch circles; a new specimen from a lake-margin deposit of the Passaic Formation (Upper Triassic), Douglassville, Pennsylvania: Northeastern Geology and Environmental Sciences, v. 21, p. 179-180.

MIALL, A.D., 1994, Reconstructing fluvial macroform architecture from two-dimentional outcrops: examples from the Castlegate sandstone, Book Cliffs, Utah: Journal of Sedimentology Research, v. B64, p. 146-158.

MIALL, A.D., 1996, The Geology of Fluvial Deposits, Springer-Verlag, New York, 582 p.

MILLER, R.F., and MCGOVERN, J.H., 1996, Preliminary report of fossil fish (Actinopterygii; Palaeonisciformes) from the Lower Carboniferous Albert Formation at Norton, New Brunswick (NTS 21 H/12): *in* Carroll, B.M.W., ed., Current Research 1996: Mineral Resource Report MRR 97-4, p. 191-200.

MILNER, A.C., 1987, The Westphalian tetrapod fauna; some aspects of its geography and ecology: Journal of the Geological Society of London, v. 144, p. 495-506.

MILNER, A.C., and LINDSAY, W., 1998, Postcranial remains of *Baphetes* and their bearing on the relationships of the Baphetidae (=Loxommatidae): Zoological Journal of the Linnean Society, v. 122, p. 211-235.

MILNER, A.R., SMITHSON, T.R., MILNER, A.C., COATES, M.I., and ROLFE, W.D.I., 1986, The search for early tetrapods: Modern Geology, v. 10, p. 1-28.

MONTGOMERY, D.R., and PIÉGAY, H., 2003, Wood in rivers: interactions with channel morphology and processes: Geomorphology, v. 51, p. 1-5.

MONTGOMERY, D.R., ABBE, T.B., BUFFINGTON, J.M., PETERSON, N.P., SCHMIDT, K.M., and STOCK, J.D., 1996, Distribution of bedrock and alluvial channels in forested mountain drainage basins: Nature, v. 381, p. 587-589.

MOORE, D.S., 1994, The Basic Practice of Statistics: New York, Freeman, 680 p.

MOORE, P.D., 1987, Ecological and hydrological aspects of peat formation: *in* Scott, A.C., ed., Coal and Coal-Bearing Strata: Recent Advances: Geological Society of London, 32, p. 7-15.

MOORE, P.D., 1995, Biological processes controlling the development of modern peat-forming ecosystems: International Journal of Coal Geology, v. 28, p. 99-110.

MOROZOVA, G.S., and SMITH, N.D., 1999, Holocene avulsion history of the lower Saskatchewan fluvial system, Cumberland Marshes, Saskatchewan-Manitoba, Canada: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 231-249.

MOROZOVA, G.S., and SMITH, N.D., 2000, Holocene avulsion styles and sedimentation patterns of the Saskatchewan River, Cumberland Marshes, Canada: Sedimentary Geology, v. 130, p. 81-105.

MOSBRUGGER, V., 1990, The Tree Habit in Land Plants: Berlin, Springer-Verlag, Lecture Notes in Earth Sciences 28, 161 p.

MOSSA, J., and SCHUMACHER, B.A., 1993, Fossil tree casts in south Louisiana soils: Journal of Sedimentary Petrology, v. 63, p. 707-713.

MÜLLER, R., NYSTUEN, J.P., and WRIGHT, V.P., 2004, Pedogenic mud aggregates and paleosol development in ancient dryland river systems: criteria for interpreting alluvial mudrock origin and floodplain dynamics: Journal of Sedimenatary Research, v. 74, p. 537-551.

NADON, G.C., 1994, The genesis and recognition of anastomosed fluvial deposits: Data from the St. Mary River Formation, southwestern Alberta, Canada: Journal of Sedimentary Research, v. B64, p. 451-463.

NAKAYAMA, K., FIELDING, C.R., and ALEXANDER, J., 2002, Variations in character and preservation potential of obstacle marks in the variable discharge Burdekin River north of Queensland, Australia: Sedimentary Geology, v. 149, p. 199-218.

NANCE, R.D., 1987, Dextral transpression and Late Carboniferous sedimentation in the Fundy coastal zone of southern New Brunswick: *in* Beaumont, C., and Tankard, A.J., eds., Sedimentary Basins and Basin-Forming Mechanisms: Calgary, Canadian Society of Petroleum Geologists, Memoir 12, p. 363-377.

NANSON, G.C., 1981, New evidence of scroll-bar formation on the Beatton River: Sedimentology, v. 28, p. 889-891.

NANSON, G.C., and KNIGHTON, A.D., 1996, Anabranching rivers: their cause, character and classification: Earth Surface Processes and Landforms, v. 21, p. 217-239.

NANSON, G.C., and HUANG, H.Q., 1998, Anabranching rivers: divided efficiency leading to fluvial diversity: *in* Miller, A., and Gupta, A., eds., Varities of Fluvial Form: New York, Wiley, p. 478-494.

NANSON, G.C., RUST, B.R., and TAYLOR, G., 1986, Coexistant mud braids and anastomosing channels in an arid-zone river - Cooper Creek, central Australia: Geology, v. 14, p. 175-178.

NEW BRUNSWICK DEPARTMENT OF NATURAL RESOURCES AND ENERGY, 2000, Bedrock Geology of New Brunswick: Minerals and Energy Division, 1:500 000.

NICHOLS, G.J., 1987, Structural controls on fluvial distributary systems-the Luna System, northern Spain: *in* Ethridge, F.G., Flores, R.M., and Harvey, M.D., eds., Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists, Special Publication 39, p. 269-277.

NOFFKE, N., GERDES, G., KLENKE, T., and KRUMBEIN, W.E., 2001, Microbially induced sedimentary structures - a new category within the classification of primary sedimentary structures: Journal of Sedimentary Research, v. 71, p. 649-656.

OBERMEIER, S.F., JACOBSON, R.B., SMOOT, J.P., WEEMS, R.E., GOHN, G.S., MONROE, J.E., and POWARS, D.S., 1990, Earthquake-induced liquefaction features in the coastal setting of South Carolina and in the fluvial setting of the New Madrid seismic zone: United States Geological Survey Professional Paper 1504, 44 p.

OLSEN, H., 1988, The architecture of a sandy braided-meandering river system: an example from the Lower Triassic Solling Formation (M. Buntsandstein) in W-Germany: Geologische Rundschau, v. 77, p. 797-814.

OLSEN, T., 1993, Large fluvial systems: the Atane Formation, a fluvio-deltaic example from the Upper Cretaceous of central West Greenland: Sedimentary Geology, v. 85, p. 457-473.

OLSEN, T., STEEL, R.J., HØGSETH, K., SKAR, T., and RØE, S.-L., 1995, Sequential architecture in a fluvial succession: Sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah: Journal of Sedimentary Research, v. B65, p. 265-280.

PASCUCCI, V., GIBLING, M.R., and WILLIAMSON, M.A., 2000, Late Paleozoic to Cenozoic history of the offshore Sydney Basin, Atlantic Canada: Canadian Journal of Earth Sciences, v. 37, p. 1143-1165.

PEMBERTON, S.G., FLACH, P.D., and MOSSOP, G.D., 1982, Trace fossils from the Athabasca Oil Sands, Alberta, Canada: Science, v. 217, p. 825-827.

PEMBERTON, S.G., MACEACHERN, J.A., and FREY, R.W., 1992, Trace fossil facies models: environmental and allostratigraphic significance: *in* Walker, R.G., and James, N.P., eds., Facies Models: St. Johns, Newfoundland, Geological Association of Canada, p. 47-72.

PÉREZ-ARLUCEA, M., and SMITH, N.D., 1999, Depositional patterns following the 1870s avulsion of the Saskatchewan River (Cumberland Marshes, Saskatchewan, Canada): Journal of Sedimentary Research, v. 69, p. 62-73.

PETRYK, S., and BOSMAJIAN, G., 1975, Analysis of flow through vegetation: Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers., v. 101, p. 871-884.

PETTIJOHN, F.J., and POTTER, P.E., 1964, Atlas and Glossary of Primary Sedimentary Structures: New York, Springer-Verlag, 370 p.

PFEFFERKORN, H.W., and FUCHS, K., 1991, A field classification of fossil plant substrate interactions: Neues Jahrbuch für Geologie und Paläontologie Abhandlungen, v. 183, p. 17-36.

PHILLIPS, J., Papers, Arkell Library, Oxford University Museum of Natural History, Oxford, U.K.

PHILLIPS, T.L., and DIMICHELE, W.A., 1992, Comparative ecology and life-history biology of arborescent lycopsids in Late Carboniferous swamps of Euramerica: Annals of the Missouri Botanical Garden, v. 79, p. 560-588.

PICKERILL, R.K., 1992, Carboniferous nonmarine invertebrate ichnocoenoses from southern New Brunswick, Eastern Canada: Ichnos, v. 2, p. 21-35.

PIGG, K.B., 2001, Isoetalean lycopsid evolution: from the Devonian to the Present: American Fern Journal, v. 91, p. 99-114.

PIPER, D.J., 1994, Late Devonian-earliest Carboniferous basin formation and relationship to plutonism, Cobequid Highlands, Nova Scotia, Current Research 1994-D: Ottawa, Geological Survey of Canada, 189, p. 109-112.

PLINT, A.G., 2002, Paleo-valley systems in the Upper Cretaceous Dunvegan Formation, Alberta and British Columbia: Bulletin of Canadian Petroleum Geology, v. in press.

PLINT, A.G., and VAN DE POLL, H.W., 1982, Alluvial fan and piedmont sedimentation in the Tynemouth Creek Formation (Lower Pennsylvanian) of southern New Brunswick: Maritime Sediments and Atlantic Geology, v. 18, p. 104-128.

PLINT, A.G., and VAN DE POLL, H.W., 1984, Structural and sedimentary history of the Quaco Head area, southern New Brunswick: Canadian Journal of Earth Sciences, v. 21, p. 753-761.

PLINT, A.G., and BROWNE, G.H., 1994, Tectonic event stratigraphy in a fluvio-lacustrine, strike-slip setting: the Boss Point Formation (Westphalian A), Cumberland Basin, Maritime Canada: Journal of Sedimentary Research, v. B64, p. 341-364.

POLIAKOV, A.N.B., PODLADCHNIKOV, Y.Y., DAWSON, E.C., and TALBOT, C.J., 1996, Salt diapirism with simultaneous brittle faulting and viscous flow: *in* Alsop, G.I., Blundell, D., and Davison, I., eds., Salt Tectonics: London, Geological Society, Special Publication 100, p. 291-302.

POOLE, H.S., 1908, A section of Carboniferous rocks in Cumberland County, Nova Scotia; (1) Detailed section of rocks from West Ragged Reef to the Joggins mines and Minudie, by Sir William E. Logan (republished); and (2) From Schulie to Spicer Cove, by Hugh Fletcher: Proceedings and Transactions of the Nova Scotian Institute of Science, v. 11, p. 417-550.

POSAMENTIER, H.W., 2001, Lowstand alluvial bypass systems: Incised vs. unincised: American Association of Petroleum Geologist Bulletin, v. 85, p. 1771-1793.

POTTER, P.E., and PETTIJOHN, F.J., 1977, Paleocurrents and Basin Analysis: New York, Springer-Verlag, 425 p.

PRENTICE, J.E., 1962, Some sedimentary structures from a Weald Clay sandstone at Warnham brickworks, Horsham, Sussex: Proceedings of the Geologists' Association, v. 73, Part 2, p. 171-185.

PRYOR, J.S., 1996, The Upper Pennsylvanian Dusquene Coal of Ohio (USA); evidence for a dynamic peat-accumulating swamp community: International Journal of Coal Geology, v. 29, p. 119-146.

PYE, K., and TSOAR, H., 1990, Aeolian Sand and Sand Dunes: London, Unwin Hyman, 396 p.

RAST, N., 1988, Tectonic implications of the timing of the Variscan Orogeny: *in* Harris, A.L., and Fettes, D.J., eds., The Caledonian-Appalachian Orogen: London, Geological Society, 643 38, p. 585-595.

RAYMOND, A., PARKER, W.C., and PARRISH, J.T., 1985, Phytogeography and paleoclimate of the Early Carboniferous: *in* Tiffney, B.H., ed., Geological Factors and the Evolution of Plants: New Haven, Yale University Press, p. 169-222.

READ, C.B., and MAMAY, S.H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U.S. Geological Survey, Professional Paper 454-K, p. K1-K35.

REED, B.C., NANCE, R.D., CALDER, J.H., and MURPHY, J.B., 1993, The Athol Syncline: tectonic evolution of a Westphalian A-B depocentre in the Maritimes Basin, Nova Scotia: Atlantic Geology, v. 29, p. 179-186.

REHILL, T.A., 1996, Late Carboniferous nonmarine sequence stratigraphy and petroleum geology of the Central Maritimes Basin, Eastern Canada [unpublished Ph.D. thesis]: Dalhousie University, Halifax, Nova Scotia, 406 p.

REHILL, T.A., GIBLING, M.R., and WILLIAMSON, M.A., 1995, Stratigraphy of the Central Maritimes Basin, eastern Canada: non-marine sequence stratigraphy: Geological Survey of Canada, Current Research 1995-E, p. 221-231.

REISZ, R.R., 1997, The origin and early evolutionary history of amniotes: Trends in Ecology and Evolution, v. 12, p. 218-222.

RETALLACK, G.J., 1976, Triassic paleosols in the Upper Narabeen Group of New South Wales. Part I: Features of the palaeosols: Journal of the Geological Society of Australia, v. 23, p. 383-399.

RETALLACK, G.J., 1990, Soils of the Past: Boston, Unwin Hyman, 520 p.

RETALLACK, G.J., 2001, Soils of the Past: Ames, Iowa, Blackwell, 404 p.

RICHTER, R., 1926, Eine geologische Exkursion in das Wattenmeer: Natur und Museum, v. 56, p. 389-407.

RIGBY, J.K., 1959, Possible eddy markings in the Shinarump Conglomerate of north-eastern Utah: Journal of Sedimentary Petrology, v. 29, p. 283-284.

ROBERTS, H.H., WELLS, J.T., and KAHN, J.H., 1983, Alluvial valley and upper deltaic plain: Guidebook prepared for the AAPG Modern Delta Field Seminar, 23 p.

ROBISON, E.G., and BESCHTA, R.L., 1990, Coarse wood debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA: Earth Surface Processes and Landforms, v. 15, p. 149-156.

ROWAN, M.G., 1995, Structural styles and evolution of allochthonous salt, central Lousiana outer shelf and upper slope: *in* Jackson, M.P.A., Roberts, D.G., and Snelson, S., eds., Salt Tectonics: A Global Perspective: American Association of Petroleum Geologists, Memoir 65, p. 199-118.

ROWAN, M.G., LAWTON, T.F., GILES, K.A., and RATLIFF, R.A., 2003, Near-salt deformation in La Popa Basin, Mexico, and the northern Gulf of Mexico; a

general model for passive diapirism: Bulletin of the American Association of Petroleum Geologists, v. 87, p. 733-756.

RUST, B.R., 1981, Sedimentation in arid-zone anastomosing fluvial system: Cooper's Creek, central Australia: Journal of Sedimentary Petrology, v. 51, p. 745-755.

RUST, B.R., and LEGUN, A.S., 1983, Modern anastomosing-fluvial deposits in arid Central Australia, and a Carboniferous analogue in New Brunswick, Canada: *in* Collinson, J.D., and Lewin, J., eds., Modern and ancient fluvial systems: International Association of Sedimentologists, Special Publication 6, p. 385-392.

RUST, B.R., and GIBLING, M.R., 1990, Braidplain evolution in the Pennsylvanian South Bar Formation, Sydney Basin, Nova Scotia, Canada: Journal of Sedimentary Petrology, v. 60, p. 59-72.

RUST, B.R., GIBLING, M.R., and LEGUN, A.S., 1984, Coal depositional in an anastomosing-fluvial system: the Pennsylvanian Cumberland Group south of Joggins, Nova Scotia, Canada: *in* Rahmani, R.A., and Flores, R.A., eds., Sedimentology of Coal and Coal-bearing Sequences: International Association of Sedimentologists, Special Publication 7, p. 105-120.

RYAN, R.J., and BOEHNER, R.C., 1990, Cumberland Basin Geology Map, Tatamagouche and Malagash, Cumberland, Colchester and Pictou Counties: Nova Scotia Department of Mines and Energy, 1: 50,000.

RYAN, R.J., and ZENTILLI, M., 1993, Allocyclic and thermochronological constraints on the evolution of the Maritimes Basin of eastern Canada: Atlantic Geology, v. 29, p. 187-197.

RYAN, R.J., and BOEHNER, R.C., 1994, Geology of the Cumberland Basin, Cumberland, Colchester and Pictou Counties, Nova Scotia: Halifax, Nova Scotia Department of Natural Resources, Memoir 10, 222 p.

RYAN, R.J., BOEHNER, R.C., and DEAL, A., 1990, Cumberland Basin Geology Map, Oxford and Pugwash, Cumberland County: Nova Scotia Department of Mines and Energy, 1:50,000.

RYAN, R.J., BOEHNER, R.C., and DEAL, A., 1990, Cumberland Basin geology map, Apple River and Cape Chignecto, Cumberland County: Nova Scotia Department of Mines and Energy, 1:50 000.

RYAN, R.J., BOEHNER, R.C., and CALDER, J.H., 1991, Lithostratigraphic revisions of the upper Carboniferous to lower Permian strata in the Cumberland Basin, Nova

Scotia and the regional implications for the Maritimes Basin in Atlantic Canada: Bulletin of Canadian Petroleum Geology, v. 39, p. 289-314.

RYAN, R.J., CALDER, J.H., DONOHOE, H.V., JR., and NAYLOR, R.D., 1987, Late Paleozoic sedimentation and basin development adjacent to the Cobequid Highlands Massif, eastern Canada: *in* Beaumont, C., and Tankard, A.J., eds., Sedimentary Basins and Basin-Forming Mechanisms: Calgary, Canadian Society of Petroleum Geologists, Memoir 12, p. 311-317.

RYAN, R.J., BOEHNER, R.C., DEAL, A., and CALDER, J.H., 1990, Cumberland Basin geology map, Amherst, Springhill and Parrsboro, Cumberland County: Nova Scotia Department of Mines and Energy, 1:50 000.

RYGEL, M.C., and GIBLING, M.R., 2001, The interaction of sediment and vegetation - some examples from the Carboniferous of Nova Scotia: Abstracts with Programs - Geological Society of America, v. 33, p. A-220.

RYGEL, M.C., and GIBLING, M.R., 2003, Centroclinal cross strata - origin, morphology, and implications for understanding ancient terrestrial ecosystems: Abstracts with Programs - Geological Society of America, v. 35, p. 25.

RYGEL, M.C., and SHIPLEY, B.C., in press, "Such a section as never was put together before": Logan, Dawson, Lyell, and mid-nineteenth-century measurements of the Joggins section: Atlantic Geology.

RYGEL, M.C., GIBLING, M.R., and CALDER, J.H., 2004, Vegetation-induced sedimentary structures from fossil forests in the Pennsylvanian Joggins Formation, Nova Scotia: Sedimentology, v. 51, p. 531-552.

RZOSKA, J., 1974, The Upper Nile Swamps: a tropical wetland study: Freshwat. Biol., v. 4, p. 1-30.

SALAS, C.J., 1986, Braided fluvial architecture within a rapidly subsiding basin: the Pennsylvanian Cumberland Group southwest of Sand River, Nova Scotia [unpublished M.Sc. thesis]: University of Ottawa, 300 p.

SANCHEZ, G., and PUIGDEFABREGAS, J., 1994, Interactions of plant growth and sediment movement on slopes in a semi-arid environment: Geomorphology, v. 9, p. 243-260.

SANFORD, B.V., and GRANT, A.C., 1990, Bedrock geological mapping and basin studies in the Gulf of St. Lawrence, Current Research (Part B): Geological Survey of Canada, Paper 90-1B, p. 33-42.

SARJEANT, W.A.S., and MOSSMAN, D.J., 1978, Vertebrate footprints from the Carboniferous sediments of Nova Scotia: a historical review and description of newly discovered forms: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 23, p. 270-306.

SARJEANT, W.A.S., and MOSSMAN, D.J., 1978, *Peratodactylopus*, new name for the vertebrate footprint ichnogenus *Anticheiropus* Sarjeant and Mossman, 1978, non Hitchcock, 1865: Journal of Paleontology, v. 52, p. 1102.

SAUNDERS, W.B., and RAMSBOTTOM, W.H.C., 1986, The mid-Carboniferous eustatic event: Geology, v. 14, p. 208-212.

SCHECKLER, S.E., 1985, Origins of the coal swamp biome: Evidence from the southern Appalachians: Geological Society of America Abstracts with Programs, v. 17, p. 134.

SCHECKLER, S.E., 1986, Old Red Continent facies in the Late Devonian and Early Carboniferous of Appalachian North America: Annales de la Société Géologique de Belgique, v. 109, p. 223-236.

SCHECKLER, S.E., 1986, Floras of the Devonian-Mississippian transition: *in* Broadhead, T.W., ed., Land Plants: Notes for a Short Course: Knoxville, University of Tennessee, Studies in Geology 15, p. 81-96.

SCHECKLER, S.E., and BEELER, H.E., 1984, Early Carboniferous coal swamp floras from eastern USA (Virginia): Second International Organization of Palaeobotany Conference, Edmonton, Alberta, Abstracts, p. 36.

SCHEIHING, M.H., and PFEFFERKORN, H.W., 1984, The taphonomy of land plants in the Orinoco Delta: a model for the incorporation of plant parts in clastic sediments of Late Carboniferous age of Euramerica: Review of Palaeobotany and Palynology, v. 41, p. 205-240.

SCHENK, P.E., 1981, The Meguma Zone of Nova Scotia - a remnant of western Europe, South America or Africa? *in* Kerr, J.W., and Fergusson, A.J., eds., Geology of the Atlantic Borderlands: Calgary, Canadian Society of Petroleum Geologists, Memoir 7, p. 119-148.

SCHENK, P.E., MATSUMOTO, R., and VON BITTER, P.H., 1994, Loch Macumber (early Carboniferous) of Atlantic Canada: Journal of Paleolimnology, v. 11, p. 151-172.

SCHLESINGER, H.W., REYNOLDS, J.F., CUNNINGHAM, G.L., HUENNEKE, L.F., JARRELL, J.M., VIRGINIA, R.A., and WHITFORD, W.G., 1990, Biological feedbacks in global desertification: Science, v. 247, p. 1043-1048.

SCHUMANN, R.R., 1989, Morphology of Red Creek, Wyoming, an arid-region anastomosing channel system: Earth Surface Processes and Landforms, v. 14, p. 277-288.

SCHUMM, S.A., 1968, Speculations concerning paleohydraulic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.

SCHUMM, S.A., ERSKINE, W.D., and TILLEARD, J.W., 1996, Morphology, hydrology, and evolution of the anastomosing Ovens and King Rivers, Victoria, Australia: Geological Society of America Bulletin, v. 108, p. 1212-1224.

SCHUTTER, S.R., and HECKEL, P.H., 1985, Missourian (Early Late Pennsylvanian) climate in midcontinent North America: International Journal of Coal Geology, v. 5, p. 111-140.

SCOTESE, C.R., 2001, Atlas of Earth History (Volume 1 - Paleogeography), Paleomap Project: Arlington, Texas, 52 p.

SCOTT, A.C., 1989, Observations on the nature and origin of fusain: International Journal of Coal Geology, v. 12, p. 443-475.

SCOTT, A.C., 1998, The legacy of Charles Lyell: Advances in our knowledge of coal and coal-bearing strata: *in* Blundell, D.J., and Scott, A.C., eds., Lyell, the Past is the Key to the Present: London, Geological Society, Special Publication 143, p. 243-260.

SCOTT, A.C., 2001, Roasted alive in the Carboniferous: Geoscientist, v. 11, p. 4-7.

SCOTT, A.C., and REX, G.M., 1987, The accumulation and preservation of Dinantian plants from Scotland and its borders: *in* Miller, J., Adams, A.E., and Wright, V.P., eds., European Dinantian Environments: Chichester, United Kingdom, John Wiley & Sons, p. 181-200.

SCOTT, A.C., and CALDER, J.H., 1994, Carboniferous fossil forests: Geology Today, v. 10, p. 213-217.

SCOTT, A.C., GALTIER, J., and CLAYTON, G., 1984, Distribution of anatomically preserved floras in the Lower Carboniferous of Western Europe: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 75, p. 311-340.

SCOTT, H.D., SELIM, H.M., and WARD, L.B., 2000, MLRA 131 Southern Mississippi Valley Alluvium, *in* Scott, H.D., ed., Water and Chemical Transport of Soils of the Southeastern USA, Southern Association of Agricultural Experiment Station Directors, http://soilphysics.okstate.edu/S257/cover.html.

SEPPÄLÄ, M., 1972, Some remarks on the formation of scratch circles on wind-blown sand: Bulletin of the Geological Society of Finland, v. 44, p. 131-132.

SHANLEY, K.W., and MCCABE, P.J., 1991, Predicting facies architecture through sequence stratigraphy; an example from the Kaiparowits Plateau, Utah: Geology, v. 19, p. 742-745.

SHANLEY, K.W., and MCCABE, P.J., 1993, Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA: *in* Flint, S.S., and Bryant, I.D., eds., The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues: International Association of Sedimentologists, Special Publication 15, p. 21-56.

SHANLEY, K.W., and MCCABE, P.J., 1994, Perspectives on the sequence stratigraphy of continental strata: American Association of Petroleum Geologists Bulletin, v. 78, p. 544-568.

SHARPE, T., and MCCARTNEY, P.J., 1998, The Papers of H.T. De la Beche (1796-1855) in the National Museum of Wales: Cardiff, Wales, National Museum of Wales, Geological Series Number 17, 257 p.

SHAW, W.S., 1951, Preliminary map, Springhill, Cumberland, and Colchester Counties, Nova Scotia: Geological Survey of Canada, Paper 51-11.

SHAW, W.S., 1951, The Cumberland Basin of deposition [unpublished Ph.D. thesis]: Massachusetts Institute of Technology, Cambridge, 170 p.

SHEETS-PYENSON, S., 1996, John William Dawson: Faith, Hope, and Science: Montreal & Kingston, McGill-Queen's University Press, 304 p.

SHEN, H.W., SCHNEIDER, V.R., and KARAKI, S., 1969, Local scour around bridge piers: Journal of the Hydraulics Division. Proceedings of the American Society of Civil Engineers., v. 95, p. 1919-1940.

SHIPLEY, B.C., 2001, 'I wish these annual reports were at the devil': William E. Logan and the publications of the Geological Survey of Canada, History of the Book in Canada's Open Conference for Volume II: Montreal, http://www.hbic.library.utoronto.ca/vol2shipley_en.htm.

SIEVER, R., 1951, The Mississippian-Pennsylvanian unconformity in southern Illinois: American Association of Petroleum Geologists, v. 35, p. 542-581.

SIGAFOOS, R.S., 1964, Botanical evidence of floods and flood-plain deposition: United States Geological Survey Professional Paper, v. 485-A, p. A1-A35.

SKELLY, R.L., BRISTOW, C.S., and ETHRIDGE, F.G., 2003, Architecture of channel-belt deposits in aggrading shallow sandbed braided river: the lower Niobrara River, northeast Nebraska: Sedimentary Geology, v. 158, p. 249-270.

SKILLITER, D.M., 2001, Distal marine influence in the Forty Brine section, Joggins, Nova Scotia, Canada [unpublished M.Sc. thesis]: Boston College, Boston, 96 p.

SMALL, T.W., 1997, The Goodlett-Denny mound: a glimpse at 45 years of Pennsylvania treethrow mound evolution with implications for mass wasting: Geomorphology, v. 18, p. 305-313.

SMITH, C.H., 2000, Sir William Edmond Logan, father of Canadian geology: His passion was precision: GSA Today, v. 10, p. 22-23.

SMITH, D.G., 1976, Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river: Geological Society of America Bulletin, v. 87, p. 857-860.

SMITH, D.G., 1986, Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America: Sedimentary Geology, v. 46, p. 177-196.

SMITH, D.G., and SMITH, N.D., 1980, Sedimentation in anastamosed river systems: examples from alluvial valleys near Banff, Alberta: Journal of Sedimentary Petrology, v. 50, p. 157-164.

SMITH, D.G., and PUTNAM, P.E., 1980, Anastomosed river deposits: modern and ancient examples in Alberta, Canada: Canadian Journal of Earth Sciences, v. 17, p. 1396-1406.

SMITH, M.G., 1991, The floodplain deposits and palaeosol profiles of the Late Carboniferous Cumberland Coal Basin, exposed at Joggins, Nova Scotia, Canada [unpublished M.Sc. thesis]: University of Guelph, Guelph, Ontario, 372 p.

SMITH, N.D., 1970, The braided stream depositional environment: comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians: Geological Society of America Bulletin, v. 81, p. 2993-3014.

SNEH, A., 1983, Desert stream sequences in the Sinai Peninsula: Journal of Sedimentary Petrology, v. 53, p. 1271-1279.

SOLEM, A., and YOCHELSON, E.L., 1979, North American Paleozoic land snails, with a summary of other Paleozoic nonmarine snails: U. S. Geological Survey, Professional Paper 1072, 42 p.

SOREGHAN, G.S., and GILES, K.A., 1999, Amplitudes of Late Pennsylvanian glacioeustasy: Geology, v. 27, p. 255-258.

ST. PETER, C., 1993, Maritimes Basin evolution; key geologic and seismic evidence from the Moncton Subbasin of New Brunswick: Atlantic Geology, v. 29, p. 233-270.

ST. PETER, C., 2001, Carboniferous geological compilation map of southeastern New Brunswick comprising NTS quadrangles 21 H/10, 21 H/15, 21 H/16, 21 I/01, 21 I/02, and 11 L/04: New Brunswick Department of Natural Resources and Energy, Minerals and Energy Division, 1:150 000.

ST. PETER, C., JOHNSON, S.C., DEBLONDE, C., and LYNCH, G., 1997, Compilation map, geology, west central Nova Scotia, southeastern New Brunswick and western Prince Edward Island: Geological Survey of Canada, 1:250,000.

STAFF, S.S., 2003, Keys to Soil Taxonomy, United States Department of Agriculture Natural Resources Conservation Service, 332 p.

STEVENSON, J.J., 1911, The formation of coal beds: Proceedings of the American Philosophical Society, v. 50, p. 1-116.

STEWART, W.N., and ROTHWELL, G.W., 1993, Paleobotany and the Evolution of Plants: Cambridge, Cambridge University Press, 521 p.

STONE, E.C., and VASEY, R.B., 1968, Preservation of coast redwood on alluvial flats: Science, v. 159, p. 157-161.

STRAYER, D.L., 1999, Use of flow refuges by unionid mussels in rivers: Journal of the North American Benthological Society, v. 18, p. 468-476.

TAYLOR, G., and WOODYER, K.D., 1978, Bank deposition in suspended-load streams: *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 257-275.

TENGBERG, A., and CHEN, D., 1998, A comparative analysis of nebkhas in central Tunisia and northern Burkina Faso: Geomorphology, v. 22, p. 181-192.

TEVESZ, M.J., and CARTER, J.G., 1980, Environmental relationships of shell form and structure of unionacean bivalves: *in* Rhoads, D.C., and Lutz, R.A., eds., Skeletal Growth of Aquatic Organisms: New York, Plenum, p. 295-322.

THOMAS, D.S.G., and TSOAR, H., 1990, The geomorphological role of vegetation in desert dune systems: *in* Thornes, J.B., ed., Vegetation and Erosion: London, Wiley, p. 471-489.

THOMAS, R.G., SMITH, D.G., WOOD, J.W., VISSER, J., CALVERLEY-RANGE, E.A., and KOSTER, E.H., 1987, Inclined heterolithic stratification, interpretation and significance: Sedimentary Geology, v. 53, p. 123-179.

THOMS, R.E., and BERG, T.M., 1985, Interpretation of bivalve trace fossils in fluvial beds of the Basal Catskill Formation (Upper Devonian), eastern U.S.A.: *in* Curran, H.A., ed., Biogenic Structures: Their Use in Interpreting Depositional Environments: Society of Economic Paleontologists and Mineralogists, Special Publication 35, p. 13-20.

THORNE, C.R., 1990, Effects of vegetation on riverbank erosion and stability: *in* Thorne, J.B., ed., Vegetation and Erosion: Chichester, Wiley, p. 125-144.

TIBERT, N.E., and SCOTT, D.B., 1999, Ostracodes and agglutinated foraminifera as indicators of Paleoenvironmental change in an Early Carboniferous brackish bay, Atlantic Canada: Palaios, v. 14, p. 246-260.

TIBERT, N.E., and DEWEY, C.P., 2005, Taxonomic significance of the ostracode species *Carbonita altilis* (Jones and Kirby 1879) from the Pennsylvanian Joggins Formation, Atlantic Canada: GAC-MAC-CSPG-CSSS Joint Meeting, May 16-18, p. 194.

TIPPER, J.C., SACH, V.J., and HEIZMANN, E.P.J., 2003, Loading fractures and Liesegang laminae: new sedimentary structures found in the north-western North Alpine Foreland Basin (Oligocene-Miocene, south-west Germany): Sedimentology, v. 50, p. 791-813.

TOOTH, S., 1999, Downstream changes in floodplain character on the Northern Plains of arid central Australia: *in* Smith, N.D., and Rogers, J., eds., Fluvial Sedimentology VI: International Association of Sedimentologists, Special Publication 28, p. 93-112.

TÖRNQVIST, T.E., 1993, Holocene alternation of meandering and anastomosing fluvial systems in the Rhine-Meuse delta (central Netherlands) controlled by sea-level rise and subsoil erodibility: Journal of Sedimentary Petrology, v. 63, p. 683-693.

TÖRNQVIST, T.E., 1994, Middle and late Holocene avulsion history of the River Rhine (Rhine-Meuse delta, Netherlands): Geology, v. 22, p. 711-714.

TÖRNQVIST, T.E., VAN REE, M.H.M., and FAESSEN, E.L.J.H., 1993, Longitudinal facies architectural changes of a Middle Holocene anastomosing distributary system (Rhine-Meuse delta, central Netherlands): Sedimentary Geology, v. 85, p. 203-219.

TÖRNQVIST, T.E., VAN REE, M.H.M., and FAESSEN, E.L.H.J., 1993, Longitudinal facies architectural changes of a Middle Holocene anatomosing distributary system (Rhine-Meuse delta, central Netherlands): Sedimentary Geology, v. 85, p. 203-219.

TÖRNQVIST, T.E., WALLINGA, J., and BUSSCHERS, F.S., 2003, Timing of the last sequence boundary in a fluvial setting near the highstand shoreline - Insights from optical dating: Geology, v. 31, p. 279-282.

TORRENS, H.S., 1999, New light on Logan in Britain: Abstracts with Programs - Geological Society of America, v. 30, p. 211-212.

TRAPPE, J., 2000, Pangea: extravagant sedimentary resource formation during supercontinent configuration, an overview: Palaeogeography Palaeoclimatology Palaeoecology, v. 161, p. 35-48.

TURNER, B.R., DEWEY, C.P., and FORDHAM, C.E., 1997, Marine ostracods in the Lower Carboniferous fluviatile Fell Sandstone Group: Evidence for base level change and marine floding of the central graben, Northumberland Basin: Proceedings of the Yorkshire Geological Society, v. 51, p. 297-306.

TWENHOFEL, W.H., 1926, Treatise on Sedimentation: Baltimore, Williams and Wilkins, 661 p.

TYE, R.S., 2004, Geomorphology: An approach to determining subsurface reservoir dimensions: American Association of Petroleum Geologist Bulletin, v. 88, p. 1123-1147.

TYE, R.S., and COLEMAN, J.M., 1989, Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi Delta plain: Journal of Sedimentary Petrology, v. 59, p. 973-996.

UNDERWOOD, J.R., and LAMBERT, W., 1974, Centroclinal cross strata, a distinctive sedimentary structure: Journal of Sedimentary Petrology, v. 44, p. 1111-1113.

UTTING, J., 1987, Palynostratigraphic investigation of the Albert Formation (Lower Carboniferous) of New Brunswick, Canada: Palynology, v. 11, p. 73-96.

UTTING, J., and WAGNER, R.H., 2005, Megaflora of the Upper Carboniferous Cumberland Group, Joggins area, Nova Scotia and New Brunswick: GAC-MAC-CSPG-CSSS Joint Meeting, Halifax, Nova Scotia May 16-18, p. 197.

UTTING, J., KEPPIE, J.D., and GILES, P.S., 1989, Palynology and stratigraphy of the Lower Carboniferous Horton Group, Nova Scotia: Contributions to Canadian Palaeontology, Geological Survey of Canada Bulletin, v. 396, p. 117-143.

VAN DE POLL, H.W., 1978, Paleoclimatic control and stratigraphic limits of synsedimentary mineral occurrences in Mississippian-Early Pennsylvanian strata of eastern Canada: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 73, p. 1069-1081.

VAN DE POLL, H.W., GIBLING, M.R., and HYDE, R.S., 1995, Upper Paleozoic rocks: *in* Williams, H., ed., Geology of the Appalachian-Caledonian Orogen in Canada and Greenland: Geological Society of America, The Geology of North America, Geology of Canada, No. 6, p. 449-566.

VAN DER MOLEN, P.C., SCHALKOORT, M., and SMIT, R., 1994, Vegetation and ecology of hummock-hollow complexes on an Irish raised bog: Biology and Environment, v. 94B, p. 145-175.

VAN DER ZWAN, C.J., 1981, Palynology, phytogeography and climate of the Lower Carboniferous: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 33, p. 279-310.

VAN DER ZWAN, C.J., 2002, The impact of Milankovitch-scale climatic forcing on sediment supply: Sedimentary Geology, v. 147, p. 271-294.

VAN HEERDEN, I.L., and ROBERTS, H.H., 1988, Facies development of Atchafalaya Delta, Louisiana: a modern bayhead delta: American Association of Petroleum Geologists Bulletin, v. 72, p. 439-453.

VAN WAGONER, J.C., 1995, Sequence stratigraphy and marine to non-marine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A.: *in* Van Wagoner, J.C., and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists, Memoir 64, p. 137-223.

VAN WAGONER, J.C., MICHUM, R.M., CAMPION, K.M., and RAHMANIAN, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops, American Association of Petroleum Geologists, Methods in Exploration Series 7, 55 p.

VEEVERS, J.J., and POWELL, C.M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, p. 475-487.

VENDEVILLE, B.C., and JACKSON, M.P.A., 1992, The rise of diapirs during thin-skinned extension: Marine and Petroleum Geology, v. 9, p. 289-314.

VON BITTER, P.H., 1998, Sir William Logan's geological maps of Canada; field methods and scientific instruments: Abstracts with Programs - Geological Society of America, v. 30, p. 101.

WADE, J.A., BROWN, D.E., TRAVERSE, A., and FENSOME, R.A., 1996, The Triassic-Jurassic Fundy Basin, eastern Canada: regional setting, stratigraphy and hydrocarbon potential: Atlantic Geology, v. 32, p. 189-231.

WAGNER, R.H., 1973, Comments on the Upper Westphalian and Stephanian floras of Czechoslovakia, with particular reference to their stratigraphic age: *in* Holub, V., and Wagner, R.H., eds., Proceedings of the Symposium on Carboniferous Stratigraphy: Prague, Geological Survey, p. 441-455.

WAGNER, R.H., 1979, Megafloral zones of the Carboniferous, *in* Sutherland, P.K., and Manger, W.L., eds., Compte Rendu - International Congress on Carboniferous Stratigraphy and Geology (9th: 1979: Washington D.C. and University of Illinois at Urbana-Champaign): Carbondale and Edwardsville, Southern Illinois University Press, p. 109-134.

WAGNER, R.H., 1999, The composition and age of the Cumberland Flora, Nova Scotia: Unpublished report to the Geological Survey of Canada.

WALDRON, J.W.F., 2004, Anatomy and evolution of a pull-apart basin, Stellarton, Nova Scotia: Geological Society America Bulletin, v. 116, p. 109-127.

WALDRON, J.W.F., and RYGEL, M.C., 2004, Evolution of the Cumberland Basin, Nova Scotia: New insights on deposition and salt tectonics from seismic reflection profiles: Abstracts, 30th Annual Atlantic Geoscience Society Meeting, Moncton, New Brunswick Jan. 30-31, p. 30.

WALDRON, J.W.F., and RYGEL, M.C., 2005, Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia: Geology, v. 33, p. 337-340.

WALDRON, J.W.F., PIPER, D.J.W., and PE-PIPER, G., 1989, Deformation of the Cape Chignecto Pluton, Cobequid Highlands, Nova Scotia: thrusting at the Meguma-Avalon boundary: Atlantic Geology, v. 25, p. 51-62.

WARREN, J.W., and WAKEFIELD, N.A., 1972, Trackways of tetrapod vertebrates from the Upper Devonian of Victoria, Australia: Nature, v. 238, p. 469-470.

WEBB, G.W., 1963, Occurrence and exploration significance of strike slip faults in southern New Brunswick, Canada: American Association of Petroleum Geologist Bulletin, v. 47, p. 1904-1927.

WEBB, G.W., 1969, Paleozoic wrench faults in Canadian Appalachians: *in* Kay, M., ed., North Atlantic Geology and Continental Drift: American Association of Petroleum Geologists, Memoir 12, p. 754-786.

WEIR, J., 1969, Superfamily Archanodontacea: *in* Moore, R.C., ed., Treatise on Invertebrate Paleontology, Part N, Volume 1, p. N402-404.

WEIR, S.L., 2002, Invertebrate Ichnofossils of the Horton Bluff Formation in the Collections of the Nova Scotia Museum of Natural History [unpublished Bachelor's thesis]: St. Mary's, Halifax, N.S., 89 p.

WELLMAN, C.H., and GRAY, J., 2001, The microfossil record of early land plants: Transactions of the Royal Society, Series B, v. 355, p. 717-731.

WELLMAN, C.H., OSTERLOFF, P.L., and MOHIUDDIN, U., 2003, Fragments of the earliest land plants: Nature, v. 425, p. 282-285.

WENDE, R., and NANSON, G.C., 1998, Anabranching rivers: ridge-form alluvial channels in tropical northern Australia: Geomorphology, v. 22, p. 205-224.

WHITEAVES, J.F., 1893, Note on the recent discovery of large Unio-like shells in the Coal Measures at the South Joggins, N.S.: Transactions of the Royal Society of Canada, Series 1, v. 12, p. 21-24 (plus one plate).

WILLIAMS, H., 1995, Geology of the Appalachian-Caledonian Orogen in Canada and Greenland: The Geology of North America, v. F-1, Geological Society of America, 944 p.

WILLIAMS, W.D., 1983, Life in Inland Waters: Melbourne, Blackwell Scientific, p.

WILSON, L.G., 1998, Lyell in America; Transatlantic Geology, 1841-1853: Baltimore, The Johns Hopkins University Press, 429 p.

WITHERS, P., PEDLAR, S., and GUPPY, M., 1997, Physiological adjustments during aestivation by the Australian land snail *Rhaga tescorum* (Mollusca: Pulmonata: Camaenidae): Australian Journal of Zoology, v. 45, p. 599-611.

WITT, A., 1985, Vegetational influences on intrachannel deposition: evidence from the Konczak Stream, Greater Poland Lowlands, western Poland: Quaestiones Geographicae, v. 9, p. 145-160.

WOOD, D., and CAMERON, B., 1998, Fish trace fossils from the Horton Bluff Formation (Lower Carboniferous) of Nova Scotia: Atlantic Geology, v. 34, p. 81.

WOOD, D.A., 1999, Vertebrate and invertebrate surficial trace fossils from the Horton Bluff Formation (Lower Carboniferous) near Avonport, Nova Scotia [unpublished Bachelor's thesis]: Acadia University, Wolfville, N.S., 114 p.

WOODROFFE, C.D., CHAPPELL, J., THOM, B.G., and WALLENSKY, E., 1989, Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia: Sedimentolgy, v. 36, p. 737-756.

WOODYER, K.D., TAYLOR, G., and CROOK, K.A.W., 1979, Depositional processes along a very low-gradient suspended-load stream: the Barwon River, New South Wales: Sedimentary Geology, v. 22, p. 97-120.

ZASLOW, M., 1975, Reading the Rocks: Ottawa, Macmillan, 599 p.

ZELLER, S., 1987, Inventing Canada: Toronto, University of Toronto Press, 356 p.

ZIEGLER, A.M., REES, P.M., and NAUGOLNYKH, S.V., 2002, The Early Permian floras of Prince Edward Island, Canada: differentiating global from local effects of climate change: Canadian Journal of Earth Sciences, v. 39, p. 223-238.

ZIERHOLZ, C., PROSSER, I.P., FOGARTY, P.J., and RUSTOMJI, P., 2001, In-stream wetlands and their significance for channel filling and the catchment sediment budget, Jugiong Creek, New South Wales: Geomorphology, v. 38, p. 221-235.

# APPENDIX 1: STUDENT CONTRIBUTION TO CO-AUTHORED MANUSCRIPTS FORMS

DALHOUSIE University

Faculty of Graduate Studies

## STUDENT CONTRIBUTION TO MANUSCRIPTS IN THESIS

| | |
|---|---|
| **Manuscript Authors:** | M.C. Rygel, M.R. Gibling, and J.H. Calder |
| **Manuscript Title:** | Vegetation-induced sedimentary structures from fossil forests in the Pennsylvanian Joggins Formation, Nova Scotia |
| **Journal:** | Sedimentology (2004, v. 51, p. 531-552) |
| **Student Contribution:** | I was the primary author of this manuscript and solely responsible for the fieldwork and background research that it is built upon. J.H. Calder helped ensure the accuracy of the paleobotanical information. |

| | |
|---|---|
| **MANUSCRIPT AUTHORS:** | M.C. Rygel, J.H. Calder, M.R. Gibling, M.K. Gingras, and C.S.A. Melrose |
| **MANUSCRIPT TITLE:** | Tournaisian forested wetlands in the Horton Group of Atlantic Canada |
| **JOURNAL:** | Wetlands Through Time, Geological Society of America Special Publication (accepted for publication by the editors in mid-2004, awaiting proofs and final confirmation from the GSA Editorial Office) |
| **STUDENT CONTRIBUTION:** | Building upon my work identifying sedimentary structures formed around standing plants at Joggins, an undergraduate thesis undertaken by C.S.A. Melrose and supervised by M.R. Gibling identified forested horizons in the Tournaisian Horton Bluff Formation and confirmed that similar structures were preserved there (Melrose and Gibling, 2003). After my presentation at the 2003 GSA meeting in Halifax, I was told by M.K. Gingras that he had seen similar structures in the Albert Formation of New Brunswick and had published preliminary descriptions of them in an Atlantic Geoscience Society fieldguide (Gingras, 2002). I wrote the vast majority of the manuscript, conducted all the background research on the biota of the Horton Group, and collected the observations and measurements presented in the text. J.H. Calder contributed the section on wetland terminology, and visited the field localities with me to discuss my paleobotanical and sedimentological observations. M.R. Gibling supervised the pilot study by C.S.A. Melrose. |

| | |
|---|---|
| **MANUSCRIPT AUTHORS:** | Rygel, M.C. and Gibling, M.R. |
| **MANUSCRIPT TITLE:** | Fluvial systems of the Pennsylvanian Joggins Formation, Atlantic Canada: Geomorphic and accommodation influences on channel body geometry and architecture |
| **JOURNAL:** | Journal of Sedimentary Research (anticipated submission in late 2005) |
| **STUDENT CONTRIBUTION:** | I wrote this manuscript and personally conducted the field work and background research upon which it is based. |

DALHOUSIE *University*

*Faculty of Graduate Studies*

## STUDENT CONTRIBUTION TO MANUSCRIPTS IN THESIS

| | |
|---|---|
| **Manuscript Authors:** | H.J. Falcon-Lang, M.C. Rygel, M.R. Gibling, M.R., J.H. Calder |
| **Manuscript Title:** | An early Pennsylvanian waterhole deposit and its fossil biota in a dryland alluvial plain setting, Joggins, Nova Scotia |
| **Journal:** | Journal of the Geological Society (2004, v. 161, p. 209-222 ) |
| **Student Contribution:** | Building upon the initial description of faunal remains by Hebert and Calder (2004), H.J. Falcon-Lang coordinated the development of a manuscript that documented the floral and faunal remains in their paleoecological and sedimentological context. I contributed stand-alone sections to this manuscript that H.J. Falcon-Lang revised and incorporated with the rest of the text. Specifically, I was responsible for the sections on the description and interpretation of the sedimentology, photographs and taphonomic descriptions of the invertebrate and vertebrate material housed in the Fundy Geological Museum, as well as much of the research on *Archanodon* and waterholes. |

| | |
|---|---|
| **MANUSCRIPT AUTHORS:** | J.H. Calder, M.C. Rygel, R.J. Ryan, H.J. Falcon-Lang, and B.L. Hebert |
| **MANUSCRIPT TITLE:** | Stratigraphy and sedimentology of Early Pennsylvanian red beds at Lower Cove, Nova Scotia, Canada: The Little River Formation with redefinition of the Joggins Formation |
| **JOURNAL:** | Atlantic Geology (submitted for review February 2005) |
| **STUDENT CONTRIBUTION:** | J.H. Calder (with the field assistance of B.L. Hebert) measured the section of redbeds exposed near Lower Cove. To expand upin this section I studied the fluvial sedimentology of the Little River channel bodies. I wrote stand-alone sections about my descriptions and interpretations, contributed a section on the history of stratigraphic nomenclature, tied the measured section to the airphotos, revised other sections of the manuscript, and drafted all the figures (but not Appendix 5). |

| | |
|---|---|
| **MANUSCRIPT AUTHORS:** | J.W.F. Waldron and M.C. Rygel |
| **MANUSCRIPT TITLE:** | Role of evaporite withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia |
| **JOURNAL:** | Geology (2005, v. 33, p. 337-340) |
| **STUDENT CONTRIBUTION:** | The text of the manuscript and the seismic interpretation represents an equal collaboration between J.W.F. Waldron and myself. After receiving training on how to use the seismic processing software in Waldron's lab, I interpreted the Cumberland Basin seismic lines with daily feedback and assistance from Waldron. I am second author on this paper with the understanding that I will be the lead author on a second paper (to be completed after my Ph.D.) that will incorporate my outcrop data and examine the history of the basin more fully. |

# APPENDIX 2: COPYRIGHT RELEASE FORMS

## APPENDIX 3: LOGAN'S MEASURED SECTION

Sir William Logan's original Joggins measured section (Logan 1845c). Although Logan measured the section from bottom to top (ascending order), the measured section is presented from top to bottom (descending order).

Appendix (W.) 27th January.

# APPENDIX.

Appendix (W.) 27th January.

## Section of the Nova Scotia Coal Measures, as developed at the Joggins, on the Bay of Fundy, in descending order, from the neighbourhood of the West Ragged Reef to Minudie, reduced to vertical thickness

1.

| | Ft. | In. |
|---|---|---|
| Greenish gray or drab coloured sandstone or grit, with some conglomerate beds, of which the matrix is sandstone and the pebbles consist of white and of red veined quartz. These are generally as large as peas: some are of the size of pigeons' eggs, and a few as large as hens' eggs, | 30 | 0 |
| Drab sandstone of a fine grit, but rather too hard for grindstones, | 2 | 0 |
| Red or chocolate coloured argillaceous shale, with small layers of sandstone of the same colour and quality as above, | 15 | 0 |
| Drab sandstone, with small layers of chocolate coloured shale, | 20 | 0 |
| Dark red argillaceous shale, with some green spots, | 10 | 0 |
| Drab sandstone in two to three beds, | 8 | 0 |
| Drab sandstone of a coarse grit; the bed has an uneven bottom, | 20 | 0 |
| Dark red or chocolate coloured argillaceous shale, with a few bands of sandstone, | 20 | 0 |
| Dark red argillaceous shale, | 10 | 0 |
| Drab sandstone, | 7 | 0 |
| Dark red shale and drab sandstone in irregular beds, | 20 | 0 |
| Drab or greenish gray sandstone, | 3 | 0 |
| Red argillaceous shale, | 9 | 0 |
| Greenish gray or drab coloured sandstone in several layers, separated by bands of dark red or chocolate coloured argillo-arenaceous shale, | 20 | 0 |
| Greenish gray or drab coloured sandstone of a fine grit, | 4 | 0 |
| Soft measures, concealed, probably dark red shale, | 20 | 0 |
| Coarse greenish gray sandstone, or rather a conglomerate with a fine matrix of sand and with fragments of plants, converted into coal, | 30 | 0 |
| Measures not well seen, | 15 | 0 |
| Greenish gray sandstone, with conglomerate beds and plants converted into coal, | 60 | 0 |
| Dark red shale, | 15 | 0 |
| Greenish gray sandstone, with conglomerate beds, | 10 | 0 |
| Dark red shale, | 3 | 0 |
| Greenish gray or drab coloured sandstone, with conglomerate beds, | 15 | 0 |
| Dark red shale, | 10 | 0 |
| Greenish gray sandstone, with conglomerate beds, | 62 | 0 |
| Dark red shale, with bands of red sandstone, | 14 | 0 |
| Greenish gray sandstone, with conglomerate beds, | 25 | 0 |
| Dark red shale, | 10 | 0 |
| Greenish gray sandstone, with plants converted into coal, | 30 | 0 |
| Dark red shale, with thin beds of sandstone, | 10 | 0 |
| Greenish gray sandstone, with thin conglomerate layers, | 3 | 0 |
| Dark red shale, | 6 | 0 |
| Greenish gray sandstone, with beds of conglomerate, | 55 | 0 |
| Dark red or chocolate coloured shale, | 1 | 0 |
| Greenish gray sandstone, with much conglomerate and fragments of drift plants coated with coal, | 30 | 0 |
| Dark red or chocolate coloured shale, | 9 | 0 |
| Greenish gray sandstone, with conglomerate beds and carbonized drift plants, | 14 | 0 |
| Dark red shale, | 3 | 0 |
| Dark red shale, with beds of sandstone, | 15 | 0 |
| Greenish gray sandstone, with conglomerate beds, | 20 | 0 |
| Greenish gray sandstone, with bands of red shale, | 21 | 0 |
| Greenish gray sandstone, with conglomerate beds and carbonized drift plants of large diameter, say one foot, and wholly converted into coal. In many cases the action of the surf against the base of the perpendicular cliff has worn deep holes or caverns, where the stems lie prostrate in the rock. The plants are *sigillariæ*, so are nearly the whole of those already mentioned as met with in the grits or conglomerates. Fragments of *calamites* are occasionally seen, | 30 | 0 |
| Red or chocolate coloured shale, | 10 | 0 |
| Greenish gray sandstone of a conglomerate character, with many carbonized drift plants imbedded in it. Some beds of grit in this, towards the bottom, have been found fit for grindstones, | 20 | 0 |
| Dark red or chocolate coloured argillaceous shale, | 60 | 0 |
| Greenish gray sandstone inclining to yellow, chiefly of a coarse grit and fine texture; some of it must be called conglomerate, the pebbles of which, consisting of quarts of various colours—white, yellow, and red, with black chert and lydian stone,—are some of them as large as hens' eggs, a great many as large as almonds, and the majority as big as peas. Some of the beds have been found fit for grindstones. This sandstone constitutes the point of West Ragged Reef, | 30 | 0 |
| Measures concealed, | 42 | 0 |
| Measures concealed, with sandstone at the bottom, | 23 | 0 |
| Greenish gray or drab coloured sandstone of a coarse grit, | 12 | 0 |
| Dark red shale with green bands, | 30 | 0 |
| Greenish gray sandstone of a coarse grit, some of which is fit for grindstones, but some parts are conglomerate, with red and white quarts pebbles, generally as large as peas, some of the size of pigeons' eggs, and a few as large as hens' eggs; some parts exhibit large spherical concretions rather harder than the surrounding material, | 30 | 0 |
| Dark red shale, with green bands, | 6 | 0 |
| Greenish gray or drab coloured sandstone of a coarse grit, | 6 | 0 |
| Dark red and light green shale, with some bands of drab sandstone, | 50 | 0 |
| Greenish gray sandstone of a coarse grit, | 30 | 0 |
| Dark red shale, | 30 | 0 |
| Greenish gray sandstone of a coarse grit, with some carbonized drift plants, | 3 | 0 |
| Greenish and red shale. This is on the west side of South Brook, Two Rivers, | 3 | 0 |
| Measures not well seen, being occupied by the brook, but consisting chiefly of greenish gray sandstone, | 42 | 0 |
| Greenish gray sandstone, with bands of greenish arenaceous shale and red arenaceous shale, | 10 | 0 |
| Red argillaceous shale, | 1 | 0 |
| Greenish gray sandstone, | 7 | 0 |
| Red arenaceous shale, | 4 | 0 |
| Red argillaceous shale, | 6 | 0 |
| Red argillo-arenaceous shale, | 17 | 0 |
| Greenish gray sandstone, | 2 | 0 |
| Red argillo-arenaceous shale, | 2 | 0 |
| Greenish gray sandstone, | 1 | 0 |
| Red argillo-arenaceous shale, | 18 | 0 |
| Greenish gray sandstone, | 7 | 0 |
| Red argillo-arenaceous shale, | 6 | 0 |
| Greenish gray sandstone, | 1 | 0 |
| Red argillo-arenaceous shale, with green bands, | 8 | 0 |
| Greenish gray sandstone of a coarse grit, | 10 | 0 |
| Measures concealed. This is where the North Branch of the Two Rivers occurs, | 16 | 0 |
| Greenish gray sandstone of a coarse grit, with some beds of conglomerate, having red and white quarts pebbles, the largest of which would weigh about two ounces, | 20 | 0 |
| Red argillaceous shale, | 12 | 0 |
| Greenish gray sandstone of a coarse grit, some parts of which are fit for large grindstones, commonly called *water-stone* by the quarrymen, | 70 | 0 |
| Greenish gray sandstone, with divisional layers of arenaceous shale, | 4 | 0 |
| Red argillaceous shale, | 19 | 0 |
| Red argillaceous shale, with greenish gray arenaceous shale at the top, | 13 | 0 |
| Greenish gray sandstone, | 1 | 0 |
| Red argillaceous shale, | 4 | 0 |

Appendix (W.) 27th January.

| | Ft. | In. |
|---|---|---|
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 6 | 0 |
| Greenish gray sandstone, ... ... ... | 5 | 0 |
| Red argillaceous shale and green arenaceous shale, with a few bands of greenish gray sandstone. This deposit is chiefly red shale, ... ... | 32 | 0 |
| Greenish gray sandstone, ... ... ... | 24 | 0 |
| Red argillaceous shale with green bands, ... ... | 10 | 0 |
| Greenish gray sandstone in four beds, separated by bands of red argillaceous shale of one to two feet thick, ... ... ... ... ... | 27 | 0 |
| Red argillaceous shale, ... ... ... | 11 | 0 |
| Greenish gray sandstone, with one foot of shale towards the bottom, ... ... ... | 5 | 0 |
| Red argillaceous shale, ... ... ... | 8 | 0 |
| Greenish gray sandstone in three small beds separated by red shale; occasionally the sandstone occupies the whole of the thickness, ... ... | 6 | 0 |
| Red argillo-arenaceous shale, with green bands, ... | 27 | 0 |
| | 1617 | 0 |

RECAPITULATION.

| | | |
|---|---|---|
| Greenish gray or drab coloured sandstones, with conglomerate beds and large carbonized drift plants, ... ... | 947 | 0 |
| Dark red or chocolate coloured argillaceous and argillo-arenaceous shales, ... | 670 | 0 |
| | 1617 | 0 |

2.

| | | |
|---|---|---|
| Gray arenaceous shale, ... ... ... | 6 | 0 |
| Greenish gray sandstone. This is an unequal band, and there are doubtful indications of the leaves of *stigmaria ficoides* at the top, ... ... | 8 | 0 |
| Reddish and greenish gray argillaceous shale, with some bands of arenaceous shale, ... ... | 28 | 0 |
| Greenish gray sandstone of a coarse grit, fit for water-stones, ... ... ... ... | 7 | 0 |
| Red argillaceous shale, with some bands of arenaceous shale, ... ... ... ... | 5 | 0 |
| Measures concealed, ... ... ... ... | 20 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |
| Measures only partially seen, and containing some arenaceous shale, ... ... ... | 13 | 0 |
| Reddish yellow sandstone, ... ... ... | 2 | 0 |
| Measures concealed, but shewn by the shape of the surface to be soft, ... ... ... | 4 | 0 |
| Reddish yellow sandstone of a coarse grit, fit for water-stones, ... ... ... ... | 15 | 0 |
| Red argillaceous shale, ... ... ... | 7 | 0 |
| Reddish yellow sandstone of a coarse grit, fit for water-stones, ... ... ... ... | 12 | 0 |
| Red argillaceous shale, with greenish gray arenaceous shale in three beds, ... ... ... | 47 | 0 |
| Greenish gray sandstone, ... ... ... | 7 | 0 |
| Red argillaceous shale, ... ... ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 14 | 0 |
| Dark green shale, ... ... ... ... | 1 | 0 |
| Gray sandstone, ... ... ... ... | 25 | 0 |
| Red argillo-arenaceous shale, with greenish gray arenaceous shale, and some few layers of sandstone, | 42 | 0 |
| Greenish gray sandstone, ... ... ... | 9 | 0 |
| Greenish gray arenaceous shale and sandstone, with red and gray argillaceous shale, ... ... | 24 | 0 |
| Red argillaceous shale, with green arenaceous shale, | 26 | 0 |
| Gray sandstone fit for grindstones, ... ... | 21 | 0 |
| Red and green shale, ... ... ... ... | 11 | 0 |
| Greenish gray sandstone, ... ... ... | 4 | 0 |
| Red argillaceous and arenaceous shale, ... ... | 5 | 0 |
| Greenish gray sandstone of various qualities, chiefly of coarse grit, fit for large grindstones or water-stones; much of it, however, is fine enough for small stones; both are made from the Reef, ... | 97 | 0 |
| Red argillaceous and greenish gray arenaceous shale, | 13 | 0 |
| Gray sandstone fit for grindstones, the bottom part of a coarse grit. This constitutes Ragged Reef Point, ... ... ... ... | 35 | 0 |
| Red argillaceous shale, ... ... ... | 15 | 0 |
| Greenish gray sandstone, fit for grindstones, ... | 10 | 0 |
| Red argillaceous shale, with one foot of greenish gray sandstone, ... ... ... | 2 | 0 |
| Greenish gray sandstone fit for grindstones; the top of the bed is uneven, ... ... ... | 20 | 0 |
| Red argillaceous shale, gray arenaceous shale, and a few bands of greenish gray sandstone, ... | 15 | 0 |
| Red argillaceous shale, ... ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Red argillaceous shale, with green bands, ... | 13 | 0 |
| Greenish gray shaly sandstone, or perhaps arenaceous shale, ... ... ... ... ... | 7 | 0 |
| Greenish gray sandstone fit for grindstones, with a few *calamites* nearly at right angles to the plane of the beds, as if in situ, but forced over at the top, ... ... ... ... ... | 30 | 0 |
| | 650 | 0 |

RECAPITULATION.

| | | | | |
|---|---|---|---|---|
| Drab coloured sandstones without conglomerate beds, ... | 219 | 0 | | |
| Gray sandstones, ... ... | 81 | 0 | | |
| Reddish yellow sandstones, ... | 28 | 0 | | |
| | | | 328 | 0 |
| Red, green, and greenish gray argillaceous and arenaceous shales, ... ... | | | 322 | 0 |
| | | | 650 | 0 |

(Indications of *stigmaria ficoides* exist near the top, and of upright *calamites* at the bottom.)

3.

| | | |
|---|---|---|
| *Black carbonaceous shale*, ... ... ... | 2 | 0 |
| Greenish gray sandstone, with *stigmaria ficoides*, (this would be called *understone* by the Welsh miners,) ... ... ... ... | 3 | 0 |
| Gray argillaceous shale, with impressions of *ferns* and other plants, (*topstone*,) ... ... ... | 2 | 0 |
| 1. Coal of inferior quality—a regular seam, ... | 0 | 1 |
| Greenish gray argillaceous shale, with *stigmaria ficoides* (*understone*), ... ... ... | 1 | 0 |
| Greenish gray argillaceous shale, with *stigmaria ficoides* and *ironstone* balls (*understone*), ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Red or chocolate coloured shale, ... ... ... | 6 | 0 |
| Greenish gray sandstone fit for grindstones, with a bed of red shale in the middle, ... ... | 23 | 0 |
| Red shale with a layer of sandstone, ... ... | 12 | 0 |
| Red shale in three beds, ... ... ... | 3 | 0 |
| Greenish gray sandstone in four beds, ... ... | 6 | 0 |
| Red argillaceous shale, ... ... ... | 7 | 0 |
| Gray sandstone in small layers, ... ... ... | 7 | 0 |
| Reddish gray sandstone, ... ... ... | 3 | 0 |
| Greenish gray sandstone in small layers, ... ... | 7 | 0 |
| Reddish and green sandstone, ... ... ... | 15 | 0 |
| Reddish and green shale, ... ... ... | 1 | 0 |
| Reddish sandstone—soft, ... ... ... | 1 | 0 |
| Red argillo-arenaceous shale, with balls of *ironstone*, | 3 | 0 |
| Red and green sandstone, ... ... ... | 12 | 0 |
| Measures concealed, but supposed to be soft, ... | 52 | 0 |
| Red and green shale, with balls of *ironstone*, ... | 7 | 0 |
| Gray sandstone and shale, ... ... ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 8 | 0 |
| Greenish gray sandstone and red shale, ... ... | 3 | 0 |
| Greenish gray or drab coloured sandstone, fit for grindstones, ... ... ... ... | 30 | 0 |
| Red shale, ... ... ... ... ... | 8 | 0 |
| Greenish gray or drab sandstone, fit for grindstones; the top is uneven, and the whole is rather of a coarse grit. This constitutes South Ragged Reef, ... ... ... ... ... | 20 | 0 |
| Red shale, ... ... ... ... ... | 7 | 0 |
| Reddish gray sandstone, ... ... ... | 9 | 0 |
| Red argillaceous shale, ... ... ... | 3 | 6 |
| 2. Coal, ... ... ... ... 0 1 | | |
| *Dark gray carbonaceous shale*, ... 0 4 | | |
| Coal, ... ... ... ... 0 1 | | |
| | 0 | 6 |
| Red shale; the upper part is of a tough quality, and has *stigmaria ficoides* in it (*understone*), ... | 13 | 0 |
| Greenish gray or drab coloured sandstone, occasionally separated into two beds. This sandstone appears to thin out within the distance of 100 yards on the strike, ... ... ... | 33 | 0 |
| Red shale, ... ... ... ... ... | 2 | 9 |
| Greenish gray or drab coloured sandstone, ... | 5 | 0 |
| 3. Coal, ... ... ... ... ... | 0 | 1 |
| Greenish gray sandstone and reddish shale, with *stigmaria ficoides* (*understone*), ... ... | 5 | 0 |
| Reddish green argillaceous shale, ... ... | 1 | 0 |
| 4. Coal, ... ... ... ... ... | 0 | 2 |
| Reddish and green argillaceous and arenaceous shale, the green colour prevailing, with *stigmaria ficoides* (*understone*), ... ... ... | 5 | 0 |
| Reddish and green argillaceous and arenaceous shale, the red prevailing, ... ... ... | 6 | 0 |

Appendix (W.) 27th January.

Appendix (W.) 7th January.

| | Ft. | In. |
|---|---|---|
| Red shale separated by thin bands of sandstone; the top is of the tough crumbly quality of underclay, but no *stigmaria* are visible, | 24 | 0 |
| Gray sandstone and shale, the sandstone of soft quality, | 11 | 0 |
| Dark red shale, | 0 | 6 |
| Tough arenaceous shale, with *stigmaria ficoides* in the upper part in two layers, a hard and a soft one, (*understone,*) | 12 | 0 |
| Red and green crumbly tough shale of the quality of underclay, but no *stigmaria* visible, | 11 | 0 |
| Greenish gray sandstone, in four thinly laminated divisions, separated by red and green shale, | 30 | 0 |
| Gray sandstone and red shale in thin beds, | 10 | 0 |
| Red and green shale, | 2 | 0 |
| Greenish gray sandstone, with red and green shale, | 4 | 0 |
| Greenish gray sandstone, in regular beds of three feet and upwards, | 17 | 0 |
| Red shale, varying from two to seven feet thick, | 5 | 0 |
| Greenish gray sandstone, | 4 | 0 |
| Greenish shale, | 1 | 0 |
| Gray sandstone and shale, | 4 | 0 |
| Dark greenish red shale, | 2 | 0 |
| Greenish gray sandstone, | 1 | 0 |
| Dark green and red shale, | 1 | 0 |
| Greenish gray or drab coloured sandstone, fit for grindstones, forming a Reef, | 26 | 0 |
| Reddish shale, | 8 | 0 |
| Greenish gray sandstone in three beds, and gray shale in beds of one foot each, | 20 | 0 |
| Gray shale, with two beds of greenish gray sandstone of one foot each, | 20 | 0 |
| (Into the above penetrate two upright stems (*calamites,*) two inches in diameter; and replaced by sandstone with a coating of coal, they start from the top of the succeeding bed.) | | |
| Dark gray argillaceous shale, | 8 | 0 |
| 5. Coal, | 0 | 2 |
| Gray argillo-arenaceous shale (*fire clay?*) with *stigmaria ficoides* (*understone,*) | 1 | 6 |
| Gray argillo-arenaceous shale, | 10 | 0 |
| Gray sandstone, | 1 | 0 |
| Gray arenaceous shale, in two equal beds, | 7 | 0 |
| 6. Coal, | 0 | 3 |
| Gray argillo-arenaceous shale with *stigmaria ficoides,* | 2 | 0 |
| Greenish gray sandstone, | 2 | 0 |
| Gray argillaceous shale, | 1 | 0 |
| Gray argillaceous sandstone, with *stigmaria ficoides* (*understone,*) | 2 | 0 |
| Gray argillaceous shale, | 3 | 0 |
| Reddish gray sandstone, | 1 | 0 |
| Gray argillaceous shale, | 1 | 6 |
| (In this shale and running into the sandstone above, is visible a *calamite* at an angle of 45° to the plane of the deposit. It appears to start from the coal below.) | | |
| 7. Coal, | 0 | 1 |
| Gray argillaceous shale, with *stigmaria ficoides* (*underclay,*) | 1 | 6 |
| Coal, | 0 | 2 |
| Gray argillaceous shale, with *stigmaria* (*underclay,*) | 0 | 4 |
| Coal, | 0 | 1 |
| | 2 | 2 |
| Gray argillaceous shale, with *stigmaria* (*underclay,*) | 2 | 0 |
| Greenish gray crumbly sandstone, with *stigmaria* at the top, | 8 | 0 |
| Red shale, | 12 | 0 |
| Greenish gray sandstone, | 3 | 0 |
| Red shale, with some few beds of sandstone, | 20 | 0 |
| Red shale and reddish gray sandstone, in beds of one to three feet, | 12 | 0 |
| Reddish gray sandstone, in thin layers alternating with red shale, | 12 | 0 |
| Red and green arenaceous shale, | 4 | 0 |
| 8. Coal, | 0 | 1 |
| Gray argillaceous shale, with *stigmaria ficoides* (*understone,*) | 3 | 0 |
| Gray argillaceous sandstone with *stigmaria ficoides* (*understone,*) | 2 | 0 |
| Hard argillo-arenaceous shale with *stigmaria ficoides* (*understone,*) | 5 | 0 |
| Red shale, | 20 | 0 |
| Greenish gray or drab coloured sandstone forming a reef, | 20 | 0 |
| Red shale, | 23 | 0 |
| Reddish gray sandstone, | 5 | 0 |
| Red shale and greenish gray sandstone; not much sandstone, | 30 | 0 |
| Red argillaceous shale and greenish gray sandstone, more sandstone than before, | 30 | 0 |
| Red argillaceous shale, | 1 | 0 |

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| | Ft. | In. |
|---|---|---|
| Reddish gray sandstone, | 1 | 0 |
| Red argillaceous shale, | 3 | 0 |
| Reddish gray sandstone, | 2 | 0 |
| Red argillaceous shale, | 12 | 0 |
| Greenish gray sandstone, | 15 | 0 |
| Red argillaceous shale, | 20 | 0 |
| Reddish sandstone, | 2 | 0 |
| Red and green shale, | 8 | 0 |
| Reddish gray sandstone, | 6 | 0 |
| Red shale, | 2 | 0 |
| Greenish gray sandstone, | 2 | 0 |
| Red argillaceous shale, | 3 | 0 |
| Greenish gray sandstone, | 3 | 0 |
| Greenish gray sandstone, fit for grindstones, which are now quarried from it. This constitutes North Ragged Reef, | 12 | 0 |
| Reddish gray sandstone in beds of one to three or four feet, separated by beds of reddish shale of one to two feet, | 60 | 0 |
| Red shale, | 4 | 0 |
| Reddish sandstone, | 2 | 0 |
| Red argillaceous shale, | 20 | 0 |
| Greenish gray sandstone in beds of two to three feet, with beds of red shale of one to two feet, | 30 | 0 |
| Red argillaceous shale, | 6 | 0 |
| Reddish sandstone separated at the top into moderate layers by red shale, | 27 | 0 |
| Red shale, | 2 | 0 |
| Reddish sandstone, | 1 | 0 |
| Red argillaceous shale, | 35 | 0 |
| Gray sandstone and red argillaceous shale in alternating beds, the sandstone has a reddish tinge towards the top, | 30 | 0 |
| Gray sandstone, | 1 | 0 |
| Reddish argillaceous shale, | 6 | 0 |
| Gray sandstone, | 1 | 0 |
| Reddish argillaceous shale, | 5 | 0 |
| Gray sandstone, | 2 | 0 |
| Reddish and gray shale, | 1 | 0 |
| Gray sandstone, | 2 | 0 |
| Reddish argillaceous shale with *ironstone* balls, | 3 | 0 |
| Gray sandstone, | 1 | 0 |
| Green and red argillaceous shale, | 2 | 0 |
| Hard argillo-arenaceous shale, | 1 | 0 |
| Gray argillaceous shale, with *ironstone* balls. This bed has something the appearance of underclay, but the *stigmaria* are not distinct, | 7 | 0 |
| 9. Coal, | 0 | 3 |
| Gray arenaceous shale with *ironstone* balls, and *stigmaria ficoides* (*underclay,*) | 5 | 0 |
| Reddish gray argillaceous shale, | 1 | 0 |
| 10. Coal and *carbonaceous* shale, | 0 | 5 |
| Gray argillaceous shale with *ironstone* balls and *stigmaria ficoides* (*underclay,*) | 2 | 0 |
| Coal, | 0 | 2 |
| | 2 | 10 |
| Gray argillaceous sandstone with *stigmaria ficoides* (*underclay,*) | 2 | 0 |
| Reddish and green argillo-arenaceous shale with *ironstone* balls. This has much the character of underclay, but the *stigmaria* are not well marked, | 12 | 0 |
| Gray sandstone, | 1 | 0 |
| Gray argillaceous shale with *ironstone* balls, | 3 | 0 |
| Greenish gray sandstone, | 4 | 0 |
| Gray argillaceous shale, | 1 | 0 |
| (From the succeeding layer of coal there springs up an erect *sigillaria.* It is 1 ft. 6 in. in diameter, and penetrates the shale and sandstone above it, five feet of the plant being visible.) | | |
| 11. Coal, | 0 | 3 |
| Gray sandstone with *stigmaria ficoides* (*underclay,*) | 2 | 0 |
| Gray argillaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay,*) | 3 | 0 |
| 12. *Black carbonaceous shale,* | 0 | 9 |
| Coal, | 0 | 2 |
| | 0 | 11 |
| Gray argillaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay,*) | 1 | 6 |
| Greenish gray sandstone, | 1 | 6 |
| Gray argillaceous shale, | 9 | 0 |
| 13. Coal, | 0 | 7 |
| Gray argillaceous shale with *ironstone* balls and *stigmaria ficoides* (*underclay,*) | 2 | 0 |
| Gray argillaceous shale, | 3 | 0 |
| 14. Coal, | 0 | 4 |
| Gray argillo-arenaceous shale with *ironstone* balls and *stigmaria ficoides* (*underclay.*) | 1 | 6 |
| Coal, | 0 | 2 |
| | 2 | 0 |

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| | Ft. | In. |
|---|---|---|
| Gray argillaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay,*) ... ... | 7 | 0 |
| Gray argillo-arenacious shale with *ironstone* balls, and *stigmaria ficoides* (*underclay,*) ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Greenish gray sandstone and red and gray argillo-arenaceous shale. The sandstone is not in thick beds. *Ironstone* balls and *stigmaria ficoides* are found through the whole deposit, ... | 40 | 0 |
| Greenish gray argillaceous shale, ... ... | 3 | 0 |
| 15. *Carbonaceous shale,* ... ... 0 2 | | |
| Grey argillaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay,*) ... ... ... 1 0 | | |
| Coal, ... ... ... ... 0 1 | | |
| | 1 | 3 |
| Gray argillaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay,*) ... ... | 3 | 0 |
| Greenish gray sandstone with three bands of red and gray shale, loaded with *ironstone* balls, ... | 12 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| 16. Coal and *carbonaceous shale,* ... ... | 0 | 2 |
| Red argillaceous shale with *ironstone* balls and *stigmaria ficoides* (*underclay,*) ... ... | 7 | 0 |
| Greenish gray sandstone, ... ... ... | 10 | 0 |
| Red and green shale, ... ... ... ... | 2 | 0 |
| Rough gray argillaceous sandstone, ... ... | 2 | 0 |
| Red and green shale, ... ... ... ... | 2 | 0 |
| Rough greenish gray argillaceous sandstone, ... | 1 | 6 |
| Red and green shale, ... ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 5 | 0 |
| Red and green argillaceous shale, ... ... | 7 | 0 |
| 17. Coal, ... ... ... ... 0 1 | | |
| Gray argillo-arenaceous shale, with *stigmaria ficoides* (*underclay,*) ... 4 0 | | |
| Coal, ... ... ... 0 4 | | |
| *Carbonaceous shale,* ... 0 4 | | |
| Coal, ... ... ... 0 1 0 9 | | |
| | 4 | 10 |
| Gray sandstone with 3 inches of soft gray argillaceous shale at the top, and penetrated by *stigmaria ficoides* (*understone,*) ... ... ... | 1 | 3 |
| Gray argillo-arenaceous shale, ... ... ... | 1 | 0 |
| 18. Coal, ... ... ... ... | 0 | 3 |
| Gray arenaceous shale with *stigmariæ* (*underclay,*)... | 2 | 0 |
| Gray argillaceous sandstone with *stigmariæ* (*underclay,*) ... ... ... ... ... | 2 | 0 |
| Red and green shale, ... ... ... ... | 3 | 0 |
| Greenish gray sandstone in several layers, ... | 6 | 0 |
| Red and green argillaceous shale, ... ... | 7 | 0 |
| Gray sandstone with *stigmariæ* (*understone,*) ... | 2 | 0 |
| Red and green argillo-arenaceous shale, ... ... | 4 | 0 |
| 19. Coal, ... ... ... ... ... | 0 | 1 |
| Red argillaceous shale with *stigmariæ* (*underclay,*) ... | 4 | 0 |
| Greenish gray sandstone and red shale alternating, the sandstone in 7 beds of 2 to 8 feet, the shale in 5 beds of ½ to 3 feet, ... ... ... | 60 | 0 |
| Red and gray argillaceous shale, ... ... | 13 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Greenish gray shale and sandstone, ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Greenish gray shale, ... ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Measures concealed, ... ... ... ... | 41 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Measures concealed, ... ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Measures concealed. Here occurs Dennis River, ... | 9 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |
| Measures concealed, but supposed to be shale, ... | 4 | 0 |
| Greenish gray and drab coloured sandstone, fit for grindstones. There are quarries in it on the South Reef, Dennis River, ... ... ... | 25 | 0 |
| Red argillo-arenaceous shale, ... ... ... | 9 | 0 |
| Greenish gray or drab coloured sandstone fit for grindstones. Some are quarried from the bed on the North Reef, Dennis River, ... ... | 18 | 0 |
| Measures concealed, but supposed to be argillaceous shale, ... ... ... ... ... | 4 | 0 |
| Greenish gray or drab sandstone, almost fit for grindstones, ... ... ... ... ... | 14 | 0 |
| Greenish gray argillaceous shale, ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Dark gray argillaceous shale, ... ... ... | 1 | 0 |
| 20. Coal, ... ... ... ... ... | 0 | 1 |
| Red and green shale with *stigmaria ficoides,* (*underclay*), ... ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Red and greenish gray argillaceous shale, with *ironstone* balls, ... ... ... ... | 6 | 0 |
| *Carbonaceous shale,* ... ... ... | 0 | 3 |
| Gray crumbly argillo-arenaceous shale, with *stigmaria ficoides* (*underclay*), ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Reddish shale, with *ironstone* balls, ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 4 | 0 |
| Red argillaceous shale, with *ironstone* balls, ... ... | 23 | 0 |
| Greenish gray sandstone, with red and green shale studded with *ironstone* balls, ... ... | 4 | 0 |
| Red and greenish gray argillaceous and arenaceous shale, in beds of five feet, with greenish gray sandstone, in beds of one to three feet, ... | 30 | 0 |
| Reddish and greenish gray argillaceous shale, with *ironstone* balls, ... ... ... ... ... | 15 | 0 |
| Greenish gray sandstone, soft, with beads of red arenaceous shale, ... ... ... ... | 21 | 0 |
| Red argillaceous shale, ... ... ... ... | 2 | 0 |
| 21. Coal, ... ... ... ... ... | 0 | 2 |
| Greenish gray argillo-arenaceous shale, with *stigmaria* (*underclay*), ... ... ... ... | 2 | 0 |
| Measures concealed, ... ... ... ... | 35 | 0 |
| Greenish gray sandstone of good grit, ... ... | 4 | 0 |
| Measures concealed, ... ... ... ... | 7 | 0 |
| Greenish gray sandstone of good grit, ... ... | 1 | 0 |
| Measures concealed, ... ... ... ... | 13 | 0 |
| Greenish gray arenaceous shale, ... ... ... | 1 | 0 |
| Measures concealed, ... ... ... ... | 43 | 0 |
| Measures concealed, but probably sandstone, ... | 7 | 0 |
| Measures not perfectly seen, but consisting in part of greenish gray *sandstone,* ... ... | 13 | 0 |
| Greenish gray sandstone, with impressions and casts of *calamites.* This layer is almost fit for grindstones, but not sufficiently regular to be worked profitably, ... ... ... ... | 13 | 0 |
| Measures not well seen, supposed to be red shale, ... | 22 | 0 |
| Red and greenish gray argillo-arenaceous shale, the red prevailing, with some beads of greenish gray sandstone of six to twelve inches, ... ... | 40 | 0 |
| Reddish and greenish gray sandstone, in beds of three to ten feet, separated by layers of red and greenish gray arenaceous shale of one to two feet. This forms Dennis River Point, ... ... | 31 | 0 |
| Greenish gray sandstone, soft and ragged, in aggregated beds of one to ten feet; the aggregations separated by beds of dark red and green argillaceous and arenaceous shale of one to two feet, having *ironstone* balls; impressions of plants, among them *sigillariæ* and *calamites,* prevail in the sandstone, ... ... ... ... ... | 60 | 0 |
| Dark red and green argillaceous shale, with six beds of red and greenish gray sandstone; the shale is loaded with *ironstone* balls, ... ... | 40 | 0 |
| 22. Coal *and Carbonaceous shale,* ... ... | 0 | 2 |
| Gray argillo-arenaceous shale of a tough quality, with *stigmariæ* (*underclay*), ... ... ... | 4 | 0 |
| Dark red and green argillaceous shale, with a band of sandstone, ... ... ... ... | 16 | 0 |
| Gray argillaceous and arenaceous shale, with *ironstone* nodules and some thin beds of sandstone, | 10 | 0 |
| Gray sandstone, with *stigmaria* (*understone*), ... | 2 | 0 |
| Dark gray shale, with *ironstone* nodules, ... ... | 22 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... ... | 2 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Greenish gray arenaceous shale, ... ... | 6 | 0 |
| Gray sandstone, in layers of four inches each, ... | 4 | 0 |
| | 2,134 | 1 |

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RECAPITULATION.

| | | | |
|---|---|---|---|
| Coal, in 22 seams, ... ... | 5 | 5 | |
| Carbonaceous shale associated with the coal seams, and in one instance without coal, ... | 3 | 10 | |
| | | | 9 3 |
| Underclay or understone, being beds of various material, immediately subjacent to the seams of Coal and Carbonaceous shale, and universally penetrated by the branches and radiating leaves of the stigmaria ficoides. Every one of the Coal and Carbonaceous seams rests upon a bed of this description, and in two cases stigmaria beds exist without superincumbent coal. The material constituting the stigmaria beds is as follows: | | | |
| Sandstone—Gray, 23 3 | | | |
| Greenish gray or drab, 43 0 | | | |
| | | | 66 3 |
| Argillaceous and arenaceous shale, hav- | | | |

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| | | | Ft. | In. |
|---|---|---|---|---|
| Gray, ... ... | 38 | 4 | | |
| Greenish gray, ... | 7 | 0 | | |
| Red and occasionally green, | 42 | 0 | | |
| | | 107 4 | | |
| | | | 173 | 7 |
| Sandstone— | | | | |
| Gray, ... ... | 82 | 0 | | |
| Greenish gray chiefly fit for grindstones, | 627 | 0 | | |
| Reddish of various shades, ... ... | 204 | 0 | | |
| | | | 913 | 0 |
| Shale—Gray—Argillaceous, | 92 | 6 | | |
| Arenaceous, | 44 | 0 | | |
| | | 136 6 | | |
| Red and green— | | | | |
| Argillaceous, | 564 | 0 | | |
| Arenaceous, | 104 | 9 | | |
| | | 668 9 | | |
| | | | 805 | 3 |
| Measures concealed, supposed to be chiefly shale, ... ... ... | | | 263 | 0 |
| | | | 2,134 | 1 |

(Among the organic remains visible are one oblique and two upright calamites, and one upright sigillaria. One top-stone bed of shale contains impressions of ferns.)

4.

| | | | Ft. | In. |
|---|---|---|---|---|
| 1. *Bituminous limestone*, with *shells* and *fish scales*, ... ... ... ... | | | 4 | 0 |
| Coal, ... ... ... ... | | | 1 | 0 |
| | | | 5 | 0 |
| Greenish gray argillo-arenaceous shale, with *stigmaria ficoides* (*underclay*), ... ... | | | 4 | 0 |
| Gray sandstone in courses of six and nine inches, with *ironstone* balls and *stigmaria ficoides* (*understone*), ... ... ... ... | | | 2 | 6 |
| Gray argillaceous shale, ... ... ... | | | 1 | 0 |
| Gray sandstone, ... ... ... | | | 6 | 0 |
| Gray argillaceous shale, ... ... ... | | | 1 | 0 |
| Gray sandstone of a rough texture, ... ... | | | 1 | 0 |
| (From the succeeding bed springs an upright stem (*sigillaria*). It widens towards the bottom, and penetrates into the sandstone above.) | | | | |
| Gray argillaceous shale, with *ironstone* balls, .... | | | 6 | 0 |
| Gray sandstone and arenaceous shale, ... ... | | | 3 | 0 |
| Gray arenaceous shale, ... ... ... | | | 2 | 0 |
| Hard gray arenaceous shale, with *stigmaria ficoides* (*underclay*), ... ... — ... ... | | | 1 | 6 |
| Gray argillaceous shale, ... ... ... | | | 20 | 0 |
| 2. Coal and *Carbonaceous shale*, ... ... | | | 1 | 0 |
| Soft gray argillo-arenaceous shale, with *stigmaria ficoides* (*underclay*,) ... ... ... | | | 1 | 0 |
| Hard gray arenaceous shale with *stigmaria ficoides* (*underclay*,) ... ... ... ... | | | 2 | 0 |
| Gray argillaceous shale, ... ... ... | | | 1 | 0 |
| 3. Coal and *Carbonaceous shale*, ... ... | | | 0 | 3 |
| Hard argillo-arenaceous shale, with *stigmaria ficoides* (*underclay*,) ... ... ... ... | | | 2 | 0 |
| Gray argillaceous shale, ... ... ... | | | 4 | 0 |
| 4. Coal, ... ... ... | 0 | 9 | | |
| *Carbonaceous shale*, ... | 0 | 6 | | |
| Coal, ... ... ... | 0 | 1 | | |
| *Carbonaceous shale*, ... | 0 | 4 | | |
| Coal, ... ... ... | 0 | 1 | | |
| *Carbonaceous shale*, ... | 0 | 8 | | |
| Coal, ... ... ... | 0 | 2 | | |
| | | | 2 | 7 |
| Gray argillaceous shale, no *stigmaria* visible, but across the bed appear two parallel regular cracks, about ¼ of an inch wide each, and about 18 inches apart, filled with coal, the fibre of which is at right angles to the cracks. This may be the section of an upright stem, ... ... | | | 1 | 7 |
| Coal, ... ... ... ... | | | 0 | 8 |
| | | | 4 | 10 |
| Hard gray argillo-arenaceous shale with *stigmaria ficoides* (*underclay*,) ... ... ... | | | 4 | 0 |
| Greenish argillaceous shale, with *ironstone* balls, ... | | | 12 | 0 |
| Gray sandstone in several layers, ... ... | | | 1 | 0 |
| Red and green argillaceous shale, with *ironstone* balls, ... ... ... ... | | | 20 | 0 |
| Gray sandstone and green shale in alternating layers, | | | 24 | 0 |

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| | | | Ft. | In. |
|---|---|---|---|---|
| Red or chocolate coloured argillaceous shale, ... | | | 3 | 0 |
| (From the succeeding bed rises an upright *sigillaria* one foot in diameter; two feet of it are seen penetrating the bed above.) | | | | |
| Gray argillaceous shale, ... ... ... | | | 1 | 6 |
| Gray sandstone in thin beds, ... ... ... | | | 8 | 0 |
| Gray argillaceous shale, ... ... ... | | | 8 | 0 |
| 5. *Bituminous limestone*, with *shells*, ... | 2 | 0 | | |
| Coal, ... ... ... ... | 0 | 0½ | | |
| Gray argillo-arenaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay*,) ... ... ... | 0 | 6 | | |
| *Carbonaceous shale*, ... ... | 0 | 0½ | | |
| Gray argillo-arenaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay*,) ... ... ... | 1 | 6 | | |
| *Carbonaceous shale*, ... ... | 0 | 1 | | |
| Gray argillo-arenaceous shale, with *ironstone* balls and *stigmaria ficoides* (*underclay*,) ... ... ... | 2 | 6 | | |
| Coal, ... ... ... ... | 0 | 6 | | |
| | | | 7 | 2 |
| Gray argillo-arenaceous shale, with *stigmaria* leaves, (*underclay*,) ... ... ... ... | | | 2 | 0 |
| Gray arenaceous shale, with *stigmaria* leaves (*underclay*,) ... ... ... ... ... | | | 6 | 0 |
| Gray arenaceous shale and rough argillaceous sandstone, ... ... ... ... ... | | | 9 | 0 |
| Greenish gray arenaceous shale, ... ... | | | 5 | 0 |
| Gray sandstone, ... ... ... ... | | | 3 | 0 |
| Red and green argillaceous shale with *ironstone* balls, | | | 7 | 0 |
| Gray rough sandstone, ... ... ... | | | 17 | 0 |
| Red argillaceous shale, with *ironstone* balls; thin beds of arenaceous shale and sandstone in the middle, ... ... ... ... | | | 10 | 0 |
| Red sandstone, ... ... ... ... | | | 1 | 0 |
| Red argillaceous shale, with *ironstone* balls, ... | | | 1 | 0 |
| Red sandstone, ... ... ... ... | | | 1 | 0 |
| Red and green shale, with *ironstone* balls and some arenaceous beds, ... ... ... ... | | | 18 | 0 |
| Gray sandstone, ... ... ... ... | | | 2 | 0 |
| Gray arenaceous shale, ... ... ... | | | 4 | 0 |
| Green and red shale, ... ... ... ... | | | 3 | 0 |
| Gray sandstone, ... ... ... ... | | | 3 | 0 |
| (From the upper part of the succeeding bed there arises an upright *sigillaria*.) | | | | |
| Gray argillaceous shale, ... ... ... | | | 17 | 0 |
| Gray argillaceous shale, with a layer of sandstone, | | | 3 | 0 |
| Gray sandstone, ... ... ... ... | | | 0 | 6 |
| Greenish gray argillaceous shale, ... ... | | | 17 | 0 |
| Gray sandstone, ... ... ... ... | | | 1 | 0 |
| Gray argillaceous shale, with *ironstone* balls and a few bands of arenaceous shale, ... ... ... | | | 17 | 0 |
| 6. *Carbonaceous shale*, ... ... | 1 | 0 | | |
| *bituminous limestone*, with *shells*, ... | 0 | 10 | | |
| Coal, ... ... ... | 0 | 4 | | |
| | | | 2 | 2 |
| Gray argillo-arenaceous shale, with *stigmaria* (*underclay*,) ... ... ... ... | | | 2 | 0 |
| Rough gray argillaceous sandstone, with the branches and leaves of *stigmaria ficoides* (*underclay*,) ... | | | 7 | 0 |
| (An upright *stem* penetrating the above bed springs from the one below.) | | | | |
| Gray argillaceous shale, with *ironstone* nodules, ... | | | 1 | 0 |
| Gray sandstone, ... ... ... ... | | | 1 | 0 |
| Gray argillaceous shale, with *ironstone* nodules, ... | | | 2 | 0 |
| Gray arenaceous shale, ... ... ... | | | 10 | 0 |
| Gray sandstone, ... ... ... ... | | | 3 | 0 |
| Gray argillaceous shale, ... ... ... | | | 2 | 0 |
| Gray sandstone, ... ... ... ... | | | 2 | 0 |
| 7. Coal, ... ... ... ... | 0 | 10 | | |
| *Carbonaceous shale*, ... ... | 0 | 2 | | |
| Coal, ... ... ... ... | 0 | 10 | | |
| *Carbonaceous shale*, ... ... | 0 | 2 | | |
| Coal, ... ... ... ... | 2 | 0 | | |
| Coal and *Carbonaceous shale*, ... | 0 | 6 | | |
| | | | 4 | 6 |
| Gray argillaceous shale, with *stigmaria* (*underclay*,) | | | 6 | 0 |
| Gray argillaceous shale, loaded with a multitude of *ironstone* balls, ... ... ... ... | | | 10 | 0 |
| Gray argillaceous shale in beds of 1 to 3 feet, with sandstone and arenaceous shale in beds of 1 foot; *ironstone* nodules are very numerous in the whole, ... ... ... ... ... | | | 20 | 0 |
| Gray argillaceous shale, with *ironstone* nodules, ... | | | 9 | 0 |
| Gray sandstone, ... ... ... ... | | | 3 | 0 |
| Gray argillaceous shale, with *ironstone* nodules, ... | | | 10 | 0 |
| Gray sandstone, ... ... ... ... | | | 1 | 0 |
| Gray argillaceous shale, ... ... ... | | | 2 | 0 |

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| | Ft. | In. |
|---|---|---|
| (From the succeeding bed springs an upright *sigillaria* of 1 foot in diameter; the lower part commences to spread.) | | |
| Gray argillaceous shale, with *ironstone* balls and some sandstone, ... ... ... ... | 2 | 0 |
| Gray argillaceous shale, with *ironstone* balls, ... | 3 | 0 |
| 8. Coal, ... ... ... ... ... | 0 | 2 |
| Gray argillaceous shale, ... ... | 0 | 4 |
| Coal, ... ... ... ... ... | 0 | 3 |
| *Carbonaceous shale and Coal*, ... | 1 | 3 |
| Coal, ... ... ... ... ... | 0 | 1 |
| Gray argillaceous shale, with *ironstone* balls and *stigmaria* (*underclay*,) ... | 4 | 0 |
| Coal, ... ... ... ... ... | 1 | 0 |
| | 7 | 1 |
| Gray argillo-arenaceous shale, with *ironstone* balls in abundance and *stigmariæ ficoides* (*underclay*), | 6 | 0 |
| Gray rough crumbly sandstone, ... ... | 9 | 0 |
| Dark gray shale, with *ironstone* balls, ... ... | 1 | 0 |
| Gray arenaceous shale, ... ... ... | 3 | 0 |
| Gray sandstone, ... ... ... ... | 3 | 0 |
| Red argillaceous shale (chocolate coloured), ... | 10 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale as before, ... ... | 10 | 0 |
| Gray rough sandstone, ... ... ... | 3 | 0 |
| Red argillaceous shale, as before, in beds of 1 to 4 feet, with *ironstone* balls, and separated by beds of gray sandstone of 1 foot, ... ... | 20 | 0 |
| Gray rough sandstone, in beds of 1 to 2 feet, alternating with beds of red or chocolate coloured shale of 1 foot, ... ... ... ... | 15 | 0 |
| Gray soft sandstone, ... ... ... ... | 1 | 0 |
| Red shale, ... ... ... ... ... | 1 | 0 |
| Gray rough sandstone, ... ... ... | 1 | 6 |
| Gray arenaceous shale, with *stigmaria* (*underclay*), | 2 | 0 |
| Gray crumbly arenaceous shale, with *ironstone* balls, | 6 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 0 |
| Gray crumbly sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 0 | 10 |
| Gray sandstone, with *stigmariæ* and upright *calamites* (*understone*), ... ... ... | 1 | 6 |
| Gray argillaceous shale, with *ironstone* balls, ... | 1 | 10 |
| Gray rough crumbly sandstone, ... ... | 0 | 10 |
| Gray argillaceous shale, with *ironstone* balls and *stigmariæ ficoides* (*underclay*),... ... ... | 10 | 0 |
| 9. Coal and *Carbonaceous shale*, ... ... | 1 | 3 |
| Greenish gray argillaceous shale, with *stigmariæ ficoides* (*underclay*), ... ... ... ... | 12 | 0 |
| Gray rough sandstone, with *stigmariæ* (*underclay*),... | 3 | 0 |
| Red argillaceous shale, with *ironstone* balls, ... | 2 | 0 |
| Reddish sandstone, ... ... ... ... | 2 | 0 |
| Red or chocolate coloured argillaceous shale, with *ironstone* balls, ... ... ... ... | 5 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... ... | 1 | 6 |
| Red or chocolate coloured and green argillaceous shale, ... ... ... ... ... | 3 | 0 |
| 10. Coal and *Carbonaceous shale*, ... | 0 | 2 |
| *Carbonaceous shale*, ... ... | 0 | 6 |
| Coal, ... ... ... ... | 0 | 4 |
| | 1 | 0 |
| Argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*), ... ... ... ... | 1 | 0 |
| Measures concealed, probably underclay. Here occurs Bell's Brook, ... ... ... | 5 | 0 |
| Red and green shale as before, ... ... ... | 9 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale and gray arenaceous shale, ... | 3 | 0 |
| Red and green shale, as before, ... ... ... | 3 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 0 |
| Red and green shale, as before, ... ... ... | 7 | 0 |
| Gray sandstone, ... ... ... ... | 3 | 0 |
| Red and green shale, as before, ... ... ... | 3 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Red or chocolate coloured argillaceous shale, ... | 2 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Red and green shale, as before, ... ... ... | 5 | 0 |
| Red or chocolate coloured argillaceous shale, ... | 1 | 0 |
| Gray arenaceous shale, ... ... ... | 14 | 0 |
| Gray sandstone, rough and uneven, ... ... | 12 | 0 |
| (From the top of the succeeding bed spring several upright *calamites*, 3 of them in the distance of 2 feet, and 8 more—the whole 11, in the distance of 20 feet.) | | |
| Gray crumbly argillaceous shale, like *underclay*, but no *stigmariæ* visible, ... ... ... | 2 | 0 |
| Greenish sandstone, ... ... ... ... | 0 | 6 |
| Red or chocolate coloured argillaceous shale, ... | 3 | 0 |
| 11. Coal and *carbonaceous shale*, ... ... | 0 | 8 |
| Gray argillaceous shale, with *stigmariæ ficoides* (*underclay*), ... ... ... ... | 7 | 0 |
| Gray rough sandstone and arenaceous shale, in alternate layers, ... ... ... ... | 12 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| Gray arenaceous shale, ... ... ... | 6 | 0 |
| Strong gray arenaceous shale and rough sandstone, | 4 | 0 |
| Gray argillaceous shale, ... ... ... | 6 | 0 |
| 12. Coal and *carbonaceous shale*, ... ... | 1 | 0 |
| Gray argillaceous shale, with *stigmaria ficoides* and *ironstone* balls (*underclay*),... ... ... | 2 | 0 |
| Gray argillaceous sandstone, with *stigmariæ* (*understone*), ... ... ... ... ... | 3 | 0 |
| Dark gray argillaceous shale, ... ... ... | 8 | 0 |
| 13. Coal and *carbonaceous shale*, ... ... | 0 | 6 |
| Gray argillaceous shale, with *stigmariæ* and *ironstone* balls (*underclay*), ... ... ... | 2 | 0 |
| Gray argillaceous sandstone, with *stigmariæ* (*underclay*), ... ... ... ... ... | 2 | 0 |
| Red and green shale, as before, ... ... ... | 7 | 0 |
| Gray argillaceous sandstone, with *stigmariæ* (*understone*), ... ... ... ... ... | 1 | 0 |
| Red and green argillaceous shale, with *stigmariæ ficoides* (*underclay*), ... ... ... | 7 | 0 |
| Gray sandstone and shale, ... ... ... | 1 | 0 |
| Red or chocolate coloured and green argillaceous shale, ... ... ... ... ... | 3 | 0 |
| Gray soft shaly sandstone, ... ... ... | 1 | 0 |
| Measures concealed, but supposed to be soft, ... | 7 | 0 |
| Greenish gray soft sandstone, ... ... ... | 4 | 0 |
| Measures concealed, but supposed to be soft, ... | 2 | 0 |
| Gray sandstone, ... ... ... ... | 4 | 0 |
| Measures concealed, but supposed to be soft, ... | 2 | 0 |
| Reddish green sandstone, ... ... ... | 3 | 0 |
| Gray sandstone and shale, ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |
| Green arenaceous shale, ... ... ... | 1 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 6 | 0 |
| Green and red shale, ... ... ... ... | 3 | 0 |
| Gray sandstone, with a bed of argillaceous shale, ... | 2 | 0 |
| Greenish gray argillaceous shale, with *ironstone* balls, | 17 | 0 |
| Reddish green sandstone, ... ... ... | 1 | 0 |
| (In this are upright *calamites*—3 of them in the space of 1 foot.) | | |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| Gray rough sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| Greenish gray or drab coloured sandstone; grindstones have been quarried from this, but they are too hard for the best quality. This constitutes Coal Mine Point, ... ... ... | 30 | 0 |
| Gray argillaceous shale, with balls of *ironstone*, ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, with balls of *ironstone*, ... | 3 | 0 |
| 14. Coal, ... ... ... 0 3 | | |
| *Carbonaceous shale*, ... 0 2 | | |
| Coal, ... ... ... 0 3 | | |
| 0 8 | | |
| Gray argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*), ... 6 0 | | |
| *Carbonaceous shale*, ... 0 4 | | |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), 1 0 | | |
| *Carbonaceous shale*, ... 0 8 | | |
| Coal, ... ... ... 0 2 | | |
| 2 2 | | |
| | 8 | 10 |
| Gray argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*,) ... ... ... ... | 2 | 6 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Gray argillo-arenaceous shale, with bands of sandstone, ... ... ... ... ... | 2 | 0 |
| (From the succeeding bed there spring up erect *calamites*, penetrating the above bed 2 feet; 2 of them are within 2 feet of one another, and there are 7 more in the space of 8 feet.) | | |
| 15. *Carbonaceous shale*, ... ... 1 0 | | |
| Coal, ... ... ... 0 4 | | |
| | 1 | 4 |
| Gray crumbly sandstone and shale, with *stigmariæ* (*underclay*), ... ... ... ... | 2 | 0 |
| Gray crumbly sandstone, very like *underclay*, but no *stigmariæ* visible, ... ... ... ... | 12 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... ... | 5 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Dark red shale, with *ironstone* balls, ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 5 | 0 |
| Dark red shale, ... ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |

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| | Ft. | In. |
|---|---|---|
| Dark red or chocolate coloured argillaceous shale, ... | 6 | 0 |
| Greenish gray sandstone, and red or chocolate coloured shale of an argillo-arenaceous character, ... | 12 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ*, and some beds of sandstone with *stigmariæ* leaves crossing them (*underclay*), ... ... ... | 12 | 0 |
| Gray crumbly sandstone, with beds of argillaceous shale, and *ironstone* balls, very like *underclay*, but no *stigmariæ* visible, ... ... ... | 25 | 0 |
| 16. Coal and *carbonaceous shale*, ... ... | 0 | 6 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 10 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| Gray soft sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 0 | 6 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 4 | 0 |
| Gray argillaceous shale, ... ... ... | 6 | 0 |
| 17. Coal and *carbonaceous shale*, ... ... | 0 | 3 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 2 | 0 |
| Gray argillaceous sandstone, ... ... ... | 14 | 0 |
| Gray argillaceous shale, ... ... ... | 11 | 0 |
| 18 Coal, ... ... ... ... ... | 0 | 8 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 1 | 6 |
| Gray soft flaggy sandstone, ... ... ... | 3 | 6 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) | 3 | 0 |
| Gray arenaceous shale, with *stigmariæ* (*underclay*,) | 3 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 4 | 0 |
| Gray soft flaggy sandstone, with *stigmariæ* at the top (*understone*,) ... ... ... | 3 | 0 |
| Fine gray argillo-arenaceous shale, ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Dark gray argillaceous shale, ... ... | 6 | 0 |
| 19. *Carbonaceous shale*, ... ... ... | 4 | 0 |
| *Bituminous limestone*, with *shells* and *fish scales*, ... ... ... | 2 | 6 |
| Coal, ... ... ... ... | 0 | 1 |
| | 6 | 7 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... | 2 | 6 |
| Greenish gray sandstone, ... ... ... | 6 | 0 |
| Gray argillaceous shale, ... ... ... | 12 | 0 |
| 20. *Black bituminous shale*, ... ... | 1 | 0 |
| *Black bituminous limestone*, with *shells*, | 1 | 6 |
| Coal, ... ... ... ... | 0 | 6 |
| | 3 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*,) ... ... ... ... | 2 | 6 |
| Greenish gray sandstone, ... ... ... | 4 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 6 |
| (From the top of the succeeding bed springs an upright *sigillaria* 10 inches in diameter; 2 feet 6 inches of it are visible.) | | |
| 21. Coal and *carbonaceous shale*, ... | 0 | 3 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 1 | 6 |
| Gray argillaceous sandstone, with *stigmariæ* (*underclay*,) ... ... | 7 | 0 |
| Gray argillaceous shale, ... ... | 4 | 0 |
| Coal, ... ... ... ... | 0 | 8 |
| | 13 | 5 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) | 2 | 0 |
| Gray argillaceous sandstone, with *stigmariæ* (*underclay*,) ... ... ... ... | 3 | 0 |
| Gray argillaceous shale, ... ... | 9 | 0 |
| Greenish gray crumbly sandstone, ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 3 | 0 |
| 22. Coal and *carbonaceous shale*, ... ... | 0 | 2 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) | 1 | 0 |
| Greenish gray argillaceous sandstone, with *stigmariæ* (*underclay*,) ... ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |
| (From the succeeding bed springs an upright *sigillaria* 4 inches in diameter; of it 3 feet are seen. On the beach there was a transverse slice of a *sigillaria* 1 foot 6 inches in diameter, with fragments of plants on the divisional surfaces.) | | |
| Argillaceous shale, ... ... ... ... | 2 | 0 |
| 23. *Carbonaceous shale*, with some layers of argillaceous shale, ... ... | 4 | 0 |
| Coal and *carbonaceous shale*, ... | 0 | 4 |
| *Bituminous limestone*, with minute shells and *stigmariæ ficoides*, ... | 0 | 4 |
| Coal and *carbonaceous shale*, ... | 1 | 0 |
| | 5 | 8 |

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| | Ft. | In. |
|---|---|---|
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... ... | 1 | 0 |
| Gray crumbly argillo-arenaceous shale, very like *underclay* in quality, but no *stigmariæ* visible, ... | 5 | 0 |
| Gray sandstone, ... ... ... ... | 3 | 0 |
| Gray crumbly argillo-arenaceous shale, or sandstone, with *stigmariæ*, (*underclay*,) ... ... | 6 | 0 |
| (From the top of the succeeding bed springs an upright *sigillaria*. Its roots spread out into the shale. It is coated with coal, and the material of the interior cast is not of uniform quality, being partly sandstone and partly shale. The shale occupies a transverse portion about 6 inches thick, and is rather less than half way up the stem, of which about 6 feet are visible, running into the underclay above. From the root of the plant, as if it had wound round or been pushed aside by the root, proceeds a *stigmaria* branch. It runs horizontally a short distance, and then turns up vertically. The leaves proceeding from the vertical portion, are not at right angles to the branch, but in part at least assume a vertical direction, and run parallel with it; those emanating from the grooved side (in ordinary cases the under part or belly of the branch) taking a downward, and those from the back an upward, course. The leaves issuing from the sides may be at right angles to the branch, and run horizontally into the bed, but being thus concealed they could not be traced. At first sight the stigmaria branch had much the appearance of being a continuation of the root of the sigillaria, but close inspection shewed that the two, although touching, were distinct. The former rested on the latter nearly one-eighth of a circle, but being then suddenly cut off, it may when entire have wound much further round, and the carbonaceous envelopes of the two plants were clearly discernible. *See fig. 5.*) | | |
| Gray argillaceous shale, ... ... ... | 10 | 0 |
| 24. *Bituminous limestone*, with *shells* and *cone in cone*, ... ... ... | 1 | 0 |
| Coal and *carbonaceous shale*, ... | 0 | 1 |
| | 1 | 1 |
| Gray argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*,) ... ... ... ... | 2 | 0 |
| Gray argillaceous shale, ... ... ... | 3 | 0 |
| 25. Coal and *carbonaceous shale*, ... ... | 0 | 8 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,)... | 2 | 0 |
| Greenish gray sandstone, with *stigmariæ* leaves (*underclay*,) ... ... ... | 6 | 0 |
| Greenish gray sandstone, ... ... ... | 9 | 0 |
| Greenish gray sandstone and shale, ... ... | 4 | 0 |
| Gray argillaceous shale, with *ironstone* balls, ... | 2 | 0 |
| Greenish gray sandstone, with some beds of arenaceous shale, ... ... ... ... | 20 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 25 | 0 |
| Gray argillaceous shale, ... ... ... | 10 | 0 |
| Gray sandstone, ... ... ... ... | 7 | 0 |
| (From the succeeding bed springs an upright *sigillaria* 1 foot 6 inches in diameter. It penetrates through the sandstone.) | | |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 10 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| 26. *Carbonaceous shale*, ... ... ... | 0 | 4 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) | 3 | 0 |
| Gray crumbly sandstone, being probably argillaceous; it contains *stigmariæ* leaves (*underclay*,) ... | 8 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| 27. Coal, ... ... ... ... ... | 0 | 3 |
| Gray argillo-arenaceous shale, with *stigmariæ* leaves (*underclay*,) ... ... ... ... | 5 | 0 |
| Greenish gray sandstone, with shale dividing the beds; in the lower part is an upright *calamite* which springs from the succeeding bed, ... | 4 | 0 |
| Gray argillaceous and arenaceous shale, with *ironstone* balls and a few beds of sandstone, ... | 14 | 0 |
| Greenish gray sandstone in 3 beds divided by argillo-arenaceous shale,... ... ... ... | 12 | 0 |
| Gray argillaceous shale, ... ... ... | 3 | 0 |
| Gray argillaceous shale, with *ironstone* balls and one course of sandstone, ... ... ... | 13 | 0 |
| Greenish gray sandstone, ... ... ... | 4 | 0 |
| Gray argillaceous shale, with *ironstone* nodules, ... | 3 | 0 |

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| | | | Ft. | In. |
|---|---|---|---|---|
| 28. | *Bituminous limestone* and *carbonaceous shale* in alternate layers of 1 to 3 inches, with *plants*, *shells* and *fish scales*, ... ... ... | 6 0 | | |
| | Coal and *carbonaceous shale*—not much coal, ... ... | 3 0 | | |
| | Coal and *carbonaceous shale*—a good deal of coal, ... | 4 0 | | |
| | | 7 0 | | |
| | Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... | 4 0 | | |
| | *Carbonaceous shale*, ... | 1 0 | | |
| | Coal, ... ... ... | 0 6 | | |
| | | 1 6 | | |
| | | | 18 | 6 |
| | Gray rough sandstone, with *stigmariæ* leaves (*underclay*,) ... ... ... ... ... | | 3 | 0 |
| | Greenish gray argillaceous shale, with *ironstone* balls, ... ... ... ... ... | | 6 | 0 |
| | Gray sandstone, ... ... ... ... | | 6 | 0 |
| | Greenish gray argillaceous shale, with nodules of *ironstone* disseminated through it, ... ... ... | | 7 | 0 |
| | Gray argillo-arenaceous shale, with *ironstone* balls and small seams of *coal*, ... ... ... | | 7 | 0 |
| | (From the succeeding bed rises an upright *sigillaria*; the roots spread on the top of it; the diameter of the plant is a foot; only 1 foot of the length is visible.) | | | |
| 29. | Coal and *carbonaceous shale*; the coal being a small seam on the top of the carbonaceous shale, ... ... | 2 0 | | |
| | Gray argillo-arenaceous shale, with *stigmariæ* and *ironstone* balls disseminated through it (*underclay*,)... | 2 0 | | |
| | Coal, ... ... ... | 1 8 | | |
| | *Carbonaceous shale*, ... | 0 3 | | |
| | Coal, ... ... ... | 0 11 | | |
| | *Carbonaceous shale*, ... | 0 4 | | |
| | Coal, ... ... ... | 0 10 | | |
| | | 4 0 | | |
| | Gray argillo-arenaceous shale, with *stigmariæ* leaves crossing the bed (*underclay*,) ... ... ... | 8 0 | | |
| | *Carbonaceous shale*, gray argillo-arenaceous shale, with *stigmariæ* and small seams of *coal*, ... ... ... | 6 0 | | |
| | Coal and *carbonaceous shale*, | 0 6 | | |
| | Gray argillaceous shale, ... | 0 6 | | |
| | Coal, ... ... ... | 0 6 | | |
| | | 1 6 | | |
| | Gray argillaceous shale (*underclay?*) | 0 10 | | |
| | *Bituminous limestone*, with *plants*, *shells* and *fish scales*, ... ... ... | 0 3 | | |
| | | | 24 | 7 |
| | Gray argillo arenaceous shale, with *ironstone* nodules and *stigmariæ* leaves (*underclay*), ... ... | | 7 | 0 |
| | Gray arenaceous shale and sandstone; the sandstone exhibits some *stigmariæ* leaves crossing it, and in the shale are *ironstone* nodules (*underclay*), ... | | 20 | 0 |
| | (From the succeeding bed rises an upright fluted stem (*sicillaria*) 10 inches in diameter, of which 12 feet are visible; and 2 upright *calamites*.) | | | |
| | Gray argillaceous shale with *ironstone* balls, ... | | 6 | 0 |
| 30. | Coal, ... ... ... ... | 0 4 | | |
| | Dark gray argillaceous shale (*underclay?*) ... ... ... | 2 0 | | |
| | Coal and *carbonaceous shale*, ... | 0 2 | | |
| | Coal, ... ... ... ... | 0 3 | | |
| | *Carbonaceous shale*, ... ... | 0 6 | | |
| | Coal, ... ... ... ... | 0 1 | | |
| | | 3 4 | | |
| | Gray soft clay (*underclay?*) ... ... ... | | 2 | 0 |
| | Gray argillo-arenaceous shale and sandstone; the shale contains balls of *ironstone* at the bottom; there are *stigmariæ* leaves visible towards the top; towards the lower part of the bed of sandstone there is an upright *calamite* of 2 inches diameter, of which 18 inches are visible, ... | | 15 | 0 |
| | Gray sandstone, with impressions of prostrate *sigillariæ* underneath, ... ... ... | | 2 | 0 |
| 31. | Coal and *carbonaceous shale*, ... | 1 0 | | |
| | Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... | 1 0 | | |
| | Gray argillaceous shale, with streaks of *coal*, ... | 0 6 | | |
| | Coal, ... ... ... | 0 2 | | |
| | | 0 8 | | |
| | Gray argillaceous shale, with *ironstone* balls and *stigmariæ* leaves (*underclay*), ... ... ... | 9 0 | | |
| | Bituminous limestone, with *stigmariæ*, *shells* and *fish scales*, ... ... | 0 2 | | |
| | | | 11 | 10 |

| | | Ft. | In. |
|---|---|---|---|
| | Gray sandstone, ... ... ... ... | 1 | 0 |
| | Gray argillaceous shale, with *ironstone* balls, ... | 7 | 0 |
| | Gray sandstone, ... ... ... ... | 2 | 0 |
| | Gray argillaceous shale, with *ironstone* balls, ... | 4 | 0 |
| | Gray sandstone, ... ... ... ... | 6 | 6 |
| | Gray argillaceous shale, ... ... ... | 4 | 0 |
| 32. | Coal, ... ... ... ... 0 8 | | |
| | *Carbonaceous shale*, ... ... 0 1 | | |
| | Coal, ... ... ... 0 8 | | |
| | *Carbonaceous shale*, ... ... 0 1 | | |
| | Coal, ... ... ... 0 4 | | |
| | *Carbonaceous shale*, ... ... 0 2 | | |
| | Coal, ... ... ... 0 1 | | |
| | *Carbonaceous shale*, ... ... 0 1 | | |
| | Coal, ... ... ... 0 1 | | |
| | | 2 | 4 |
| | Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*,) ... ... ... ... ... | 4 | 0 |
| | Greenish gray argillo-arenaceous sandstone, with *stigmariæ feroules* (*underclay*), ... ... | 1 | 0 |
| | Greenish gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 4 | 0 |
| | Greenish gray sandstone, with *stigmariæ* (*underclay*), | 4 | 0 |
| | Greenish argillaceous shale, ... ... ... | 6 | 0 |
| | Reddish sandstone, with dividing bands of red shale of 3 inches to 1 foot, ... ... ... | 20 | 0 |
| | Reddish sandstone. The bed is of irregular thickness, the bottom swelling out suddenly in many places. The bed holds carbonized plants, ... | 2 | 0 |
| | (From the top of the succeeding bed there springs an upright *sigillaria*. Two feet of the length is seen, but it is cut clean off at the top and at the bottom by the measures, which pass both without disturbance. *See fig.* 6.) | | |
| | Red argillaceous shale, ... ... ... | 3 | 0 |
| | Reddish arenaceous shale, with thin bands of sandstone, ... ... ... ... ... | 3 | 0 |
| | Reddish and greenish sandstone, ... ... | 4 | 0 |
| | Red and green arenaceous shale with *ironstone* balls, and some bands of sandstone, ... ... | 23 | 0 |
| | Red and green sandstone, ... ... ... | 12 | 0 |
| | Reddish and greenish argillaceous shale, loaded with *ironstone* balls, and having bands of sandstone, | 10 | 0 |
| | Reddish and greenish sandstone, ... ... | 10 | 0 |
| | Red and green argillaceous shale, loaded with *ironstone* nodules, ... ... ... ... | 10 | 0 |
| | Red and green sandstone, ... ... ... | 3 | 0 |
| | Greenish gray argillaceous shale, ... ... | 13 | 0 |
| | Greenish gray sandstone, ... ... ... | 2 | 0 |
| | (From the succeeding bed there starts an upright *sigillaria* 4 inches in diameter; it is planted 2 feet in it, and penetrates the sandstone above, being 4 feet in length altogether.) | | |
| | Greenish gray argillaceous shale, ... ... | 6 | 0 |
| 33. | *Carbonaceous shale*, ... ... 1 0 | | |
| | Coal, ... ... ... ... 0 1 | | |
| | | 1 | 1 |
| | Greenish-gray argillaceous shale, with *stigmariæ* leaves (*underclay*), ... ... ... | 4 | 0 |
| | Red and gray sandstone, with arenaceous shale, ... | 7 | 0 |
| | Red argillaceous shale, with a band of sandstone, ... | 4 | 0 |
| | Red sandstone, with bands of red arenaceous shale, | 10 | 0 |
| | Red and green argillaceous shale, ... ... | 20 | 0 |
| | Reddish sandstone, ... ... ... ... | 1 | 0 |
| | Red and green argillaceous shale, ... ... | 3 | 0 |
| | Reddish sandstone in uneven layers, with reddish bands of arenaceous shale, ... ... ... | 18 | 0 |
| | Red and green argillaceous shale, ... ... | 18 | 0 |
| | Reddish sandstone, ... ... ... ... | 2 | 0 |
| | Red arenaceous shale,... ... ... ... | 3 | 0 |
| | Red and green argillaceous shale, ... ... | 4 | 0 |
| | Reddish sandstone, ... ... ... ... | 1 | 0 |
| | Red and green arenaceous shale, ... ... | 4 | 0 |
| | Reddish sandstone, ... ... ... ... | 1 | 0 |
| | Red and green arenaceous shale, ... ... | 7 | 0 |
| | Reddish sandstone, ... ... ... ... | 1 | 0 |
| | Red argillaceous shale, ... ... ... | 3 | 0 |
| | Red and green argillaceous shale, with bands of sandstone, ... ... ... ... ... | 23 | 0 |
| | Red sandstone, ... ... ... ... | 1 | 0 |
| | Red and green shale, with bands of sandstone, ... | 12 | 0 |
| | Red and green sandstone, ... ... ... | 4 | 0 |
| | Red and green argillaceous shale, with bands of reddish sandstone, ... ... ... ... | 13 | 0 |
| | Red and green sandstone and shale, ... ... | 3 | 0 |
| | Red or chocolate coloured shale, with large balls of red argillaceous *ironstone*, ... ... ... | 12 | 0 |
| | Red and green sandstone, separated by bands of red and green argillaceous shale of about 1 foot each, | 30 | 0 |

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| | Ft. | In. |
|---|---|---|
| Red or chocolate coloured argillaceous shale, with some balls of red argillaceous *ironstone*, ... | 12 | 0 |
| Reddish sandstone, ... ... ... ... | 4 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 6 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 2 | 0 |
| Reddish sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale, with a band of sandstone, ... | 12 | 0 |
| Gray sandstone, with *ironstone* nodules and *stigmariæ* leaves (*underclay*), ... ... ... | 10 | 0 |
| (From the succeeding bed arise 2 upright *sigillariæ*. The roots of one of them spread out just on the top of the bed, and 2 feet of the plant are visible. The roots of the other spread out likewise, but they sink deeper into the shale by 2 feet, and the plant penetrates farther into the superincumbent sandstone. *See fig.* 7.) | | |
| Red and dark gray variegated shale, with small balls of *ironstone* and *stigmariæ* (*underclay*), ... | 28 | 0 |
| Gray sandstone, ... ... ... ... | 2 | 0 |
| Greenish shale, with *ironstone* balls and *stigmariæ ficoides* (*underclay*), ... ... ... | 4 | 0 |
| 34. *Carbonaceous shale and coal*, ... | 0 | 2 |
| Greenish gray argillaceous shale, with *ironstone* balls and *stigmariæ* branches and leaves; one of the branches, replaced by *ironstone*, is 6 feet long, | 4 | 0 |
| *Carbonaceous shale*, ... ... | 0 | 2 |
| | 4 | 4 |
| Gray argillo-arenaceous shale, with black streaks and *stigmariæ* (*underclay*), ... ... ... | 3 | 0 |
| Gray sandstone, with *stigmariæ* (*understone*), ... | 0 | 10 |
| Red and green argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 4 | 0 |
| Gray crumbly sandstone, ... ... ... | 3 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 3 | 0 |
| 35. *Carbonaceous shale*, ... ... ... | 0 | 3 |
| Red and green argillaceous shale, with *stigmariæ* leaves at the top (*underclay*), ... ... | 6 | 0 |
| Argillaceous *ironstone*, in a bed, ... ... | 0 | 6 |
| Red and green argillaceous shale, ... ... | 1 | 0 |
| Gray sandstone, with *stigmariæ* leaves (*underclay*), | 1 | 0 |
| Greenish gray argillaceous shale, with dark bands; *argillaceous iron ore* nodules abound, and towards the top *stigmariæ* branches and leaves are visible (*underclay*), ... ... ... | 28 | 0 |
| Greenish gray crumbly sandstone, ... ... | 8 | 0 |
| Gray argillaceous shale, with *ironstone* balls. In this there is visible an upright stem (*sigillaria*), 1 foot in diameter; the top only is visible, and it is at the top of the bed, ... ... ... | 12 | 0 |
| 36. *Black bituminous limestone*, with branches and leaves of *stigmariæ* well marked, and very minute *shells*, ... | 1 | 3 |
| *Carbonaceous shale* and streaks of *coal*, | 0 | 3 |
| | 1 | 6 |
| Red argillaceous shale, with *ironstone* (*underclay?*) | 4 | 0 |
| Gray argillo-arenaceous shale, with *stigmariæ* and *ironstone* balls (*underclay*), ... ... ... | 6 | 0 |
| Gray argillaceous shale, with *ironstone* balls, ... | 5 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 0 |
| Gray argillaceous shale, ... ... ... | 5 | 0 |
| 37. *Dark bituminous limestone*, with *shells*, replaced by pyrites, ... ... | 0 | 3 |
| Coal and *carbonaceous shale*, ... | 0 | 10 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 1 | 6 |
| Coal, ... ... ... ... | 0 | 6 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 1 | 0 |
| *Dark bituminous limestone*, with *stigmaria* branches and leaves, and also *shells*, ... ... ... | 0 | 3 |
| Gray argillaceous shale, ... ... | 0 | 3 |
| Coal, ... ... ... ... | 1 | 0 |
| | 5 | 7 |
| Gray argillaceous shale of a crumbly character, with *ironstone* balls and *stigmariæ* (*underclay*), ... | 6 | 0 |
| Greenish gray rough sandstone, ... ... | 4 | 0 |
| Dark gray argillaceous shale, with *ironstone* balls, ... | 7 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Red argillaceous shale, with *ironstone* balls, ... | 8 | 0 |
| Red and green sandstone, with bands of red argillaceous shale under 8 inches thick, ... ... | 6 | 0 |
| Red argillaceous shale, with bands of sandstone under 8 inches thick, ... ... ... | 20 | 0 |
| Reddish sandstone, hard, ... ... ... | 1 | 0 |
| Red argillaceous shale, with balls of *ironstone*, ... | 4 | 0 |
| Reddish sandstone, hard, ... ... ... | 0 | 3 |
| Green argillaceous shale, ... ... ... | 0 | 6 |

| | Ft. | In. |
|---|---|---|
| Greenish gray sandstone, with carbonized fragments of drift plants, ... ... ... ... | 1 | 0 |
| Dark gray argillaceous shale, with a red band near the top, ... ... ... ... | 10 | 0 |
| 38. Coal, ... ... ... ... | 0 | 1 |
| *Black bituminous limestone*, with *shells* and *plants*, *stigmariæ* branches and leaves, ... ... ... | 0 | 6 |
| Coal, ... ... ... ... | 0 | 2 |
| | 0 | 9 |
| Red argillaceous shale, studded with *ironstone* balls; *stigmariæ* not visible (*underclay?*)... ... | 10 | 0 |
| Reddish sandstone, ... ... ... ... | 2 | 0 |
| Green arenaceous shale, with red argillaceous bands, | 15 | 0 |
| Red and green sandstone, ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |
| Green arenaceous shale, ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 3 | 0 |
| Green arenaceous shale, ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 3 | 0 |
| *Gray bituminous limestone*, with *minute shells*, ... | 0 | 6 |
| Red argillaceous shale, with *ironstone* balls, ... | 11 | 0 |
| Green and dark gray argillaceous shale, with *ironstone* balls, ... ... ... ... | 14 | 0 |
| Red and green argillaceous shale, with *ironstone* balls; in this are some dark bands of shale, ... | 25 | 0 |
| Greenish gray sandstone, with a confused mass of carbonized drift plants, ... ... ... | 10 | 0 |
| Greenish gray sandstone, ... ... ... | 2 | 6 |
| Red argillaceous shale, with a band of sandstone, ... | 2 | 0 |
| Gray and black shale, ... ... ... ... | 3 | 0 |
| *Carbonaceous shale*, ... ... ... ... | 1 | 0 |
| Red and green argillaceous shale, studded with *ironstone* balls; no *stigmariæ* visible (*underclay?*) | 13 | 0 |
| 39. Coal, ... ... ... ... | 0 | 0½ |
| Gray argillaceous shale, with *stigmariæ*, | 0 | 6 |
| *Dark gray limestone*, with *stigmariæ* branches and leaves, and minute *shells*, ... ... ... | 0 | 4 |
| | 0 | 10½ |
| Red and green argillaceous shale, with *stigmariæ* leaves (*underclay*), ... ... ... | 1 | 6 |
| Red and green sandstone, ... ... ... | 1 | 0 |
| Red argillaceous shale, with some green and gray bands; the whole containing thin bands of sandstone, ... ... ... ... ... | 18 | 0 |
| Greenish gray sandstone, ... ... ... | 8 | 0 |
| Dark red and green argillaceous shale, studded with *ironstone* balls, ... ... ... ... | 15 | 0 |
| Gray hard argillaceous sandstone, ... ... | 1 | 0 |
| Dark gray argillaceous shale, with *ironstone* balls in considerable number, with some red argillaceous beds, ... ... ... ... ... | 20 | 0 |
| 40. *Black bituminous limestone*, with *shells*, | 0 | 1½ |
| *Carbonaceous shale*, ... ... | 0 | 0½ |
| *Black bituminous limestone*, with *shells*, | 0 | 1 |
| Gray argillaceous shale, ... ... | 0 | 2 |
| *Black bituminous limestone*, with *shells*, | 0 | 2 |
| Gray argillaceous shale, with *ironstone* balls (*underclay?*) ... ... | 1 | 0 |
| Coal, ... ... ... ... | 0 | 1 |
| *Carbonaceous shale*, with thin seams of *coal*, ... ... ... ... | 0 | 3 |
| Gray argillo-arenaceous shale, with *stigmariæ ficoides* (*underclay*,) ... | 1 | 0 |
| *Black bituminous limestone*, with *shells* and *stigmaria*, ... ... ... | 0 | 6 |
| *Carbonaceous shale* and thin laminæ of *coal*, ... ... ... ... | 0 | 2 |
| | 3 | 7 |
| Green argillaceous shale, with many coarse nodules of clay *ironstone*, all small, and impressions of *stigmariæ* leaves crossing the bed (*underclay*), | 5 | 0 |
| 41. *Black calcareo-bituminous shale*, with *shells*, ... ... ... | 0 | 8 |
| *Black calcareo-bituminous shale*, more calcareous, with *shells*, ... ... | 0 | 2 |
| *Black calcareo-bituminous shale*, less calcareous, with *shells*, ... ... | 1 | 0 |
| *Carbonaceous shale*, with laminæ of coal, | 1 | 6 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) ... ... ... | 3 | 0 |
| *Carbonaceous shale*, ... ... | 0 | 1 |
| | 6 | 5 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*,) | 2 | 0 |
| Greenish gray argillo-arenaceous shale, in alternate hard and soft layers, with *stigmariæ* leaves (*underclay*), ... ... ... ... | 2 | 6 |
| Greenish gray sandstone, ... ... ... | 2 | 0 |
| Dark gray argillaceous shale, studded with *ironstone* nodules, ... ... ... ... | 4 | 0 |

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| | Ft | In. |
|---|---|---|
| 42. *Carbonaceous shale*, ... ... | 0 | 7 |
| *Black bituminous limestone*, with *shells* replaced by pyrites, ... ... | 0 | 2 |
| Coal, ... ... ... ... | 0 | 3 |
| *Carbonaceous shale*, ... ... | 1 | 0 |
| Coal, ... ... ... ... | 1 | 0 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 1 | 0 |
| Coal, ... ... ... ... | 0 | 2 |
| | 4 | 2 |
| Dark gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 5 | 0 |
| Red argillaceous shale, with some green bands, and studded with *ironstone* balls, ... ... | 25 | 0 |
| Reddish sandstone, ... ... ... | 1 | 0 |
| Red argillaceous shale, with *stigmariæ* (*underclay*,) | 4 | 0 |
| 43. *Carbonaceous shale*, ... ... ... | 0 | 1 |
| Red shale, with *stigmariæ* (*underclay*), ... | 0 | 3 |
| Gray sandstone, very hard, (*ganister*, as the Lancashire miners call it,) with *stigmariæ*, ... ... ... ... | 0 | 8 |
| Red argillaceous shale, with *stigmariæ* (*underclay*,) ... ... ... | 3 | 0 |
| Gray sandstone, very hard, with *stigmariæ* (*ganister* or *understone*), ... | 0 | 10 |
| Gray argillaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 0 | 10 |
| Gray sandstone, very hard, with *stigmariæ* (*understone*), ... ... | 1 | 0 |
| Gray sandstone, very hard, with *stigmariæ* leaves running across the bed, (*ganister* or *understone*,) ... ... | 2 | 0 |
| | 8 | 7 |
| Red argillaceous shale, green at the bottom, ... | 15 | 0 |
| Gray arenaceous and argillaceous shale, with greenish gray sandstone containing prostrate carbonized plants, ... ... ... ... | 12 | 0 |
| (Into this bed penetrate several upright *calamites* which start from the one subjacent, on the top of which one of 3 inches in diameter is seen to spread its roots, and 21 more are visible along the face of the bank in the space of 20 yards their diameters vary from ½ inch to 4 inches.) | | |
| Dark gray argillaceous shale, ... ... ... | 2 | 0 |
| Gray sandstone, ... ... ... ... | 1 | 0 |
| Dark gray argillaceous shale, ... ... ... | 15 | 0 |
| Gray sandstone, ... ... ... ... | 0 | 4 |
| Dark gray argillaceous shale, with *ironstone* balls and bands of sandstone, ... ... ... | 4 | 0 |
| Dark gray argillaceous shale, with *ironstone* balls, ... | 5 | 0 |
| 44. *Carbonaceous shale*, ... ... | 1 | 6 |
| Dark gray argillaceous shale, ... | 2 | 0 |
| *Carbonaceous shale*, with *ironstone* balls, | 0 | 4 |
| Dark gray argillaceous shale, with *ironstone* balls, ... ... ... | 6 | 0 |
| *Black bituminous limestone*, with *shells*, | 0 | 1½ |
| Dark green argillaceous shale, ... | 0 | 1½ |
| Coal, ... ... ... ... | 0 | 0½ |
| *Black bituminous limestone*, with *plants* and minute *shells*, ... ... | 0 | 0½ |
| Coal, ... ... ... ... | 0 | 5 |
| *Black bituminous limestone*, with *stigmariæ* and other plants, ... ... | 0 | 2 |
| Coal, ... ... ... ... | 0 | 1 |
| *Black bituminous limestone*, with *stigmariæ* branches and leaves, and fragments of other plants, ... ... | 0 | 2 |
| Coal, ... ... ... ... | 0 | 0½ |
| | 11 | 0½ |
| Gray crumbly argillo-arenaceous shale, with indistinct *stigmariæ* leaves (*underclay*,) ... ... | 3 | 0 |
| Red and green crumbly argillaceous shale (*underclay*,) | 10 | 0 |
| Red and green sandstone, ... ... ... | 5 | 0 |
| Red or chocolate coloured argillaceous shale, ... | 1 | 6 |
| Reddish sandstone, ... ... ... ... | 1 | 0 |
| Red or chocolate coloured argillaceous shale, ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 9 | 0 |
| Red argillaceous shale, with thin green beds and some patches of sandstone, ... ... | 40 | 0 |
| Red shale, with a considerable number of small beds of sandstone, ... ... ... ... | 6 | 0 |
| Greenish gray sandstone, with upright *calamites* about 2 inches in diameter; some of them are traceable for 4 feet in the upper part of the bed; 6 of them are visible; the top of the bed is reddish in colour, ... ... ... ... | 10 | 0 |
| Red argillaceous shale, studded with *ironstone* balls, | 10 | 0 |
| Gray hard argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |

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| | Ft | In. |
|---|---|---|
| 45. *Carbonaceous shale*, ... ... | 0 | 10 |
| Coaly matter, ... ... ... | 0 | 0½ |
| Gray hard argillo-arenaceous stone, with *stigmariæ* (*underclay*), ... ... | 2 | 0 |
| Coaly matter, ... ... ... ... | 0 | 0½ |
| Green argillaceous shale, with *stigmariæ* (*underclay*), ... ... | 7 | 0 |
| Coal, ... ... ... ... | 0 | 3 |
| | 10 | 4 |
| Greenish gray arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... ... | 3 | 0 |
| Red arenaceous and argillaceous shale, with sandstone, ... ... ... ... | 2 | 0 |
| Red sandstone of a soft quality, ... ... | 0 | 6 |
| | 2539 | 1 |

RECAPITULATION.

| | | | |
|---|---|---|---|
| Coal in 45 seams, ... ... | | 37 | 9½ |
| Carbonaceous shale associated with the above coal seams, and in one instance without coal, ... ... ... | | 36 | 4 |
| Gray argillaceous shale interstratified with the coal seams in 8 cases, in two of which the shale is 1 foot and upwards thick without exhibiting any remains of stigmariæ, ... | | 4 | 4½ |
| Black and gray bituminous limestone touching the coal and carbonaceous shale, often interstratified, and containing the remains of fishes, shells, and occasionally stigmariæ. In one instance the limestone has no coal with it, in 16 cases it is associated with the coal seams, ... ... | | 23 | 3 |
| | | 101 | 9 |

Underclay or understone, being beds of various material, immediately subjacent to the seams of coal and carbonaceous shale and bituminous limestone, and invariably penetrated by the recumbent branches or radiating leaves of the stigmaria ficoides. Every one of the seams of coal and carbonaceous shale rests upon a stigmaria bed with the exception of one instance, where 4 feet of gray argillaceous shale, destitute of the plant, is interposed between the stigmaria bed and the coal, and one instance where the stigmariæ are doubtful. There are 12 instances of stigmariæ beds without superincumbent coal. The material constituting the stigmariæ beds is as follows:

| | | | |
|---|---|---|---|
| Ganister, a hard siliceous stone, ... ... | | | |
| Sandstone— | | | |
| Gray and crumbly, sometimes a doubtful fireclay, ... | 72 | 10 | |
| Greenish gray, ... | 4 | 0 | |
| | | 76 | 10 |
| Arenaceous shale, often fit for fireclay— | | | |
| Gray, ... ... | 189 | 0 | |
| Greenish gray, ... | 25 | 6 | |
| Red, ... ... | 6 | 0 | |
| | | 220 | 6 |
| Argillaceous shale, sometimes fit for fireclay— | | | |
| Gray, ... ... | 99 | 4 | |
| Greenish gray, ... | 29 | 0 | |
| Green, ... | 12 | 10 | |
| Red and green, | 45 | 0 | |
| Red, ... ... | 17 | 3 | |
| | | 202 | 5 |
| | | 504 | 3 |

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| | | | Ft. | In. |
|---|---|---|---|---|
| Sandstone— | | | | |
| Gray in colour, and much of it of a crumbly nature, resembling the quality in which the remains of stigmariæ are found, ... ... ... | | | 259 | 2 |
| Greenish, ... ... ... | | | 4 | 6 |
| Greenish gray or drab coloured, some of it fit for grindstones, and patches of it containing carbonized drift plants, ... | | | 232 | 6 |
| Red and green, less durable in quality than the drab coloured stone, ... ... ... | | | 69 | 0 |
| Reddish, similar to the preceding in durability, ... ... | | | 67 | 3 |
| Red or chocolate coloured, easily yielding to the influence of weather, ... ... | | | 15 | 6 |
| | | | 647 | 11 |
| Shale—Arenaceous— | | | | |
| Gray, ... ... | 91 | 0 | | |
| Gray, with ironstone balls, ... ... | 13 | 0 | | |
| | | | 104 | 0 |
| Greenish gray, ... ... | | | 3 | 0 |
| Green, ... ... | | | 18 | 6 |
| Reddish, ... ... | | | 15 | 8 |
| Red and green, ... | 42 | 0 | | |
| Red and green, with ironstone balls, ... | 4 | 0 | | |
| | | | 46 | 0 |
| | | | 189 | 2 |
| Shale—Argillaceous— | | | | |
| Gray, ... ... | 224 | 8 | | |
| Gray, with ironstone balls, ... ... | 199 | 4 | | |
| | | | 424 | 0 |
| Greenish gray, ... | 32 | 0 | | |
| Greenish gray, with ironstone balls, ... | 17 | 0 | | |
| | | | 49 | 0 |
| Green, ... ... | | | 38 | 6 |
| Red and green, ... | 153 | 6 | | |
| Red and green, with ironstone balls, ... | 118 | 6 | | |
| | | | 272 | 0 |
| Red or chocolate coloured, ... | 230 | 6 | | |
| Red or chocolate coloured, with ironstone balls, ... | 82 | 0 | | |
| | | | 312 | 6 |
| | | | 1096 | 0 |
| | | | 2330 | 1 |

(Among the organic remains visible, are to be enumerated 13 upright sigillariæ and 56 upright calamites.)

5.

| | Ft. | In. |
|---|---|---|
| Red argillaceous shale, with ironstone balls, ... | 6 | 0 |
| Red arenaceous shale, ... ... ... | 2 | 0 |
| Red argillaceous shale, with beds of arenaceous shale, | 16 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 22 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 7 | 0 |
| Red argillaceous shale, with a bed of sandstone, ... | 38 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale, with a bed of red sandstone, | 50 | 0 |
| Measures concealed, but supposed to be red shale and sandstone, ... ... ... ... | 19 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Measures concealed, (red shale and sandstone?) ... | 33 | 0 |
| Greenish gray soft sandstone with fragments of plants carbonized, ... ... ... ... | 3 | 0 |
| Measures concealed, ... ... ... | 32 | 0 |
| Measures concealed, (red shale and sandstone?) a bed of sandstone at the top, ... ... | 39 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |
| Measures concealed, (red shale and sandstone?) ... | 19 | 0 |
| Measures concealed, (red shale and sandstone?) a bed of red sandstone at the top, ... ... | 60 | 0 |
| Red sandstone, ... ... ... ... | 30 | 0 |
| Measures concealed, (red shale?) ... ... | 3 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Measures concealed (red shale and sandstone?) | 40 | 0 |
| Red shale, with some red sandstone, ... ... | 33 | 0 |
| Measures concealed, (red shale and sandstone,) ... | 30 | 0 |

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| | Ft. | In. |
|---|---|---|
| Reddish gray sandstone, ... ... ... | 3 | 0 |
| Measures concealed, ... ... ... | 3 | 0 |
| Red and gray sandstone of a soft quality, ... | 32 | 0 |
| Red arenaceous shale and sandstone, ... ... | 6 | 0 |
| Reddish gray sandstone, of a soft quality, ... | 6 | 0 |
| Red argillaceous and arenaceous shale, ... ... | 20 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 25 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red argillaceous and arenaceous shale, ... ... | 12 | 0 |
| Red sandstone and shale, ... ... ... | 8 | 0 |
| Red shale and sandstone, ... ... ... | 54 | 0 |
| Measures concealed, (red shale?) ... ... | 12 | 0 |
| Measures concealed, (red sandstone and shale?) ... | 3 | 0 |
| Measures concealed, (red shale?) ... ... | 28 | 0 |
| Red shale and sandstone, ... ... ... | 11 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Measures concealed, but supposed to be red shale, ... | 6 | 0 |
| Measures concealed; but supposed to be red sandstone, ... ... ... ... ... | 12 | 0 |
| Measures concealed, but supposed to be red shale, ... | 138 | 0 |
| Red arenaceous shale, with some beds of red sandstone, ... ... ... ... ... | 12 | 0 |
| Red arenaceous shale with some beds of red sandstone, ... ... ... ... ... | 43 | 0 |
| Red sandstone, ... ... ... ... | 17 | 0 |
| Red arenaceous shale, ... ... ... | 14 | 0 |
| Measures concealed, ... ... ... | 30 | 0 |
| Red sandstone, ... ... ... ... | 6 | 0 |
| Measures concealed, but supposed to be red shale and sandstone, ... ... ... ... | 6 | 0 |
| Reddish gray sandstone, ... ... ... | 2 | 0 |
| Measures concealed, but supposed to be red shale and sandstone, ... ... ... ... | 5 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Measures concealed, but supposed to be red sandstone, ... ... ... ... ... | 44 | 0 |
| Red shale and sandstone, ... ... ... | 12 | 0 |
| Measures concealed, but supposed to be red shale and sandstone, ... ... ... ... | 33 | 0 |
| Red argillaceous and arenaceous shale with some beds of red sandstone, ... ... ... | 132 | 0 |
| Red sandstone, ... ... ... ... | 3 | 0 |
| Red arenaceous shale and sandstone, ... ... | 17 | 0 |
| Greenish gray sandstone, with patches of concretionary limestone, ... ... ... ... | 13 | 0 |
| Red argillaceous and arenaceous shale, ... ... | 51 | 0 |
| Reddish sandstone, ... ... ... ... | 17 | 0 |
| Measures concealed, ... ... ... ... | 37 | 0 |
| Reddish green sandstone, ... ... ... | 24 | 0 |
| Measures concealed, ... ... ... ... | 17 | 0 |
| Reddish gray sandstone, ... ... ... | 18 | 0 |
| Measures concealed, ... ... ... ... | 19 | 0 |
| Reddish sandstone, ... ... ... ... | 6 | 0 |
| Measures concealed, probably red shale, ... ... | 73 | 0 |
| Reddish gray sandstone, soft, with fragments of plants carbonized, ... ... ... ... | 22 | 0 |
| Measures concealed, but supposed to be red shale, ... | 37 | 0 |
| Red and green sandstone, with probably some patches of concretionary limestone, ... ... | 37 | 0 |
| Red argillaceous and arenaceous shale, with bands of sandstone, ... ... ... ... | 35 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red argillaceous and arenaceous shale, with bands of sandstone, ... ... ... ... | 18 | 0 |
| Red sandstone, ... ... ... ... | 3 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 9 | 0 |
| Green argillaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 5 | 0 |
| Red argillaceous and arenaceous shale, with some beds of red sandstone, ... ... ... | 50 | 0 |
| Greenish gray sandstone, ... ... ... | 7 | 0 |
| Greenish gray sandstone, with concretions of limestone giving it much the appearance of a conglomerate, | 1 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |
| Red and green sandstone, ... ... ... | 6 | 0 |
| Green shale, ... ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Greenish gray sandstone, with many calcareous concretions, giving it much the appearance of a conglomerate, ... ... ... ... | 6 | 0 |
| Red arenaceous and argillaceous shale, with some beds of sandstone, ... ... ... | 17 | 0 |
| Red argillaceous shale and sandstone, ... ... | 16 | 0 |
| Red arenaceous and argillaceous shale, with some sandstone, ... ... ... ... | 8 | 0 |
| Red argillaceous shale, ... ... ... | 6 | 0 |
| Red arenaceous shale, with some bands of sandstone, | 6 | 0 |
| Red sandstone, ... ... ... ... | 12 | 0 |
| Red argillaceous shale, ... ... ... | 1 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous and arenaceous shale, with a two feet bed of sandstone, ... ... ... | 29 | 0 |

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| | Ft. | In. |
|---|---|---|
| Red sandstone, thinning off and replaced by red shale, | 5 | 0 |
| Red argillaceous shale, | 5 | 0 |
| Red sandstone, | 2 | 0 |
| Red argillaceous shale, | 3 | 0 |
| Red arenaceous shale, | 1 | 0 |
| Red argillaceous shale, | 3 | 0 |
| Red arenaceous shale and sandstone, | 3 | 0 |
| Red argillaceous shale, | 22 | 0 |
| Reddish sandstone, | 7 | 0 |
| Reddish sandstone with a one foot bed, having calcareous concretionary nodules, and resembling a conglomerate, with carbonized plants on the top, | 16 | 0 |
| Red argillaceous and arenaceous shale, | 20 | 0 |
| Red sandstone, | 8 | 0 |
| Red arenaceous shale and argillaceous shale, | 12 | 0 |
| Red sandstone and shale, half of each, | 12 | 0 |
| Red argillaceous shale, | 3 | 0 |
| Red arenaceous shale, | 1 | 0 |
| Red sandstone, | 3 | 0 |
| Red arenaceous shale, | 7 | 0 |
| Red sandstone, | 3 | 0 |
| Red arenaceous shale, | 2 | 0 |
| Red sandstone, | 2 | 0 |
| Red argillaceous shale, | 8 | 0 |
| Red sandstone, | 1 | 0 |
| Red arenaceous shale, | 5 | 0 |
| Red sandstone, | 1 | 0 |
| Red argillaceous shale, | 6 | 0 |
| Red sandstone, | 1 | 0 |
| Red argillaceous shale, | 28 | 0 |
| Red arenaceous shale, | 2 | 0 |
| Red argillaceous shale, | 15 | 0 |
| | 2082 | 0 |

RECAPITULATION.

| | | | | | |
|---|---|---|---|---|---|
| Sandstone— | | | | | |
| Greenish gray, with occasional drift plants carbonized, | 28 | 0 | | | |
| Greenish gray, with concretionary limestone, having the aspect of conglomerate, | 20 | 0 | | | |
| | | | 48 | 0 | |
| Reddish gray, with occasional drift plants carbonized, | 104 | 0 | | | |
| Reddish gray, with concretionary limestone, | 16 | 0 | | | |
| | | | 120 | 0 | |
| Reddish green, | 24 | 0 | | | |
| Reddish green, with concretionary limestone, | 37 | 0 | | | |
| | | | 61 | 0 | |
| Red and green, | | | 6 | 0 | |
| Red, | | | 233 | 0 | |
| | | | | | 468 0 |
| Shale— | | | | | |
| Red argillaceous, | 640 | 0 | | | |
| Red arenaceous, | 230 | 0 | | | |
| | | | 870 | 0 | |
| Green argillaceous, | | | 4 | 0 | |
| | | | | | 874 0 |
| Measures not well exposed, but probably composed of red shale and sandstone, | | | | | 740 0 |
| | | | | | 2082 0 |

G.

| | Ft. | In. |
|---|---|---|
| Greenish gray or drab coloured sandstone, fit for grindstones of good quality, which are extensively quarried from it. This is called the South Reef, | 50 | 0 |
| Red argillaceous shale, | 14 | 0 |
| Red sandstone, | 20 | 0 |
| Measures concealed, probably red shale, | 2 | 0 |
| Red sandstone, | 3 | 0 |
| Red sandstone, with probably red shale on the top, | 7 | 0 |
| Measures concealed, but said to be red argillaceous and arenaceous shale, with occasional beds of red sandstone, | 103 | 0 |
| Dark gray argillaceous shale, with a small quantity of fine grit in it. This would be called a fine *bluestone* in some parts of South Wales. At the Joggins, there is usually a bed of it above a good grindstone reef, | 4 | 0 |
| Greenish gray or drab coloured sandstone, fit for grindstones of the very best quality. The whole reef has been quarried away up to the bank, | 36 | 0 |
| Greenish gray sandstone, fit for grindstones of good quality. This has been much quarried, | 17 | 0 |
| Greenish gray sandstone, fit for grindstones. This has been very much quarried, | 7 | 0 |
| Greenish gray sandstone, fit for grindstones. This and the preceding greenish gray sandstones constitute what is called the North Reef, | 9 | 6 |
| Red and green argillaceous shale, | 18 | 0 |
| Red sandstone of a soft quality, | 6 | 0 |
| Red argillaceous shale, | 14 | 0 |
| Red argillaceous and arenaceous shale, with 6 bands of red sandstone, | 27 | 0 |
| Greenish gray sandstone, | 7 | 0 |
| Red argillaceous shale, | 6 | 0 |
| Red sandstone, | 4 | 0 |
| Red arenaceous shale, | 4 | 0 |
| Red argillaceous and arenaceous shale, | 10 | 0 |
| Red argillaceous and arenaceous shale and red sandstone, in alternating beds, | 12 | 0 |
| Red argillaceous shale, with 2 small beds of red sandstone, | 21 | 0 |
| Red sandstone, with bands of red argillaceous shale, | 9 | 0 |
| Red arenaceous shale, with bands of red sandstone, | 6 | 0 |
| Red sandstone, | 1 | 0 |
| Red argillo-arenaceous shale, with thin bands of red arenaceous shale and red sandstone, | 30 | 0 |
| *Black calcareous* bed, no shells visible, | 0 | 1 |
| Red and green variegated argillaceous shale, | 6 | 0 |
| Green arenaceous shale, | 1 | 0 |
| Red arenaceous and argillaceous shale, in alternating beds, | 4 | 0 |
| Red argillaceous shale, | 6 | 0 |
| Reddish gray sandstone, | 6 | 0 |
| Red argillaceous and arenaceous shale, | 10 | 0 |
| Red and green variegated shale and sandstone, | 13 | 0 |
| Red and green argillaceous shale, | 4 | 0 |
| Red and green variegated sandstone, | 2 | 0 |
| Red argillaceous shale, | 12 | 0 |
| Red and green calcareous band, | 0 | 6 |
| Green arenaceous shale, mixed in patches with red arenaceous shale, | 9 | 0 |
| Red arenaceous shale, of a crumbly character, | 12 | 0 |
| Dark gray argillaceous shale, with *ironstone* balls, | 3 | 0 |
| 1. *Culcareous* shale, | 1 | 0 |
| Dark gray argillaceous shale, | 3 | 0 |
| Coaly clay, | 0 | 2 |
| | 4 | 2 |
| Reddish and dark gray argillaceous and arenaceous shale, crossed by *stigmariæ* leaves, (*underclay,*) | 6 | 0 |
| Gray argillaceous shale, | 2 | 0 |
| Dark gray argillo-arenaceous shale, of a fine smooth quality, (*bluestone,*) | 7 | 0 |
| Greenish gray or drab coloured sandstone, fit for grindstones, | 10 | 0 |
| Gray arenaceous shale of a fine quality, in even beds, | 8 | 0 |
| Dark gray argillo-arenaceous shale, of a fine smooth quality, such as usually covers grindstone beds, | 3 | 0 |
| Greenish gray sandstone, fit for grindstones. The top part contains large spherical concretions of harder sandstone, with a rusty exterior, and concentric variations of colour. This constitutes Bacon Ledge, | 54 | 0 |
| Greenish gray sandstone, with a vast number of drift plants with a coating of coal, chiefly *sigillaria* and *calamites*. It holds also patches of limestone concretions, which have much the aspect of a conglomerate, | 10 | 0 |
| Dirty green calcareous concretionary bed.—This has so much the appearance of conglomerate bed with limestone pebbles, that there is some doubt whether it be not so. It is a very irregular bed and holds carbonized plants, | 4 | 0 |
| Reddish green argillo-arenaceous shale, | 1 | 0 |
| Greenish arenaceous shale of a hard quality, probably fireclay, crossed by *stigmariæ* leaves, (*underclay,*) | 8 | 0 |
| Red and green variegated argillaceous shale, with 2 feet of sandstone, | 8 | 0 |
| Red arenaceous shale with green spots, | 3 | 0 |
| Green arenaceous shale, | 1 | 0 |
| Red arenaceous shale, | 1 | 0 |
| Green arenaceous shale, | 1 | 0 |
| Red argillaceous shale, | 2 | 0 |
| Red and green arenaceous shale, | 2 | 0 |
| Red argillaceous shale, | 1 | 0 |

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Appendix (W.) 27th January.

| | Ft. | In. |
|---|---|---|
| Greenish gray arenaceous shale, ... ... | 3 | 0 |
| Red and green arenaceous shale, ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 3 | 0 |
| Greenish gray arenaceous shale, ... | 4 | 0 |
| Green clay, ... ... ... ... ... | 0 | 1 |
| Red argillaceous shale, ... ... | 6 | 0 |
| Reddish sandstone, ... ... ... ... | 1 | 0 |
| Red argillaceous shale, ... ... ... | 5 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| 2. Coal clay, probably coal further in the bank, ... | 0 | 1 |
| Red and green argillo-arenaceous shale of a soft quality, crossed by *stigmariæ* leaves, (*underclay,*) | 3 | 0 |
| Red and green crumbly argillo-arenaceous shale, rather harder than the preceding, crossed by *stigmariæ* leaves, (*underclay,*) ... ... | 6 | 0 |
| Reddish sandstone, no stigmariæ visible, ... ... | 0 | 6 |
| Red crumbly argillo-arenaceous shale, with *stigmariæ* (*underclay,*) ... ... ... ... | 2 | 0 |
| Red argillo arenaceous shale of a tough crumbly nature, with *stigmariæ* strongly marked (*underclay,*) ... ... ... ... ... | 2 | 0 |
| Red argillaceous shale, with thin green bands, and nodules of *ironstone*, a tough crumbly mass, ... | 6 | 0 |
| 3. *Carbonaceous shale,* ... ... | 0 | 1 |
| Greenish argillaceous shale, ... ... | 0 | 6 |
| *Carbonaceous shale,* ... ... | 0 | 1 |
| Greenish argillaceous shale, ... ... | 2 | 6 |
| *Carbonaceous shale,* ... ... | 0 | 2 |
| Greenish argillaceous shale in thin leaves, | 0 | 1 |
| *Coaly matter* and *carbonaceous shale,* ... | 0 | 3 |
| | 3 | 9 |
| Green argillo-arenaceous shale of a soft quality, crossed by *stigmariæ* leaves, (*underclay,*) ... | 3 | 0 |
| Gray argillo-arenaceous shale, rather harder than the preceding, with *stigmariæ* leaves and many nodules of *ironstone* at the top where the bed is more arenaceous (*underclay,*) ... ... | 4 | 0 |
| Gray sandstone, with *stigmariæ* leaves (*underclay*), | 1 | 0 |
| Green argillo-arenaceous shale of a rather soft quality, with *stigmariæ* leaves (*underclay,*) ... | 4 | 0 |
| 4. Coal and *carbonaceous shale,* ... ... | 0 | 3 |
| Green argillo-arenaceous shale, with *stigmariæ* leaves (*underclay*), ... ... ... ... | 2 | 0 |
| Red and green tough crumbly arenaceous shale, with *stigmariæ* branches and leaves (*underclay*), ... | 2 | 0 |
| Red and green tough crumbly claystone, with balls of *argillaceous iron ore, stigmariæ* leaves crossing the bed (*underclay*), ... ... ... | 2 | 0 |
| Gray rough sandstone and tough crumbly red and green arenaceous shale; one *stigmariæ* branch visible without leaves, but leaves exist in other parts of the bed (*underclay*), ... ... | 4 | 0 |
| Red and green tough crumbly clay, some very like *underclay*, but no *stigmariæ* leaves visible, ... | 2 | 0 |
| Dark gray argillaceous shale, no *stigmariæ* visible, but the mass tough and crumbly, ... ... | 1 | 0 |
| Reddish argillo-arenaceous shale, with *stigmariæ* branches and leaves (*underclay*), ... ... | 2 | 0 |
| Red sandstone with green spots, ... ... | 3 | 0 |
| Red and green variegated sandstone, the green in spots, ... ... ... ... ... | 3 | 0 |
| Gray argillaceous shale, ... ... ... | 3 | 0 |
| 5. Coaly matter, ... ... ... ... | 0 | 0½ |
| Greenish arenaceous shale, with *stigmariæ* branches and leaves, the recumbent branches crossing one another and running in all directions (*underclay*), | 8 | 0 |
| Green sandstone, ... ... ... ... | 2 | 0 |
| (From the succeeding bed there starts an upright *sigillaria* about 1 foot in diameter, only 2 feet of the length are visible.) | | |
| 6. *Carbonaceous shale,* ... ... ... | 0 | 3 |
| Gray argillo-arenaceous shale, with *stigmariæ* leaves (*underclay*), ... ... ... ... | 6 | 0 |
| Greenish gray sandstone, with *stigmariæ* leaves (*underclay*), ... ... ... ... | 4 | 0 |
| Greenish gray sandstone, with *stigmariæ* branches and leaves (*underclay,*) ... ... ... | 2 | 0 |
| Red argillo-arenaceous shale, with *stigmariæ* leaves (*underclay*), ... ... ... ... | 3 | 0 |

(In these 15 feet of underclay there is a beautiful exhibition of stigmariæ. They are not very abundant, that is to say, in such profuse confusion as usual, but each plant is very distinct. One branch floats along just beneath the surface of the 2 feet bed mentioned, and 24 feet of its length are finely exposed without interruption. The leaves radiate from it distinctly, and individual leaves can be followed down 3 feet, crossing both the hard and the soft parts of the deposit continuously, and others can be traced 2 feet upwards. Where the branch enters a projecting part of the bed, its measurement is 2 inches vertically by 3 inches horizontally, and where the other extremity is lost beneath the beach the measurement is about the same; so that I could not come to any conclusion as to the direction in which the branch issues from the stem, if it has one. *See fig.* 8.)

| | Ft. | In. |
|---|---|---|
| Greenish gray or drab sandstone in irregular beds, ... | 70 | 0 |
| Greenish gray sandstone, with a vast quantity of drift plants lying in confusion and coated with coal. In one of the beds there appears a bundle of no less than 10 plants squeezed together side by side, as represented in fig. 8. Each has a core of sandstone surrounded by a good thick coating of crystallized coal. They run through and through a projecting ledge of 10 feet, (see fig. 9,) and lie rather oblique to the plane of the bed, but conformably with its elementary layers, ... ... ... ... ... | 30 | 0 |
| Greenish gray sandstone, with some spherical concretions of a harder quality, with a rusty exterior, ... ... ... ... ... | 50 | 0 |
| Greenish gray sandstone, ... ... ... | 22 | 0 |
| Dark gray argillaceous shale, ... ... ... | 0 | 6 |
| Greenish gray arenaceous shale, with some fibrous impressions like *stigmariæ* leaves crossing the bed (*underclay*), ... ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 0 | 6 |
| Greenish gray arenaceous shale, ... ... | 0 | 6 |
| Red argillaceous shale, ... ... ... | 2 | 0 |
| Green arenaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, with spherical concretions, | 4 | 0 |
| Greenish gray sandstone and shale, ... ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 0 | 10 |
| Gray tough crumbly sandstone, ... ... ... | 3 | 0 |
| Gray calcareous sandstone, ... ... ... | 0 | 6 |
| 7. *Bituminous limestone,* ... ... | 0 | 3 |
| Gray argillaceous shale, ... ... | 3 | 0 |
| Gray calcareous bed, ... ... | 0 | 2 |
| *Carbonaceous shale,* ... ... | 0 | 6 |
| *Bituminous limestone,* with *shells* and *fish scales*; *fish jaws* occur, ... ... | 0 | 3 |
| *Carbonaceous shale,* being a mass of plotted plants, apparently grasses, ... | 1 | 0 |
| Coal, ... ... ... ... | 0 | 1 |
| | 5 | 3 |
| Gray argillo-arenaceous shale, with *stigmariæ* (*underclay*), ... ... ... | 5 | 0 |
| Gray arenaceous shale, ... ... ... | 5 | 0 |
| Greenish gray sandstone, ... ... ... | 7 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 6 |
| Greenish gray sandstone, ... ... ... | 0 | 6 |
| Grey soft arenaceous shale, ... ... ... | 4 | 0 |
| Greenish gray soft flaggy sandstone, with ripple mark, | 10 | 0 |
| Greenish gray soft flaggy sandstone, ... ... | 4 | 0 |
| Gray arenaceous shale, ... ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 4 | 0 |
| Greenish gray soft flaggy sandstone, scarcely standing the weather, ... ... ... ... | 14 | 0 |
| Greenish gray sandstone, in regular beds, ... | 27 | 0 |
| Measures concealed, but no doubt soft, probably argillaceous shale, with a mixture of arenaceous, ... | 100 | 0 |
| Gray arenaceous shale, ... ... ... ... | 8 | 0 |
| Gray argillaceous shale, ... ... ... | 6 | 0 |
| Greenish gray sandstone, fit for grindstones. This has been quarried to a considerable extent, and worked deep into the bank. It is the best quarry of this reef, but the stone is rather too hard, ... | 10 | 0 |
| Greenish gray sandstone of grindstone quality, ... | 6 | 0 |
| Greenish gray sandstone. This has been worked for grindstones, but the quality is rather hard, ... | 14 | 0 |
| Greenish gray sandstone fit for grindstones, but rather too hard. This bed exhibits spherical concretions in some parts, some of which are 6 to 8 inches in diameter. These grindstone beds constitute what is called the Upper Core Reef, ... | 18 | 0 |
| Greenish gray sandstone, ... ... ... | 34 | 0 |
| Greenish gray sandstone in flaggy beds, ... ... | 49 | 0 |
| Greenish gray sandstone of a stronger quality, ... | 8 | 0 |
| Greenish gray sandstone in flaggy beds, ... ... | 15 | 0 |
| Greenish gray sandstone, ... ... ... | 34 | 0 |
| Greenish gray argillaceous shale, ... ... | 9 | 0 |
| Greenish gray sandstone. This constitutes Boss Point, ... ... ... ... | 42 | 0 |
| Greenish gray sandstone, ... ... ... | 6 | 0 |
| Greenish gray sandstone, with drift plants coated with coal, ... ... ... | 12 | 0 |
| Greenish gray sandstone in regular beds, ... ... | 28 | 0 |
| Greenish gray sandstone, with carbonized drift plants, | 7 | 0 |

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| | Ft. | In. |
|---|---|---|
| Greenish gray sandstone in more regular beds, ... | 9 | 0 |
| Greenish gray sandstone, with drift carbonized plants, | 9 | 0 |
| Greenish gray sandstone, pervaded by a tangled mass of carbonized drift plants, ... ... ... | 6 | 0 |
| Greenish gray sandstone, ... ... ... | 12 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| 8. Coal occurring in patches, ... ... ... | 0 | 0½ |
| Gray argillo-arenaceous shale, with the aspect of fireclay, with *stigmariæ* branches and leaves very distinctly exhibited (*underclay*), ... ... | 7 | 0 |
| Gray arenaceous shale, ... ... ... | 3 | 0 |
| Greenish gray argillaceous shale, with nodules of *clay ironstone* disseminated in considerable quantity, ... ... ... ... ... | 5 | 0 |
| Gray argillaceous shale, ... ... ... | 10 | 0 |
| Greenish gray sandstone, ... ... ... | 18 | 0 |
| Greenish gray sandstone, with carbonized drift plants in confusion, ... ... ... ... | 7 | 0 |
| Greenish gray sandstone, ... ... ... | 10 | 0 |
| Greenish gray sandstone, with carbonized drift plants in confusion, ... ... ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 7 | 0 |
| Greenish gray sandstone, with carbonized drift plants in confusion, ... ... ... ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 15 | 0 |
| Greenish gray sandstone, with spherical concretions of a harder quality, ... ... ... | 7 | 0 |
| Greenish gray sandstone, with a few carbonized drift plants, ... ... ... ... | 18 | 0 |
| Gray arenaceous shale, ... ... ... | 2 | 0 |
| Greenish gray sandstone, ... ... ... | 12 | 0 |
| Greenish gray sandstone, with a confused multitude of carbonized drift plants, ... ... ... | 4 | 0 |
| Greenish gray sandstone, with a few carbonized drift plants, ... ... ... ... ... | 21 | 0 |
| Greenish sandstone, with calcareous concretionary nodules, having much the aspect of a conglomerate, with limestone pebbles. The bed is very uneven,... ... ... ... ... | 1 | 0 |
| Greenish gray sandstone, with carbonized drift plants, | 13 | 0 |
| Greenish gray sandstone, in even beds, ... ... | 12 | 0 |
| Greenish gray sandstone, with carbonized drift plants, | 10 | 0 |
| Greenish gray sandstone, ... ... ... | 51 | 0 |
| Gray argillaceous and red argillaceous shale, ... | 23 | 0 |
| Greenish gray sandstone, fit for grindstones, but rather hard. This constitutes Boss Quarry, ... | 10 | 0 |
| Greenish gray sandstone, ... ... ... | 25 | 0 |
| Greenish gray sandstone, with carbonized drift plants, | 6 | 0 |
| Greenish gray sandstone, ... ... ... | 24 | 0 |
| Greenish gray sandstone, with nodules of *clay ironstone*, casts of *calamites* and other plants, ... | 1 | 0 |
| Gray arenaceous shale, ... ... ... | 4 | 0 |
| Red argillaceous shale, ... ... ... | 6 | 0 |
| Greenish gray arenaceous shale, ... ... | 3 | 0 |
| Gray argillaceous shale, ... ... ... | 12 | 0 |
| Gray arenaceous shale, ... ... ... | 3 | 0 |
| Yellow sandstone, very soft and yielding to the weather, ... ... ... ... | 4 | 0 |
| Gray argillaceous shale, ... ... ... | 7 | 0 |
| Yellow sandstone, very soft and yielding to the weather, ... ... ... ... | 21 | 0 |
| Greenish gray sandstone in even beds, ... ... | 4 | 0 |
| Gray arenaceous shale, ... ... ... | 4 | 0 |
| Greenish gray sandstone, fit for grindstones, ... | 18 | 0 |
| Gray arenaceous shale, ... ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... ... | 7 | 0 |
| Greenish gray sandstone, with carbonized drift plants, | 9 | 0 |
| Greenish gray sandstone in regular beds, ... | 21 | 0 |
| Gray arenaceous shale and sandstone, ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 13 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 27 | 0 |
| Gray argillaceous shale, ... ... ... | 6 | 0 |
| Greenish gray sandstone, ... ... ... | 30 | 0 |
| Greenish bed with concretions of limestone, very much resembling a calcareous conglomerate, ... | 5 | 0 |
| Gray argillaceous shale, ... ... ... | 5 | 0 |
| Greenish bed of calcareous concretions, very much resembling a calcareous conglomerate ... | 9 | 0 |
| Gray arenaceous shale, with some bands of sandstone, ... ... ... ... ... | 23 | 0 |
| Greenish gray sandstone, ... ... ... | 64 | 0 |
| Greenish gray sandstone, ... ... ... | 27 | 0 |
| (Here there appears to be a small fault. It does not disturb the strike, but the dislocation, if there is any, is not ascertained. I do not think it can be many yards.) | | |
| Greenish gray sandstone, ... ... ... | 34 | 0 |
| Greenish gray sandstone, with many carbonized drift plants, ... ... ... ... ... | 14 | 0 |
| Greenish gray sandstone, more regular in the beds, | 16 | 0 |
| Greenish gray sandstone, with some carbonized drift plants, ... ... ... ... ... | 18 | 0 |
| Greenish gray sandstone, with many carbonized drift plants in great confusion, ... ... ... | 9 | 0 |
| Greenish bed with calcareous concretions, having much the aspect of a calcareous conglomerate,... | 1 | 0 |
| Greenish gray sandstone with many prostrate carbonized drift plants, ... ... ... | 9 | 0 |
| Greenish gray sandstone, a solid mass without divisions, ... ... ... ... ... ... | 21 | 0 |
| Greenish gray sandstone, with a vast and confused collection of carbonized drift plants, one lying prostrate measured 25 feet in length and about 1 foot in diameter, at the small end, ... | 19 | 0 |
| Greenish gray sandstone more regular, ... ... | 117 | 0 |
| Greenish gray sandstone with carbonized drift plants, and holding small patches of concretionary nodulous limestone very like conglomerate, ... | 39 | 0 |
| Gray arenaceous shale, with small *clay ironstone* balls desseminated. This has something of the character of underclay but the *stigmariæ* are not distinct, ... ... ... ... | 4 | 0 |
| Gray arenaceous shale, ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 3 | 0 |
| Gray arenaceous shale, ... ... ... | 3 | 0 |
| Gray argillaceous shale with some balls of *clay ironstone*, ... ... ... ... ... | 5 | 0 |
| Gray arenaceous shale, ... ... ... | 1 | 0 |
| Gray argillaceous shale with 2 beds of arenaceous shale, ... ... ... ... ... | 8 | 0 |
| Greenish gray sandstone in regular beds, ... | 61 | 0 |
| Greenish gray sandstone, with carbonized drift plants, and occasional patches of concretionary nodulous limestone, very like conglomerate, ... | 63 | 0 |
| Greenish gray sandstone with carbonized drift plants, | 1 | 0 |
| Greenish gray sandstone fit for grindstones, ... | 20 | 0 |
| Gray concretionary limestone, very like a conglomerate with calcareous pebbles, ... ... | 4 | 0 |
| Greenish gray sandstone, ... ... | 25 | 0 |
| Lead gray concretionary limestone with carbonized drift plants, and mixed up with calcareous sandstone, ... ... ... ... ... | 8 | 0 |
| Gray argillaceous shale, ... ... ... | 10 | 0 |
| Red or chocolate coloured argillaceous shale, ... | 40 | 0 |
| *Dark gray coarse limestone*, no organic remains visible, ... ... ... ... ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 1 | 0 |
| 9. Coaly matter and *carbonaceous shale*, ... | 0 | 2 |
| Gray argillo-arenaceous shale, resembling fireclay with the leaves and branches of *stigmariæ ficoides* strongly marked, the branches recumbent, and near the top of the bed *ironstone* balls are disseminated through the deposit, (*underclay,*) ... | 5 | 0 |
| Gray argillaceous shale and greenish gray sandstone, ... ... ... ... ... | 2 | 0 |
| Gray argillaceous shale, ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 5 | 0 |
| Greenish argillaceous shale, ... ... ... | 7 | 0 |
| Greenish gray sandstone, ... ... ... | 96 | 0 |
| Greenish concretionary limestone, ... ... | 2 | 0 |
| Greenish gray hard sandstone with a number of large spherical masses still harder. Some of them are 1 foot in diameter, and in section exhibit beautiful deep black and bright red concentric circles towards the exterior. These spheres are said to be occasionally 4 feet in diameter. This constitutes Dogfish Reef, ... | 20 | 0 |
| Greenish concretionary limestone, the calcareous concretions are lodged in an argillaceous matrix, ... | 1 | 0 |
| Gray argillaceous shale, ... ... ... | 12 | 0 |
| Greenish gray sandstone, ... ... ... | 6 | 0 |
| Measures concealed, but supposed to be soft, ... | 3 | 0 |
| Dark gray argillaceous shale with disseminated *clay ironstone* balls, ... ... ... ... | 10 | 0 |
| Dark gray argillaceous shale with a course of *clay ironstone* balls at the bottom, some of them 6 inches in diameter, ... ... ... | 5 | 0 |
| *Black carbonaceous shale*, with *shells* in some parts, | 4 | 0 |
| Dark gray argillaceous shale, ... ... ... | 0 | 10 |
| Dark gray argillaceous shale with a course of poor *ironstone* balls at the top, making about ½ inch, | 8 | 0 |
| Greenish gray sandstone fit for grindstones, ... | 17 | 0 |
| Greenish concretionary limestone, having much the appearance of a calcareous conglomerate, ... | 3 | 0 |
| Greenish gray sandstone, ... ... ... | 5 | 0 |
| Greenish gray sandstone with carbonized drift paste, *calamites* and others squeezed flat, ... ... | 3 | 0 |
| Brown argillaceous shale, ... ... ... | 1 | 0 |
| Greenish gray sandstone, ... ... ... | 1 | 0 |
| Reddish gray shale, ... ... ... ... | 1 | 0 |
| Measures concealed, probably shale, ... ... | 77 | 0 |
| Red or chocolate coloured sandstone, ... ... | 3 | 0 |
| Red or chocolate coloured arenaceous shale, ... | 7 | 0 |
| Red or chocolate coloured sandstone and shale, ... | 21 | 0 |
| Red sandstone, ... ... ... ... | 1 | 0 |

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| | Ft. | In. |
|---|---|---|
| Red shale, ... ... ... ... ... | 1 | 0 |
| Red sandstone, ... ... ... ... ... | 0 | 0 |
| Red shale, ... ... ... ... ... | 1 | 0 |
| Red sandstone, ... ... ... ... ... | 2 | 0 |
| Red arenaceous shale, ... ... ... | 1 | 0 |
| Red sandstone, ... ... ... ... ... | 10 | 0 |
| Red shale, ... ... ... ... ... | 2 | 0 |
| Red sandstone, ... ... ... ... ... | 0 | 6 |
| Red shale, ... ... ... ... ... | 0 | 8 |
| *Dark green limestone*, ... ... ... ... | 0 | 4 |
| Red shale, ... ... ... .. ... | 3 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red argillaceous shale, ... ... ... | 6 | 0 |
| Greenish argillaceous shale, ... ... ... | 0 | 3 |
| Red or chocolate coloured shale, ... ... | 1 | 0 |
| Red or chocolate coloured sandstone, ... ... | 1 | 0 |
| Red or chocolate coloured shale, ... ... | 8 | 0 |
| *Black bituminous limestone*, ... ... ... | 0 | 3 |
| Red or chocolate coloured shale, ... ... | 1 | 0 |
| *Black bituminous limestone*, ... ... ... | 0 | 6 |
| Red or chocolate coloured argillaceous shale, ... | 1 | 6 |
| *Black bituminous limestone*, with *fish scales*, ... | 0 | 6 |
| Brownish red soft shale, ... ... ... | 32 | 0 |
| Red or chocolate coloured shale, ... ... | 13 | 0 |
| Greenish gray sandstone, ... ... ... | 3 | 0 |
| Red shale, ... ... ... ... ... | 37 | 0 |
| *Black bituminous limestone*, with *fish scales*, ... | 0 | 6 |
| | 3240 | 9 |

RECAPITULATION.

| | | | Ft. | In. |
|---|---|---|---|---|
| Coal in 9 seams, ... ... | 0 | 10 | | |
| Carbonaceous shale associated with the coal, and in one instance without coal, and then containing remains of shells, | 7 | 4 | | |
| Bituminous limestone with remains of fish, and calcareous beds, associated with the coal and carbonaceous shale seams in one instance, and in six instances independant, ... | 4 | 10 | | |
| Greenish and gray argillaceous shale, associated in some instances with the coal and carbonaceous seams,... ... | 9 | 1 | | |
| | | | 22 | 1 |
| Underclay or understone, being beds of various material, immediately subjacent to the seams of coal and carbonaceous shale, and invariably penetrated by the recumbent branches and radiating leaves of the stigmaria ficoides. Every one of the coal seams rests upon a stigmaria bed, and there is one instance of the stigmaria bed without superincumbent coal. The material of which the stigmaria beds consists is as follows: | | | | |
| Sandstone of a gray colour and crumbly quality, ... | 5 | 0 | | |
| Shale— | | | | |
| Gray argillo-arenaceous, frequently fit for fireclay, ... | 50 | 0 | | |
| Green argillo-arenaceous, ... | 21 | 0 | | |
| Red and green argillo-arenaceous, | 17 | 0 | | |
| | 88 | 0 | | |
| | | | 93 | 0 |
| Sandstone— Greenish gray or drab coloured, of which much is fit for the purpose of good grindstones, and it is in it that the chief quarries of the Joggins exist. Of this mass 350 feet in various parts are filled with vast collections of drift plants, coated with crystalline coal. The plants are in great confusion, and are in general prostrate. Spherical concretions some 4 feet in diameter with a rusty black exterior, occur in 51 feet of it, ... | 1886 | 6 | | |
| Greenish, ... ... | 2 | 0 | | |
| Yellow of a finer but less durable quality than the drab, | 25 | 0 | | |
| Reddish gray (and gray 5,) ... | 19 | 6 | | |
| Red and green, ... ... | 15 | 0 | | |
| Red and chocolate colored, ... | 95 | 6 | | |
| | 2043 | 6 | | |
| Limestone of a concretionary character very much resembling conglomerate generally of a greenish colour and in very irregular layers, ... ... ... | 43 | 0 | | |
| Shale— | | | | |
| Greenish gray arenaceous and argillaceous, ... ... | 136 | 0 | | |
| Gray arenaceous and argillaceous with a few small beds containing ironstone balls, ... | 234 | 0 | | |
| Red and green variegated, ... | 77 | 0 | | |
| Red and chocolate coloured, ... | 592 | 2 | | |
| | 1039 | 2 | | |
| | | | 3240 | 9 |
| (Among the organic remains is to be remarked one upright sigillaria.) | | | | |

Appendix (W.)

27th January.

| | Ft. | In. |
|---|---|---|
| Measures concealed, ... ... ... ... | 19 | 0 |
| Red arenaceous shale, ... ... ... | 1 | 0 |
| Measures concealed, ... ... ... ... | 37 | 0 |
| Red arenaceous shale, ... ... ... | 1 | 0 |
| Measures concealed, probably red shale, ... ... | 139 | 0 |
| (Here is said to occur a bed of gypsum. I am informed that it has been occasionally seen when the beach was washed clean by the tide. A fragmentary mass of gypsum of about half a hundred weight lay on the beach.) | | |
| Measures, concealed, probably red shale, ... ... | 83 | 0 |
| Red sandstone conglomerate with white, red, yellow and black silicious pebbles. The black is lydian stone, the others are quartz. The pebbles vary in size from that of a pea to that of a hen's egg, | 103 | 0 |
| Red sandstone conglomerate of a coarser quality. The pebbles are of the same colour, but some of them would weigh two pounds, ... ... | 3 | 0 |
| Red sandstone conglomerate, not quite so coarse, ... | 16 | 0 |
| Red arenaceous shale with several bands of sandstone, ... ... ... ... ... | 21 | 0 |
| Red sandstone, ... ... ... ... | 5 | 0 |
| Red shale, ... ... ... ... | 3 | 0 |
| Red sandstone, ... ... ... ... | 6 | 0 |
| Red shale, ... ... ... ... | 3 | 0 |
| Red sandstone conglomerate with white, gray and black silicious pebbles as before, ... ... | 16 | 0 |
| Red sandstone, ... ... ... ... | 22 | 0 |
| Red and green spotty variegated sandstone, ... | 11 | 0 |
| Red sandstone of soft quality, ... ... ... | 3 | 0 |
| Red and green spotty variegated sandstone. The green colour constitutes the spots which are circular with a black speck in the centre. The bed appears to be partly calcareous, ... ... | 9 | 0 |
| Red sandstone of a soft quality and red arenaceous shale, ... ... ... ... ... | 11 | 0 |
| Red arenaceous shale, ... ... ... | 24 | 0 |
| Red sandstone conglomerate with white, red and yellow quartz, and black lydian stone pebbles, varying in size from that of a pea to that of an egg. ... ... ... ... ... | 17 | 0 |
| Red sandstone of a very coarse grit, with streaks of white parallel with the bedding, ... ... | 16 | 0 |
| Red sandstone conglomerate with quartz and limestone pebbles. The matrix is coarse, ... | 4 | 0 |
| Red sandstone with thin white streaks deposited in it, ... ... ... ... ... | 35 | 0 |
| (This bed is cut by a regular vein of sulphate of barytes 3 inches wide. Its colour is tinged with red. The course of the vein is N. & S. The underlie E. < 82°) | | |
| Red sandstone conglomerate. The bed is very uneven and contains calcareous material, ... | 3 | 0 |
| Greenish concretionary limestone, looking very like a conglomerate with limestone pebbles, ... | 8 | 0 |
| Greenish gray sandstone, ... ... ... ... | 1 | 0 |
| Greenish concretionary limestone as before, ... | 3 | 0 |
| Reddish sandstone, ... ... ... ... | 7 | 0 |
| Greenish concretionary limestone as before, ... | 4 | 0 |
| Red or chocolate coloured shale, ... ... | 8 | 0 |
| Red sandstone, ... ... ... ... | 2 | 0 |
| Red or chocolate coloured shale, ... ... | 1. | 0 |
| | 450 | 0 |

Appendix (W.) 27th January.

RECAPITULATION.

| | | | Ft. | In. |
|---|---|---|---|---|
| Sandstone— | | | | |
| Greenish gray, ... | 1 0 | | | |
| Reddish, ... | 7 0 | | | |
| Red and green, ... | 20 0 | | | |
| Red, ... ... | 65 0 | | | |
| | | 93 0 | | |
| Red with white streaks, ... | 51 0 | | | |
| | | 144 | 0 | |
| Conglomerate, with red, white, gray and yellow quartz and black lydian stone pebbles, in a matrix of red sandstone, | | 143 | 0 | |
| Limestone in concretionary nodules placed in a matrix of greenish sandstone and shale, occasionally associated with carbonized fragments of plants, ... | | 16 | 0 | |
| Shale— | | | | |
| Deep red and chocolate red, arenaceous, ... ... | 62 0 | | | |
| Measures concealed, but supposed to be of the same quality, ... ... | 240 0 | | | |
| | | 342 | 0 | |
| | | 650 | 0 | |

8.

| | | | |
|---|---|---|---|
| Greenish gray sandstone, red towards the top, ... | 12 | 0 | |
| Greenish gray arenaceous limestone, with a band of concretionary limestone, resembling conglomerate, ... ... ... ... ... | 6 | 0 | |
| Greenish concretionary limestone and coarse sandstone, with carbonized drift plants, ... ... | 1 | 0 | |
| Greenish gray sandstone, ... ... ... | 11 | 0 | |
| Greenish gray sandstone, with two bands of concretionary limestone, ... ... ... | 12 | 0 | |
| Reddish black and reddish brown shale, with beds containing calcarvous septaria, ... ... | 9 | 0 | |
| Dark gray sandstone, with nodules of concretionary limestone, ... ... ... | 2 | 0 | |
| Reddish black argillaceous shale, with nodules of ferruginous limestone, ... ... ... | 9 | 0 | |
| Greenish gray sandstone, ... ... ... | 30 | 0 | |
| Greenish concretionary limestone, ... ... | 1 | 0 | |
| Greenish gray sandstone, ... ... ... | 21 | 0 | |
| Greenish concretionary limestone, with carbonized drift plants, ... ... ... ... | 3 | 0 | |
| Greenish gray sandstone, ... ... ... | 17 | 0 | |
| Greenish concretionary limestone, ... ... | 1 | 0 | |
| Greenish gray or drab coloured sandstone, ... | 4 | 0 | |
| Red shale, ... ... ... ... ... | 8 | 0 | |
| Red sandstone, ... ... ... ... | 12 | 0 | |
| Red shale, with some bands of soft red sandstone, ... | 37 | 0 | |
| Red sandstone of a soft quality,... ... ... | 6 | 0 | |
| Red shale, with bands of red sandstone, ... ... | 40 | 0 | |
| Greenish gray sandstone, ... ... ... | 30 | 0 | |
| Greenish concretionary limestone, ... ... | 1 | 0 | |
| Greenish gray sandstone, 10 feet; greenish concretionary limestone, 2 feet, ... ... ... | 12 | 0 | |
| Greenish gray sandstone, at the bottom of which there is a layer of carbonized drift plants, occasionally replaced by *gray sulphuret of copper* invested with a thin pellicle of the *green carbonate*, ... ... ... ... ... | 8 | 0 | |
| Red shale, ... ... ... ... ... | 8 | 0 | |
| Red sandstone, ... ... ... ... | 17 | 0 | |
| Red shale, ... ... ... ... ... | 3 | 0 | |
| Greenish gray sandstone, at the bottom of which is a layer of drift plants converted into coal, and occasionally replaced by *gray sulphuret of copper* invested with the *green carbonate*, ... | 6 | 0 | |
| Red shale, ... ... ... ... ... | 9 | 0 | |
| Red shale and red sandstone ... ... ... | 10 | 0 | |
| Red shale, ... ... ... ... ... | 10 | 0 | |
| Red sandstone, ... ... ... ... | 7 | 0 | |
| Red shale, ... ... ... ... ... | 8 | 0 | |
| Red and greenish gray sandstone, ... ... | 19 | 0 | |
| Greenish gray sandstone, with drift plants converted into coal, and occasionally replaced by *gray sulphuret of copper* with *green carbonate*, ... | 1 | 0 | |
| Red arenaceous shale,... ... ... ... | 37 | 0 | |
| Red sandstone of a soft quality,... ... ... | 16 | 0 | |
| Greenish gray sandstone, ... ... ... | 6 | 0 | |
| Red hard arenaceous shale, ... ... ... | 25 | 0 | |
| Reddish sandstone, ... ... ... ... | 13 | 0 | |
| Red shale, ... ... ... ... ... | 2 | 0 | |
| Greenish gray sandstone, with carbonized remains of plants, ... ... ... ... | 6 | 0 | |
| Greenish concretionary limestone, 2 feet; red shale, 1 foot, ... ... ... ... ... | 3 | 0 | |
| Greenish gray sandstone, with concretionary limestone and carbonized remains of plants at the bottom,... ... ... ... ... | 11 | 0 | |
| Greenish gray sandstone, with one foot of red shale on top, ... ... ... ... ... | 3 | 0 | |
| Red shale, ... ... ... ... ... | 16 | 0 | |
| Red sandstone, with some of a drab colour at the bottom, with carbonized remains of plants and balls of argillaceous shale, ... ... ... | 12 | 0 | |
| Red arenaceous shale,... ... ... ... | 3 | 0 | |
| Red sandstone, ... ... ... ... | 3 | 0 | |
| Red arenaceous shale,... ... ... ... | 60 | 0 | |
| Red sandstone of a coarse quality, ... ... | 14 | 0 | |
| Greenish gray sandstone, coloured red in parts, ... | 10 | 0 | |
| Red arenaceous shale,... ... ... ... | 4 | 0 | |
| Greenish gray sandstone, with remains of plants converted into coal, ... ... ... ... | 6 | 0 | |
| Red arenaceous shale,... ... ... ... | 30 | 0 | |
| Red sandstone fit for first quality of flagging, ... | 15 | 0 | |
| Greenish gray sandstone, with many remains of plants converted into coal, and occasionally replaced by *gray sulphuret of copper* with a pellicle of *green carbonate* around it, ... ... ... | 6 | 0 | |
| Red arenaceous shale,... ... ... ... | 14 | 0 | |
| Red sandstone fit for flagging, ... ... ... | 16 | 0 | |
| Red arenaceous shale,... ... ... ... | 16 | 0 | |
| Red sandstone fit for inferior flagging, ... ... | 3 | 0 | |
| Red arenaceous shale,... ... ... ... | 100 | 0 | |
| Red sandstone fit for flagging, ... ... ... | 4 | 0 | |
| Red arenaceous shale,... ... ... ... | 29 | 0 | |
| Red sandstone fit for flagging, ... ... ... | 6 | 0 | |
| Red arenaceous shale,... ... ... ... | 39 | 0 | |
| Red sandstone fit for flagging, ... ... ... | 30 | 0 | |
| Red arenaceous shale, with two bands of red sandstone, ... ... ... ... ... | 19 | 0 | |
| Red sandstone fit for flagging, ... ... ... | 22 | 0 | |
| Red arenaceous shale,... ... ... ... | 119 | 0 | |
| (Here is said to occur gypsum of a red colour, in small quantities, but the bank being rather obscured by debris it was not visible.) | | | |
| Red arenaceous shale,... ... ... ... | 104 | 0 | |
| Red arenaceous shale, with bands of red sandstone, | 3 | 0 | |
| Red arenaceous shale,... ... ... ... | 79 | 0 | |
| Red arenaceous shale, with bands of red sandstone, | 3 | 0 | |
| Red arenaceous shale,... ... ... ... | 43 | 0 | |
| Red arenaceous shale, with green veins crossing it, | 19 | 0 | |
| Red sandstone, ... ... ... ... | 1 | 0 | |
| Red arenaceous shale,... ... ... ... | 2 | 0 | |
| Red sandstone, ... ... ... ... | 1 | 0 | |
| Red arenaceous shale,... ... ... ... | 39 | 0 | |
| Red sandstone, partly greenish gray, ... ... | 4 | 0 | |
| Red arenaceous shale,... ... ... ... | 1 | 0 | |
| Red sandstone of a soft quality, ... ... | 3 | 0 | |
| Red arenaceous shale,... ... ... ... | 12 | 0 | |
| Red sandstone, ... ... ... ... | 1 | 0 | |
| Red arenaceous shale,... ... ... ... | 14 | 0 | |
| Red arenaceous shale of a hard quality, with a band of red sandstone above, ... ... ... | 9 | 0 | |
| Red sandstone of a soft quality, ... ... | 1 | 0 | |
| Measures concealed, probably red shale, ... ... | 4 | 0 | |
| Red arenaceous shale, with a band of greenish gray sandstone above,... ... ... ... | 14 | 0 | |
| Red arenaceous shale,... ... ... ... | 10 | 0 | |
| Measures not well seen, but probably red arenaceous shale, ... ... ... ... ... | 27 | 0 | |
| Red arenaceous shale, with a band of red sandstone above, ... ... ... ... ... | 7 | 0 | |
| Red hard arenaceous shale, ... ... ... | 1 | 0 | |
| Measures concealed, but probably arenaceous shale, | 15 | 0 | |
| Red arenaceous shale,... ... ... ... | 53 | 0 | |
| Measures concealed, but probably red arenaceous shale of the same quality as before. Here occurs Seaman's Brook, Mill Cove, ... ... | 75 | 0 | |
| | 1658 | 0 | |

(In the exact strike of the lower gypsum above mentioned, in its course to Hebert River, there is a sink-hole about half way, in which gypsum has been found by excavation; and where the strike would come upon the Hebert, a mass of the mineral, apparently in situ, is seen in the bank, with red shale on both sides of it. At such a distance to the north of this mass as gives a vertical thickness of 300 feet of subjacent red shale, there is exposed a deposit of limestone, which, with some associated strata, appears to be about 100 feet thick; and this may, therefore, be considered as terminating the foregoing section. The limestone contains organic remains, among which there is in some abundance, a bivalve shell, which I recognise as identical with the *productus Lyelli* of Windsor, in Nova Scotia.)

Appendix (W.) 27th January.

Appendix (W.) 27th January.

RECAPITULATION.

| | | | |
|---|---|---|---|
| Sandstone— | | | |
| Greenish gray, occasionally holding carbonized reliquiæ of plants, and in four instances the plants (underlying the sandstone) are replaced by gray sulphuret and green carbonate of copper, ... | 206 | 0 | |
| Reddish, ... ... ... | 13 | 0 | |
| Deep red, ... ... ... | 213 | 0 | |
| | | | 432 0 |
| Concretionary limestone associated with the greenish gray sandstone. The concretions are held in an argillo-arenaceous matrix. In one instance the whole of the bed is calcareous, and there occur 9 beds altogether, ... ... | | | 20 0 |
| Shale— | | | |
| Red arenaceous, sometimes more and sometimes less argillaceous, ... ... | 1186 | 0 | |
| Reddish black and gray, with calcareous sceptaria and nodules, ... ... | 20 | 0 | |
| | | | 1206 0 |
| | | | 1658 0 |

TOTAL THICKNESS

| | | | |
|---|---|---|---|
| No. 1, ... ... ... | 1617 | 0 | |
| " 2, ... ... ... | 650 | 0 | |
| " 3, ... ... ... | 2134 | 1 | |
| " 4, ... ... ... | 2539 | 1 | |
| " 5, ... ... ... | 2082 | 0 | |
| " 6, ... ... ... | 3240 | 9 | |
| " 7, ... ... ... | 650 | 0 | |
| " 8, ... ... ... | 1658 | 0 | |
| | 14570 | 11 | |

*Fig. 5.*

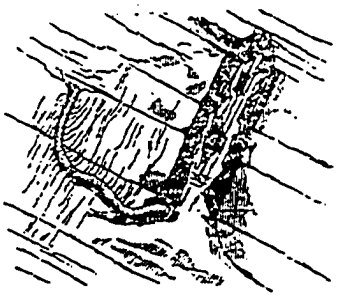


*Fig. 6.*

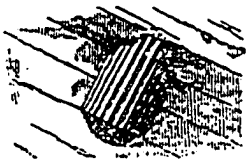


*Fig. 7.*

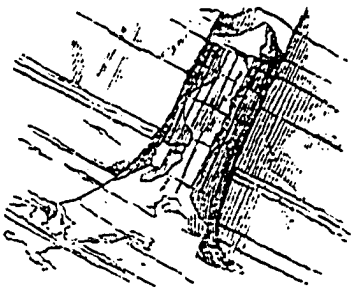


*Fig. 8.*

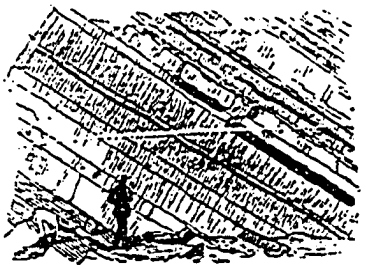
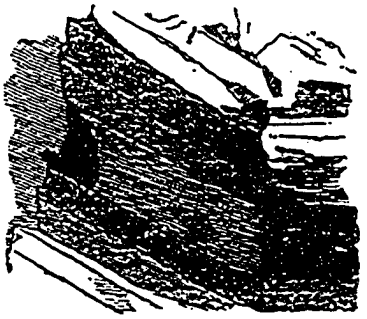


*Fig. 9.*

FRONT VIEW

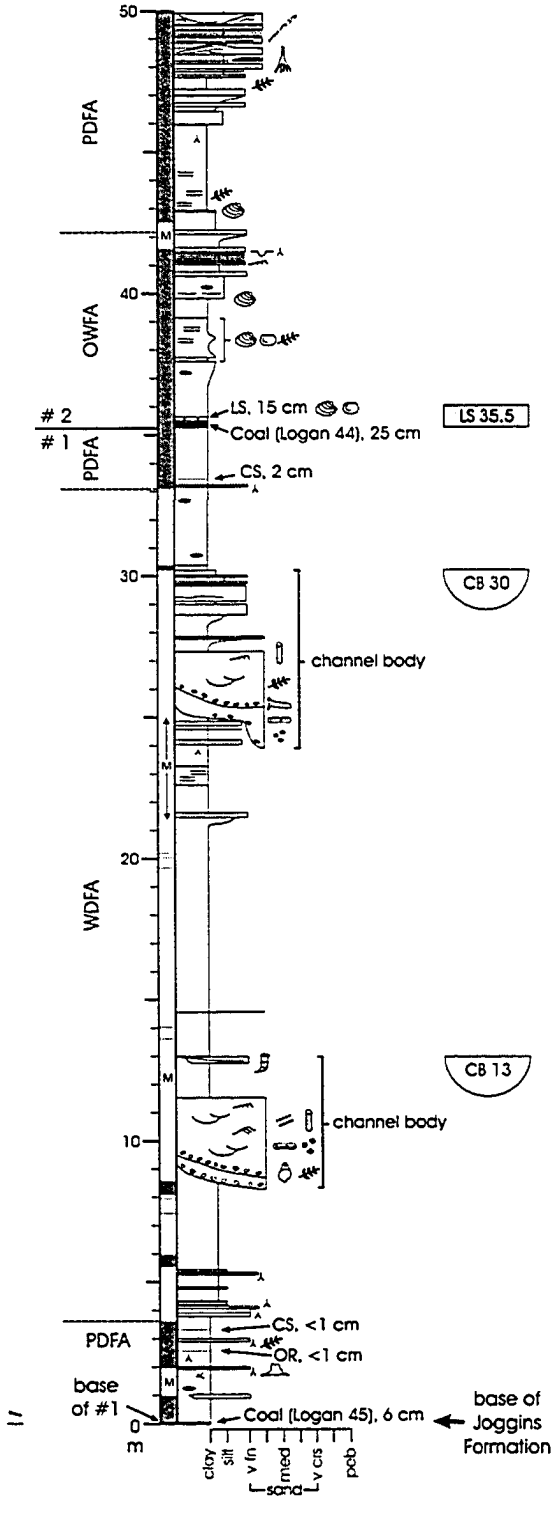
*Fig. 10.*

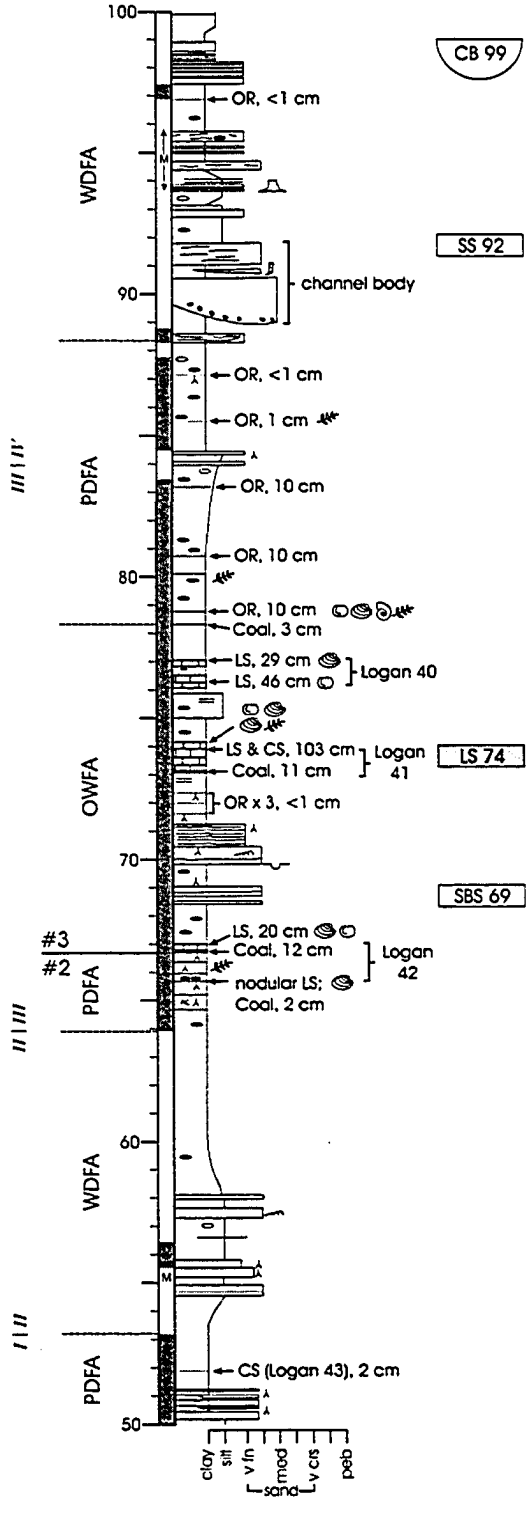
SIDE VIEW

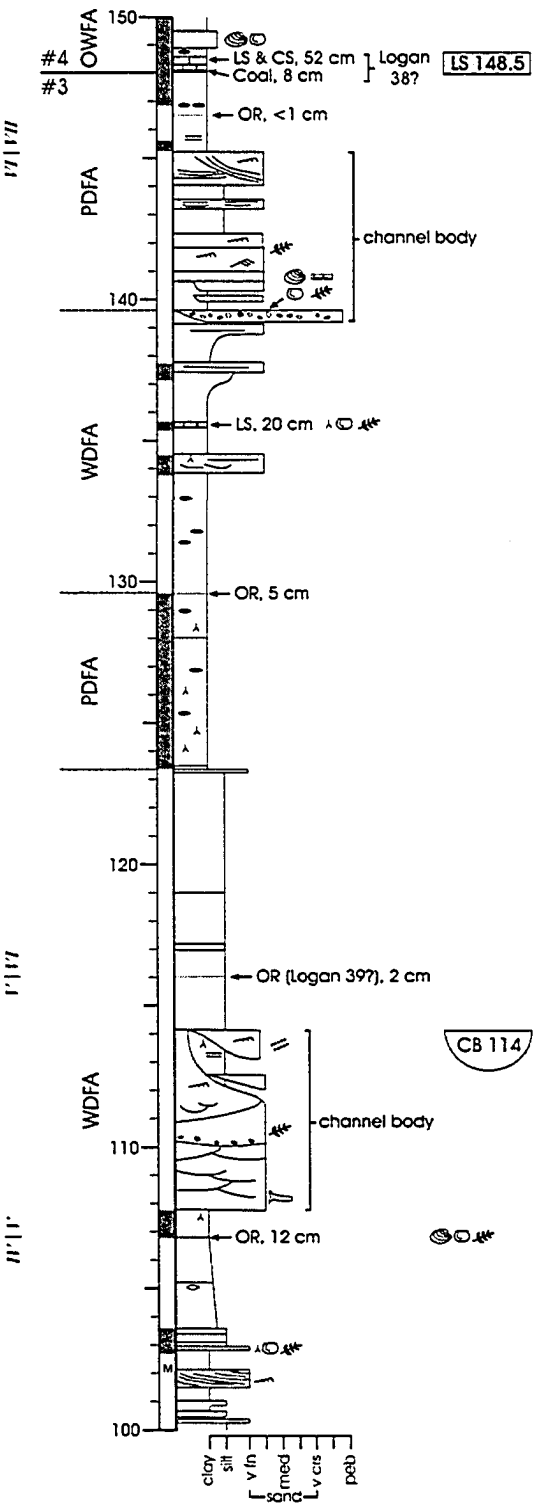


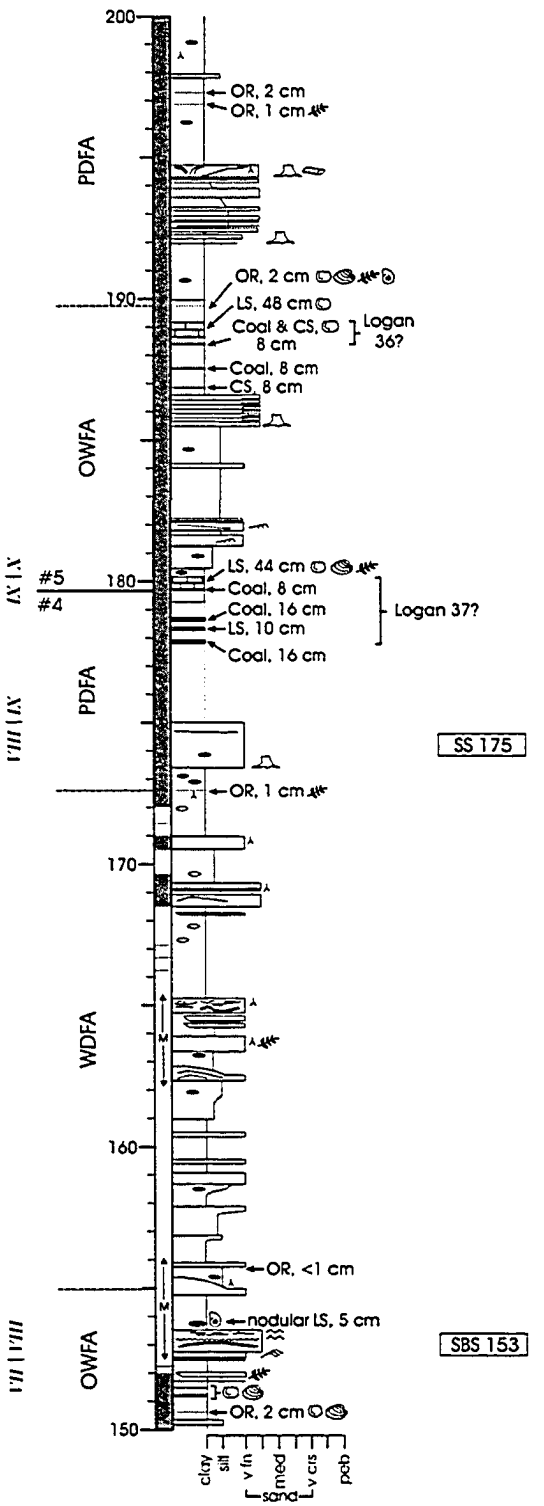
## APPENDIX 4: THE JOGGINS MEASURED SECTION

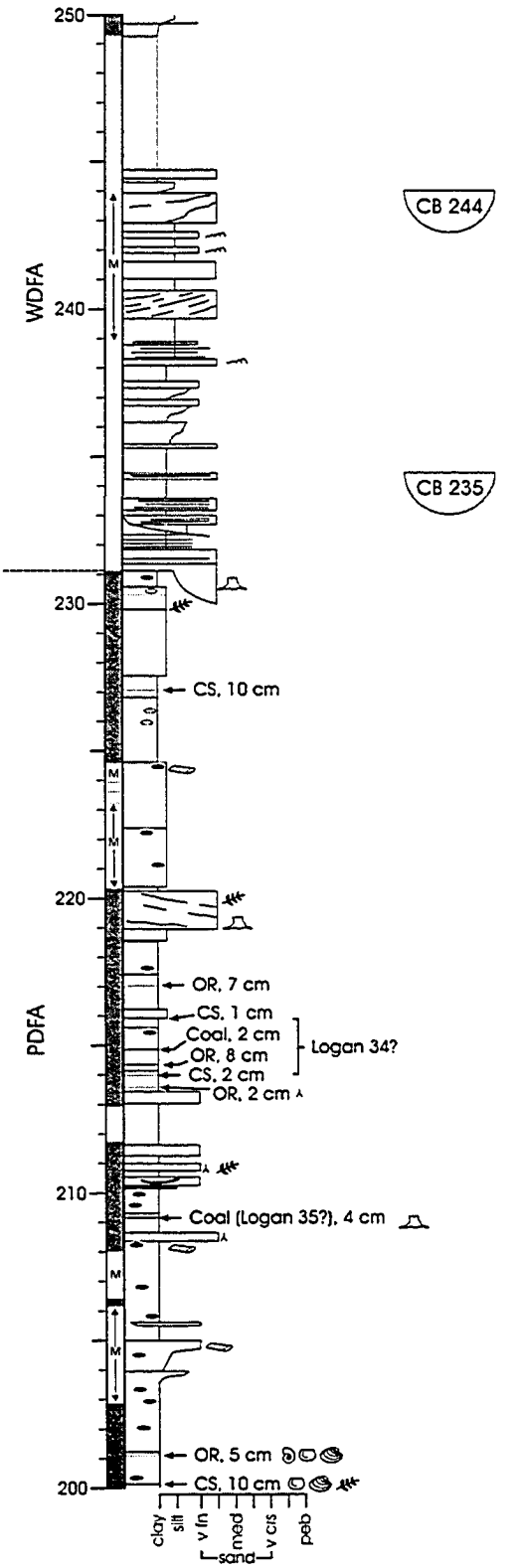
The following eleven pages show the detailed measured section of the Joggins Formation, from the base in the low cliffs at Lower Cove to the formation top south of Bell's Brook (from Davies *et al.*, submitted). A key to the symbols and features shown on the measured section is provided on the final page of the measured section.

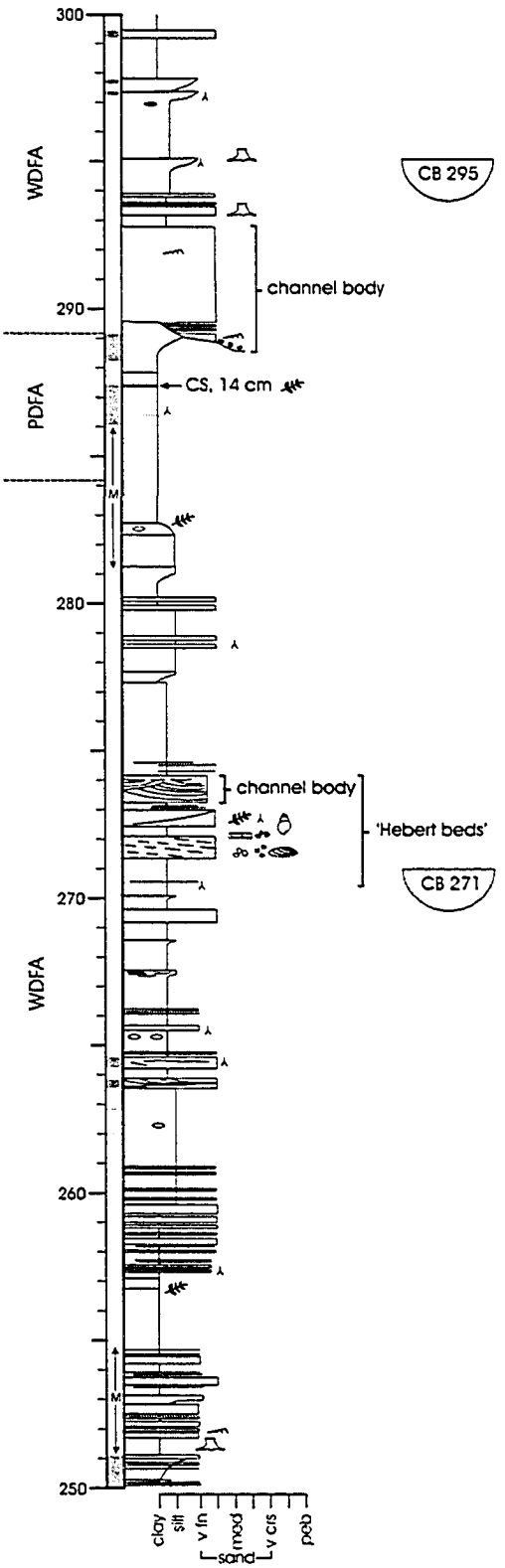

50
PDFA
40
OWFA
# 2
# 1
PDFA
LS, 15 cm
Coal (Logan 44), 25 cm
CS, 2 cm
LS 35.5
30
CB 30
channel body
WDFA
20
CB 13
channel body
10
CS, <1 cm
PDFA
OR, <1 cm
base of #1
Coal (Logan 45), 6 cm
base of Joggins Formation
0
m
clay
silt
v fn
fn
med
crs
v crs
peb
sand

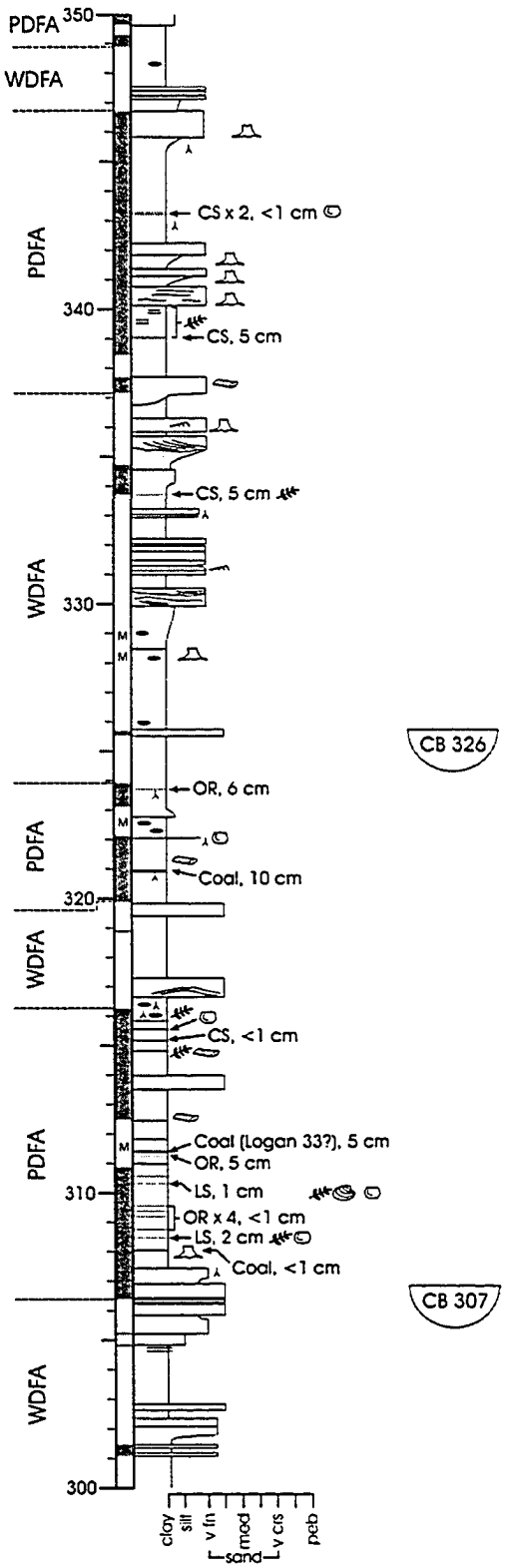

100
CB 99
OR, <1 cm
WDFA
SS 92
channel body
90
OR, <1 cm
OR, 1 cm
PDFA
OR, 10 cm
OR, 10 cm
80
OR, 10 cm
Coal, 3 cm
LS, 29 cm
LS, 46 cm
Logan 40
LS & CS, 103 cm
Coal, 11 cm
Logan 41
LS 74
OWFA
OR x 3, <1 cm
70
SBS 69
#3
#2
LS, 20 cm
Coal, 12 cm
Logan 42
PDFA
nodular LS;
Coal, 2 cm
60
WDFA
CS (Logan 43), 2 cm
50
clay
silt
v fn
fn
med
crs
v crs
peb
sand

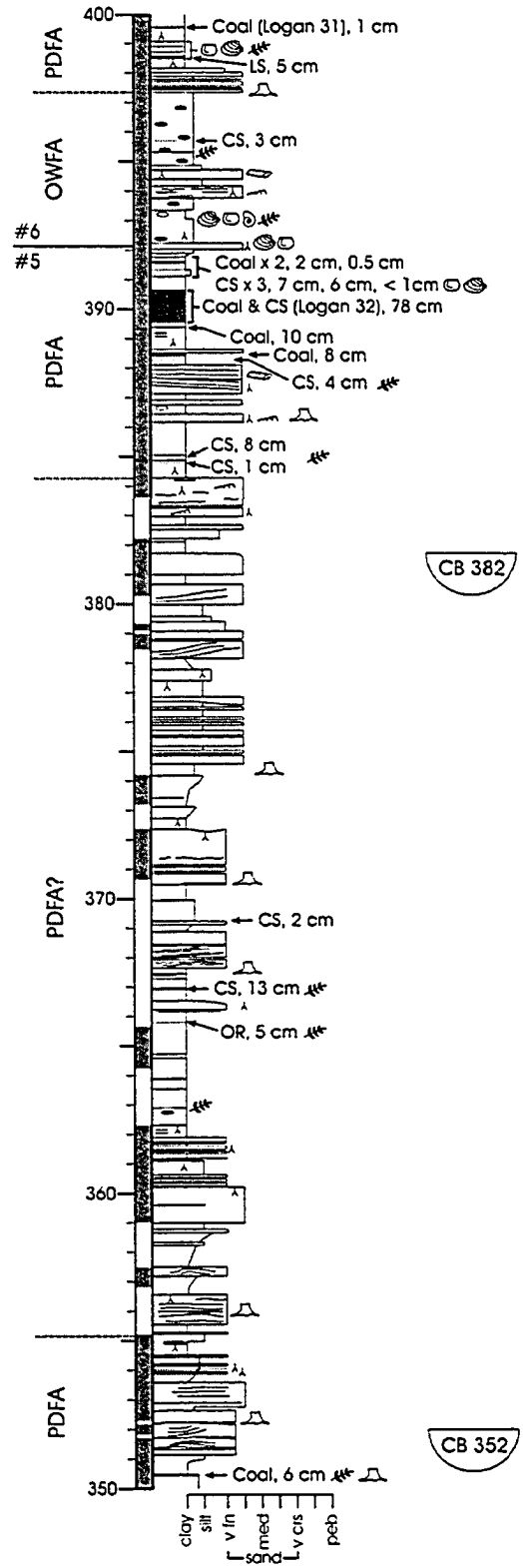

150
#4
#3
OWFA
LS & CS, 52 cm
Coal, 8 cm
Logan 38?
LS 148.5
OR, <1 cm
PDFA
channel body
140
WDFA
LS, 20 cm
130
OR, 5 cm
PDFA
120
OR (Logan 39?), 2 cm
CB 114
WDFA
channel body
110
OR, 12 cm
M
100
clay
silt
v fn
med
v crs
peb
sand

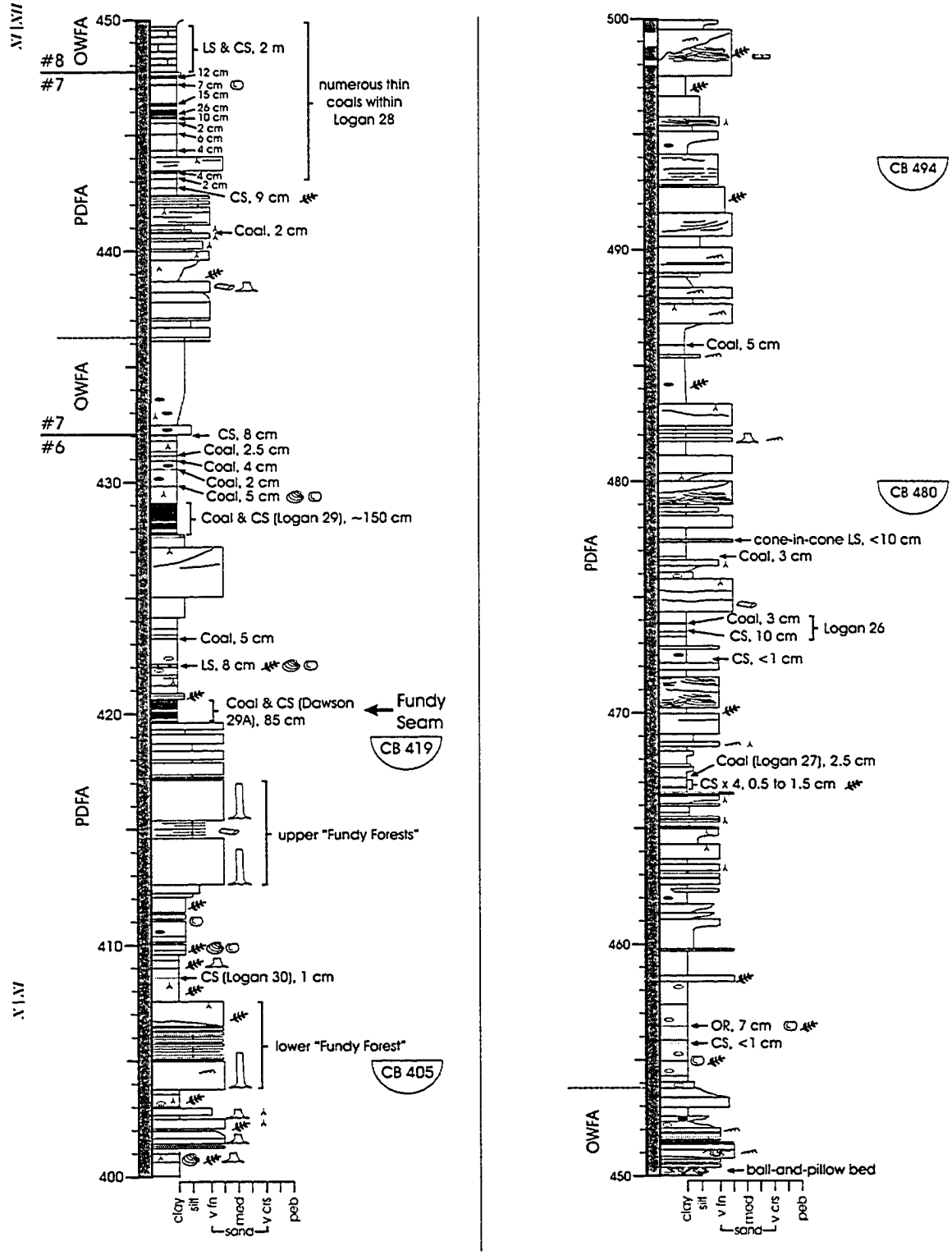

200
PDFA
OR, 2 cm
OR, 1 cm
OR, 2 cm
190
LS, 48 cm
Coal & CS, 8 cm
Logan 36?
Coal, 8 cm
CS, 8 cm
OWFA
LS, 44 cm
#5
180
#4
Coal, 8 cm
Coal, 16 cm
LS, 10 cm
Logan 37?
Coal, 16 cm
PDFA
SS 175
OR, 1 cm
170
WDFA
M
160
OR, <1 cm
M
nodular LS, 5 cm
SBS 153
OWFA
OR, 2 cm
150
clay
silt
v fn
med
v crs
peb
sand

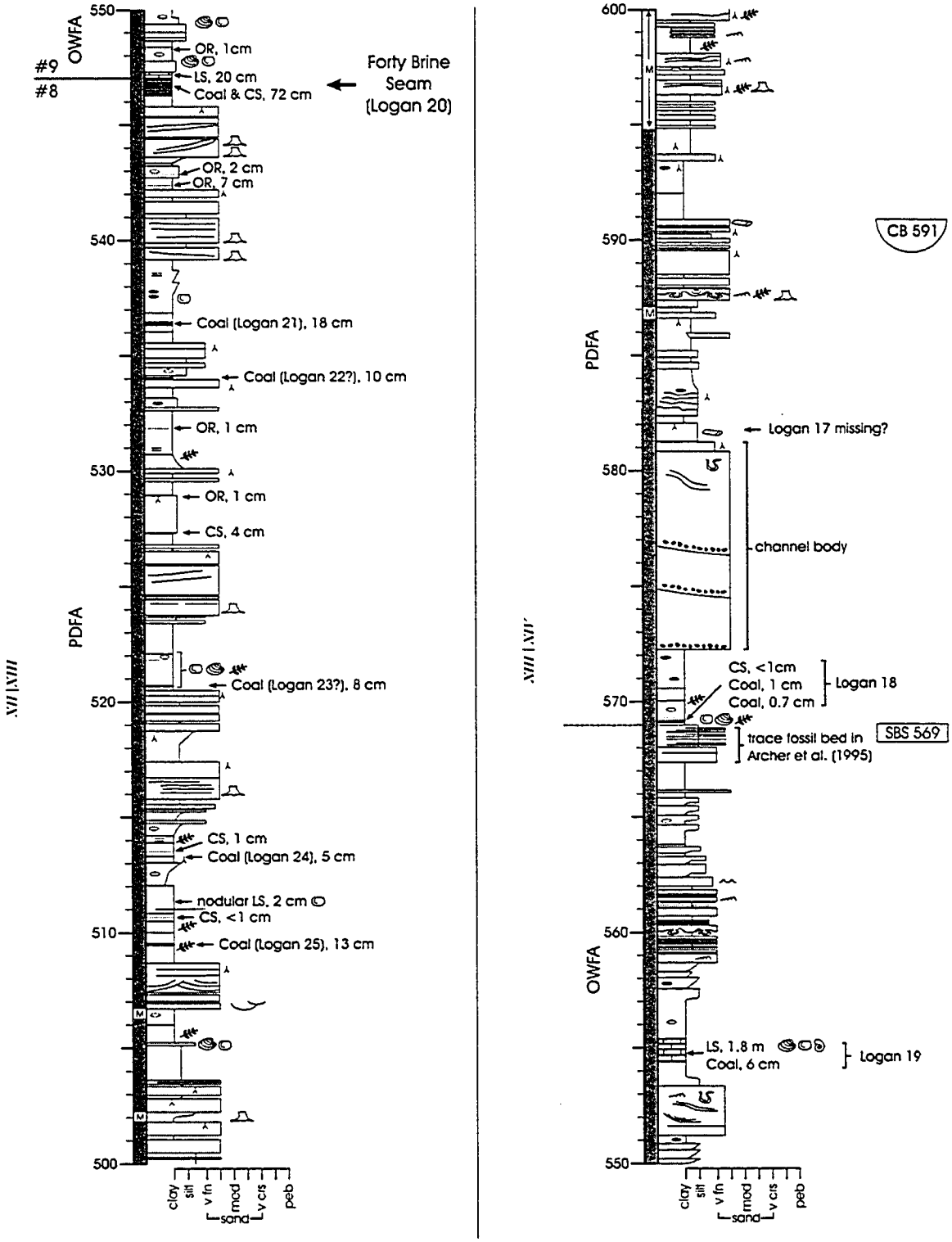

250
240
230
220
210
200
WDFA
PDFA
CB 244
CB 235
CS, 10 cm
OR, 7 cm
CS, 1 cm
Coal, 2 cm
OR, 8 cm
CS, 2 cm
OR, 2 cm
Logan 34?
Coal (Logan 35?), 4 cm
OR, 5 cm
CS, 10 cm
clay
silt
v fn
fn
mod
v crs
crs
peb
sand

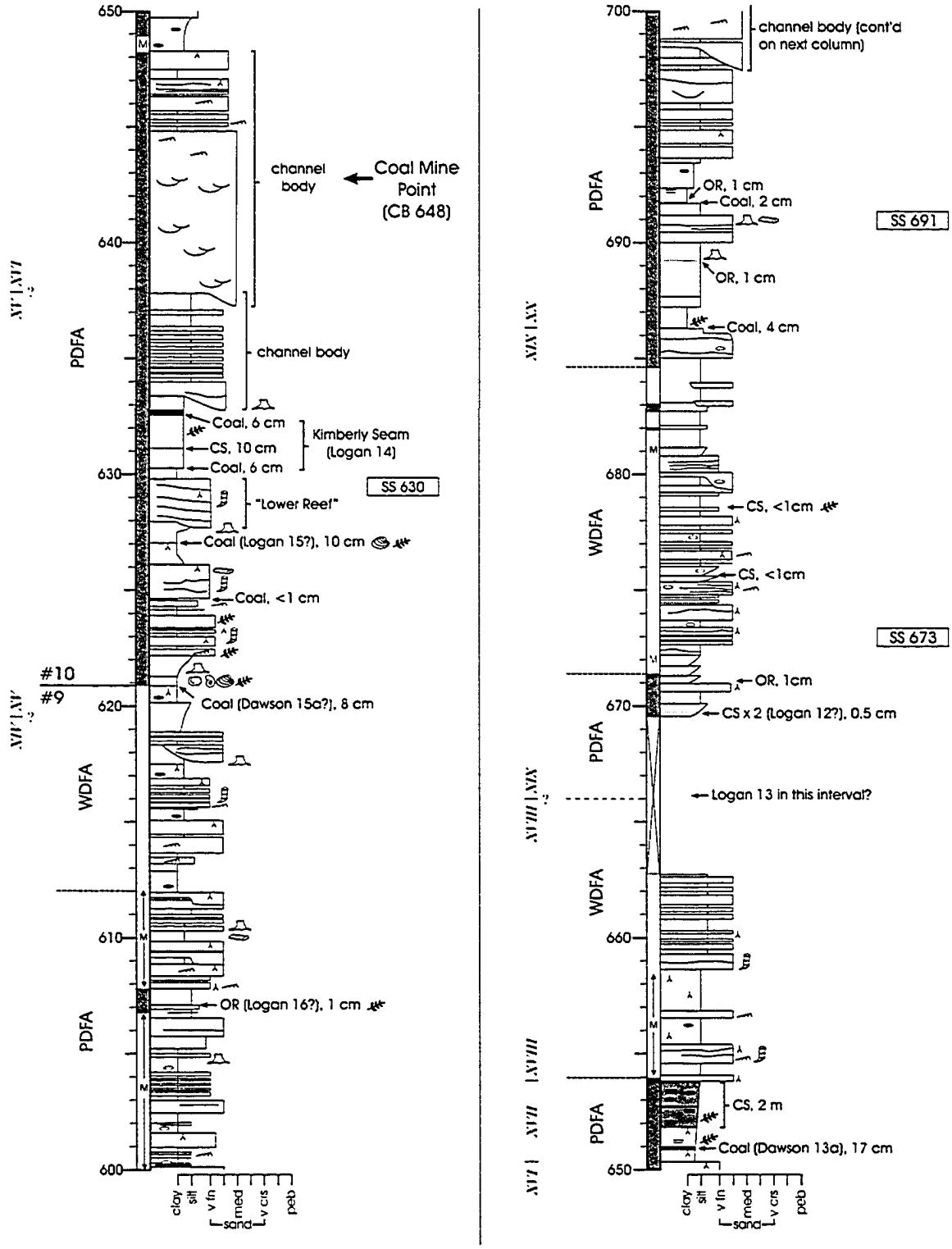

300
290
280
270
260
250
WDFA
PDFA
CB 295
channel body
CS, 14 cm
channel body
'Hebert beds'
CB 271
clay
silt
v fn
fn
mod
v crs
crs
peb
sand

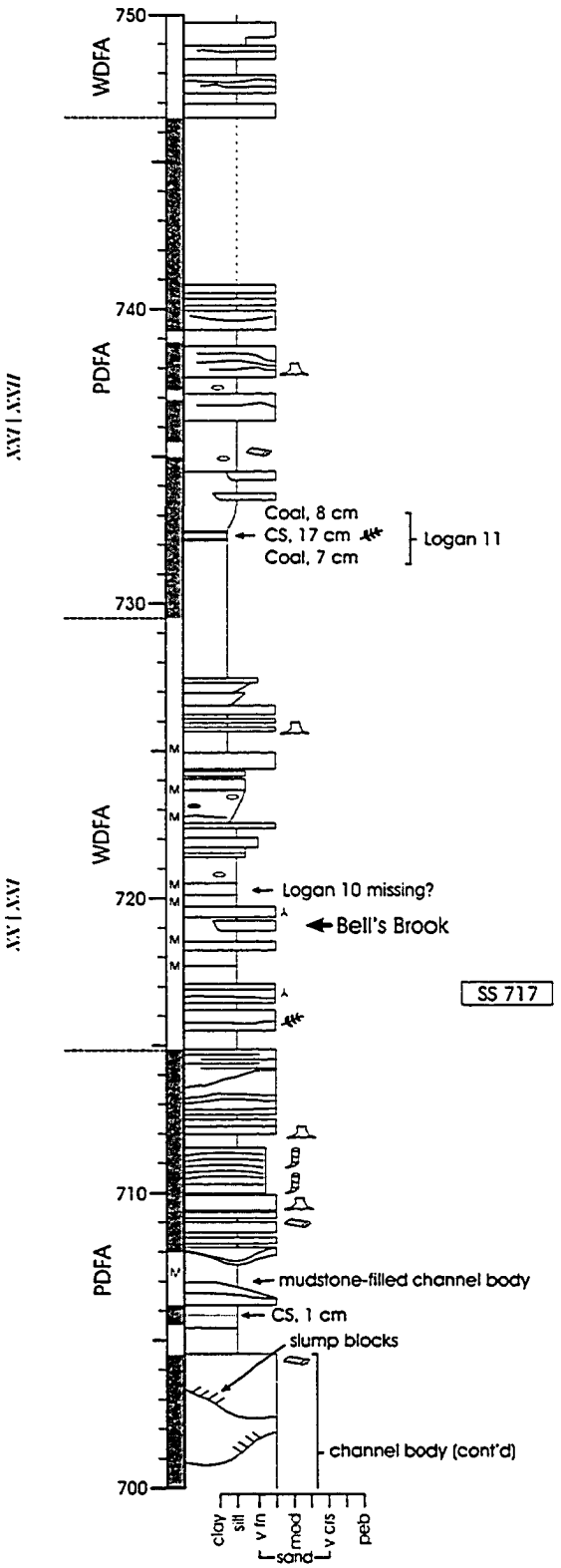

PDFA
350
WDFA
CS x 2, <1 cm
PDFA
340
CS, 5 cm
CS, 5 cm
WDFA
330
CB 326
OR, 6 cm
PDFA
Coal, 10 cm
320
WDFA
CS, <1 cm
PDFA
Coal (Logan 33?), 5 cm
OR, 5 cm
310
LS, 1 cm
OR x 4, <1 cm
LS, 2 cm
Coal, <1 cm
CB 307
WDFA
300
clay
sil
v fn
fn
med
v crs
crs
peb
sand

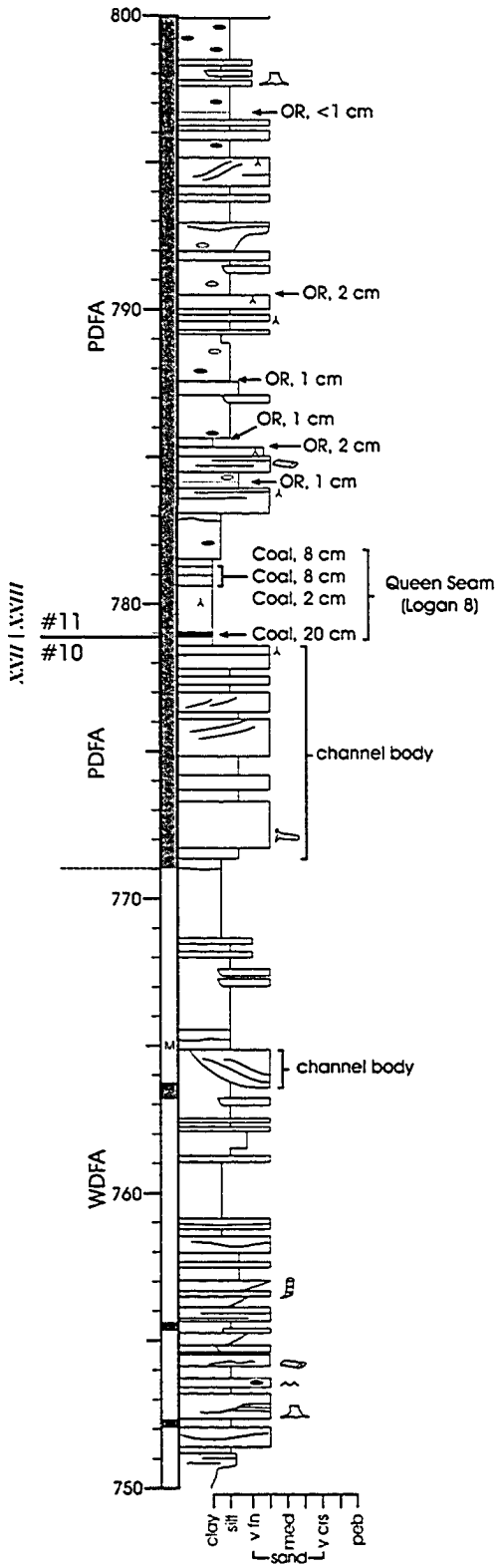

400
PDFA
Coal (Logan 31), 1 cm
LS, 5 cm
CS, 3 cm
OWFA
#6
#5
Coal x 2, 2 cm, 0.5 cm
CS x 3, 7 cm, 6 cm, < 1cm
Coal & CS (Logan 32), 78 cm
390
Coal, 10 cm
Coal, 8 cm
PDFA
CS, 4 cm
CS, 8 cm
CS, 1 cm
CB 382
380
PDFA?
370
CS, 2 cm
CS, 13 cm
OR, 5 cm
360
PDFA
CB 352
Coal, 6 cm
350
clay
sil
v fn
fn
med
v crs
crs
peb
sand

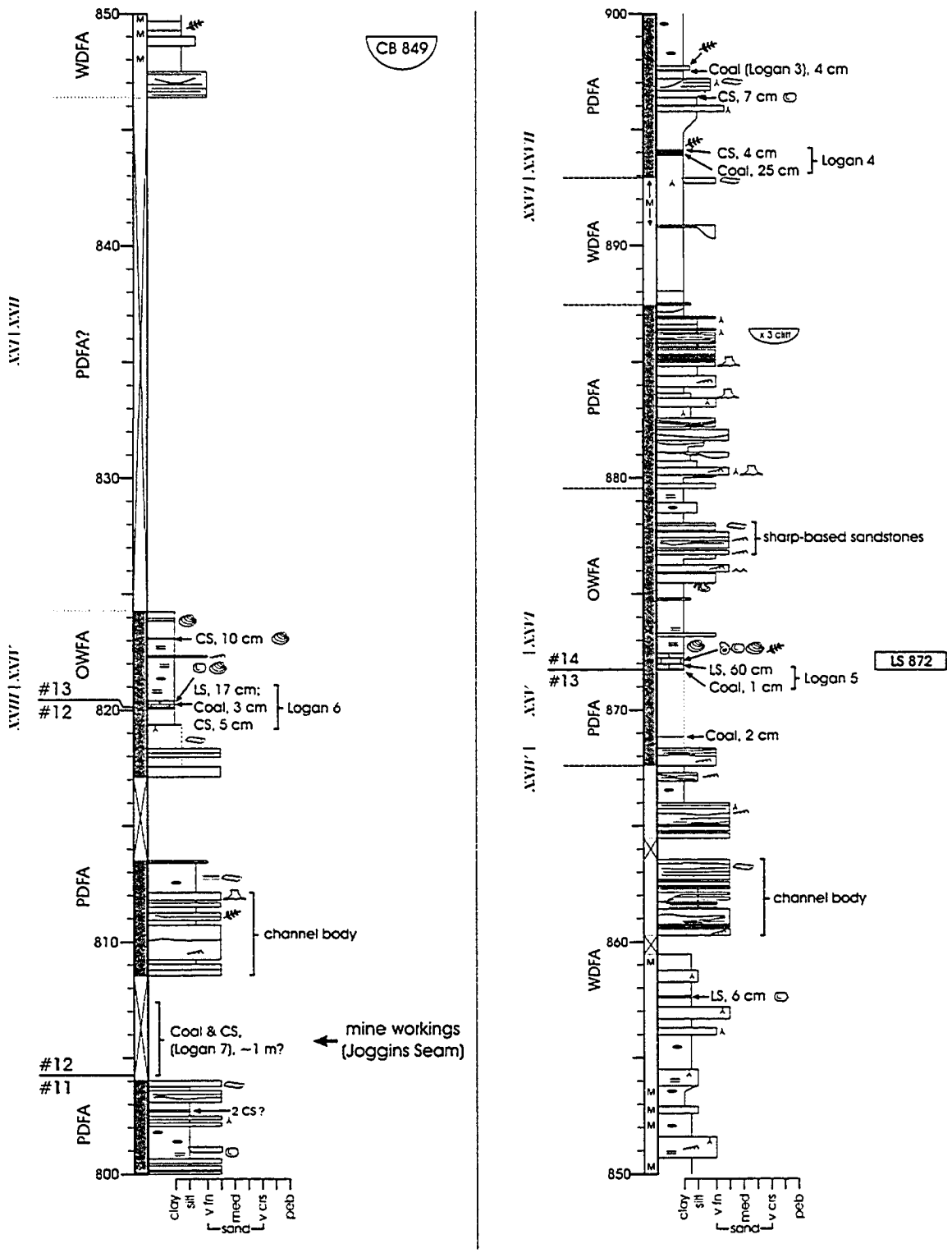

XVIII
XVII
OWFA
#8
#7
PDFA
OWFA
#7
#6
PDFA
OWFA
450
440
430
420
410
400
LS & CS, 2 m
12 cm
7 cm
15 cm
26 cm
10 cm
2 cm
6 cm
4 cm
4 cm
2 cm
numerous thin coals within Logan 28
CS, 9 cm
Coal, 2 cm
CS, 8 cm
Coal, 2.5 cm
Coal, 4 cm
Coal, 2 cm
Coal, 5 cm
Coal & CS (Logan 29), ~150 cm
Coal, 5 cm
LS, 8 cm
Coal & CS (Dawson 29A), 85 cm
Fundy Seam
CB 419
upper "Fundy Forests"
CS (Logan 30), 1 cm
lower "Fundy Forest"
CB 405
clay
silt
v fn
fn
mod
v crs
crs
peb
sand
500
490
480
470
460
450
CB 494
Coal, 5 cm
CB 480
cone-in-cone LS, <10 cm
Coal, 3 cm
Coal, 3 cm
CS, 10 cm
Logan 26
CS, <1 cm
Coal (Logan 27), 2.5 cm
CS x 4, 0.5 to 1.5 cm
OR, 7 cm
CS, <1 cm
ball-and-pillow bed

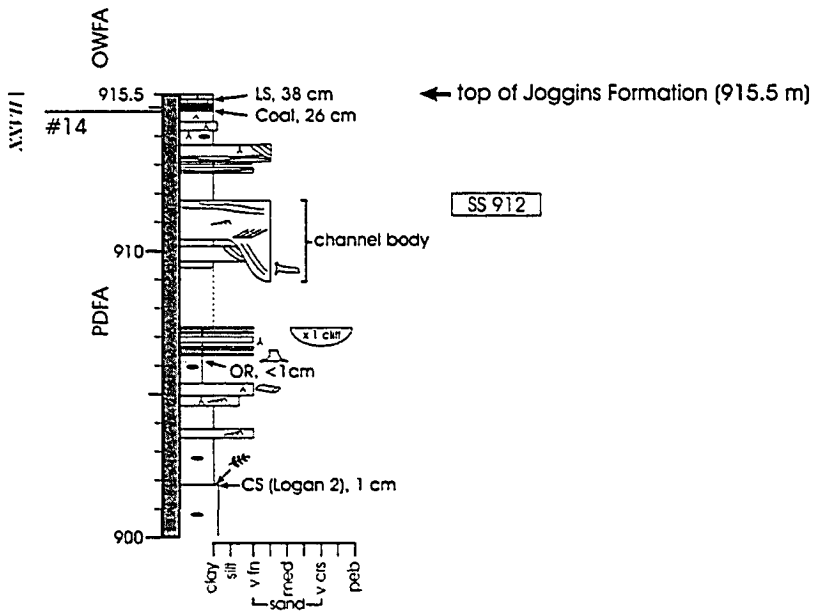

OWFA
#9
#8
550
OR, 1cm
LS, 20 cm
Coal & CS, 72 cm
Forty Brine Seam (Logan 20)
OR, 2 cm
OR, 7 cm
540
Coal (Logan 21), 18 cm
Coal (Logan 22?), 10 cm
OR, 1 cm
530
OR, 1 cm
CS, 4 cm
PDFA
Coal (Logan 23?), 8 cm
520
CS, 1 cm
Coal (Logan 24), 5 cm
nodular LS, 2 cm
CS, <1 cm
510
Coal (Logan 25), 13 cm
500
clay
silt
v fn
fn
mod
v crs
peb
sand
600
590
CB 591
PDFA
Logan 17 missing?
580
channel body
CS, <1cm
Coal, 1 cm
Coal, 0.7 cm
Logan 18
570
trace fossil bed in Archer et al. (1995)
SBS 569
560
OWFA
LS, 1.8 m
Coal, 6 cm
Logan 19
550


650
640
630
620
610
600
700
690
680
670
660
650
PDFA
WDFA
channel body
Coal Mine Point (CB 648)
channel body
Coal, 6 cm
CS, 10 cm
Coal, 6 cm
Kimberly Seam (Logan 14)
SS 630
"Lower Reef"
Coal (Logan 15?), 10 cm
Coal, <1 cm
#10
#9
Coal (Dawson 15a?), 8 cm
OR (Logan 16?), 1 cm
channel body (cont'd on next column)
OR, 1 cm
Coal, 2 cm
SS 691
OR, 1 cm
Coal, 4 cm
CS, <1cm
CS, <1cm
SS 673
OR, 1cm
CS x 2 (Logan 12?), 0.5 cm
Logan 13 in this interval?
CS, 2 m
Coal (Dawson 13a), 17 cm
clay
silt
v fn
fn
med
f crs
v crs
peb
sand

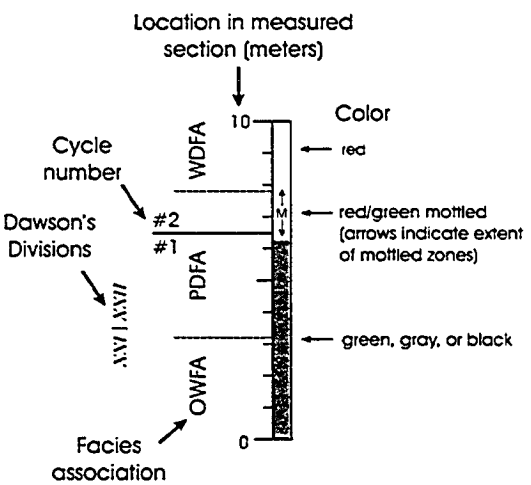

750
740
730
720
710
700
WDFA
PDFA
WDFA
PDFA
XXV | XXVI
XXV | XXV
Coal, 8 cm
CS, 17 cm
Coal, 7 cm
Logan 11
Logan 10 missing?
Bell's Brook
SS 717
mudstone-filled channel body
CS, 1 cm
slump blocks
channel body (cont'd)
clay
silt
v fn
fn
mod
v crs
crs
peb
sand


800
790
780
770
760
750
PDFA
PDFA
WDFA
XXVI | XXVIII
#11
#10
OR, <1 cm
OR, 2 cm
OR, 1 cm
OR, 1 cm
OR, 2 cm
OR, 1 cm
Coal, 8 cm
Coal, 8 cm
Coal, 2 cm
Coal, 20 cm
Queen Seam
(Logan 8)
channel body
channel body
clay
silt
v fn
fn
mod
v crs
crs
peb
sand


CB 849
WDFA
PDFA?
OWFA
PDFA
WDFA
PDFA
OWFA
PDFA
WDFA
PDFA
XVI | XVII
XVIII | XVII
XVII | XVI
XVI | XV
XV | XIV
#13
#12
#12
#11
#14
#13
850
840
830
820
810
800
900
890
880
870
860
850
CS, 10 cm
LS, 17 cm;
Coal, 3 cm
CS, 5 cm
Logan 6
channel body
Coal & CS,
(Logan 7), ~1 m?
mine workings
(Joggins Seam)
2 CS?
Coal (Logan 3), 4 cm
CS, 7 cm
CS, 4 cm
Coal, 25 cm
Logan 4
x 3 cm
sharp-based sandstones
LS, 60 cm
Coal, 1 cm
Logan 5
LS 872
Coal, 2 cm
channel body
LS, 6 cm
clay
silt
v fn
fn
med
crs
v crs
peb
sand




## EXPLANATION OF SEDIMENTOLOGICAL LOG




### TIDAL FLAT OUTCROPS

CB # = channel body

SBS # = sharp-based sandstone

SS # = sheet sandstone

LS # = limestone

# indicates meterage at top of the bed (to the nearest meter)

### FACIES ASSOCIATIONS

OWFA = open-water facies association

PDFA = poorly drained facies association

WDFA = well drained facies association

### ORGANIC HORIZONS

LS = limestone

Coal (Logan # if applicable)

CS = carbonaceous shale

OR = organic-rich horizon

# SYMBOLS USED IN SEDIMENTOLOGICAL LOG

## SEDIMENTARY FEATURES

- concretion or nodule (calcareous)
- concretion or nodule (non-calcareous)
- calcareous rip-up clast
- mud-chip rip-up clast
- climbing ripple cross-lamination
- wave ripple
- ripple cross-lamination
- trough cross-bedding
- planar cross-bedding
- horizontal lamination
- groove cast or tool mark
- pedogenic slickenside
- convolute bedding

## FLORA

- calamite (*in situ*)
- calamite (transported)
- lycopsid trunk (*in situ*)
- lycopsid trunk (transported)
- *Stigmaria* Sp.
- cordaite gymnosperm (*in situ*)
- *Artisia transversa* (cordaite pith cast)
- *Cordaites principalis* (cordaite leaf)
- finely macerated plant material
- root compression
- charcoal

## FAUNA

- *Diplichnites* (*Arthropleura* trackway)
- bivalve
- ostracode
- *Spirorbis*
- *Dendropupa vetusta*
- tetrapod bone
- tetrapod trackway
- fish bone or scale

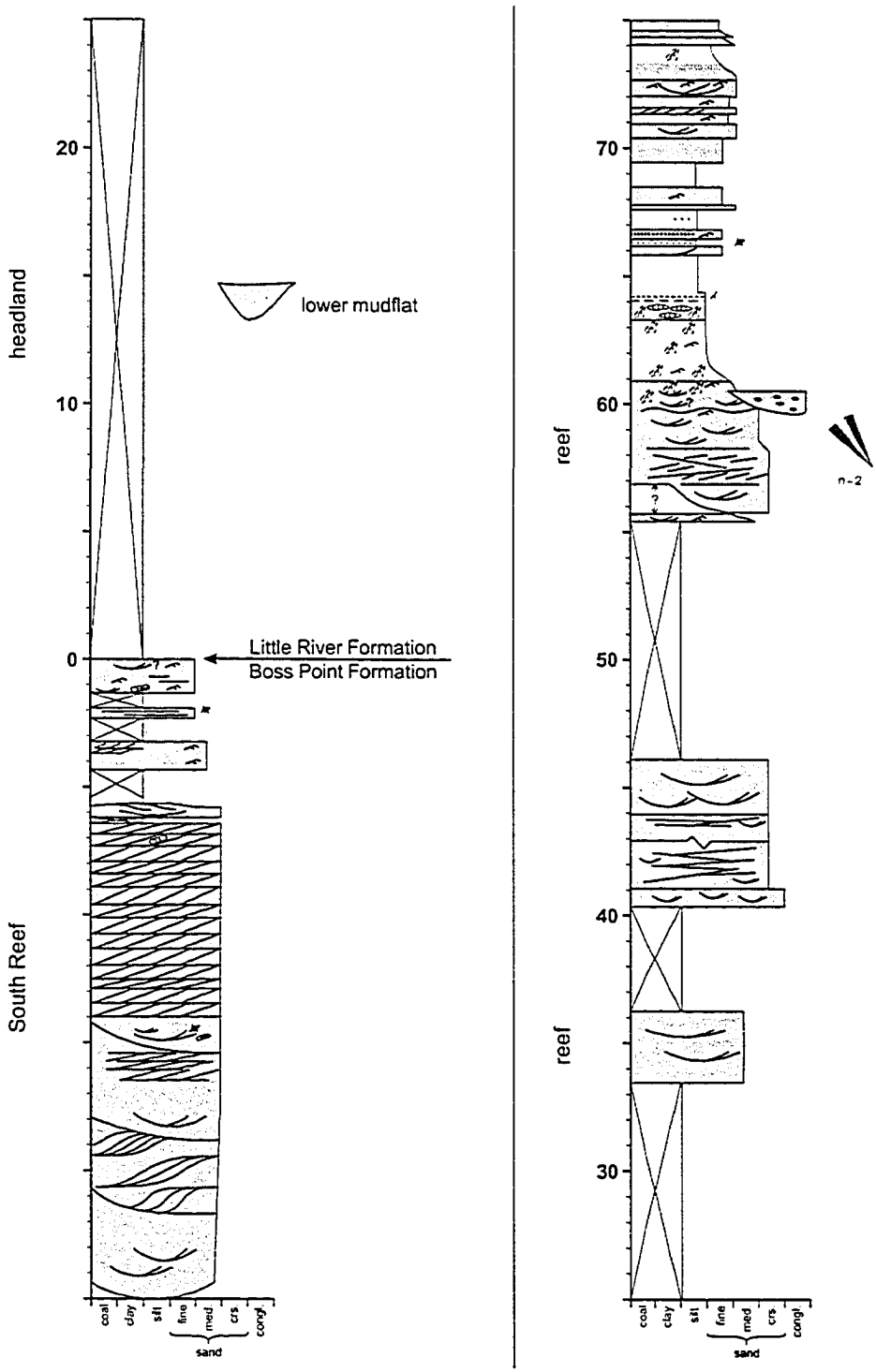
# APPENDIX 5: JOGGINS CHANNEL BODY INFORMATION

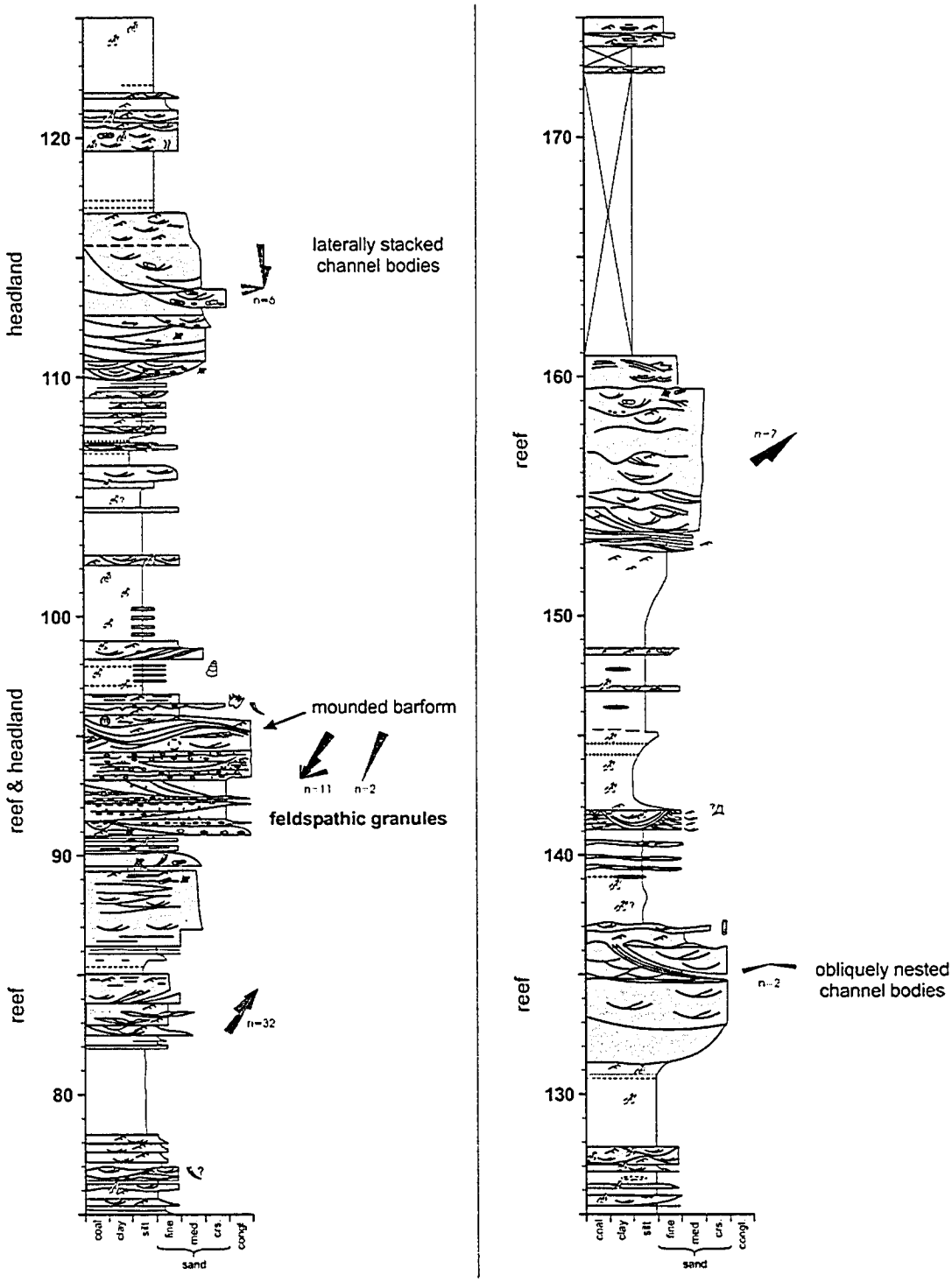
| Stratigraphic Position | Type | Thickness (m) | Width (m) | Width/ Thickness | Paleoflow | Facies Association | Exposure |
|---|---|---|---|---|---|---|---|
| 13 | Multistorey | 5.3 | >115.0 | >21.7 | 150 | WDF | cliff/intertidal |
| 30 | Multistorey | 6 | >338.0 | >56.3 | 148 | WDF | cliff/intertidal |
| 49A | Fixed | 1 | <14.2 | <14.2 | ? | PDF | intertidal |
| 49B | Fixed | 1 | 7.1 | 7.1 | 326 | PDF | intertidal |
| 58 | Fixed | 1.6 | <22.6 | <14.1 | ? | WDF | intertidal |
| 93 | Fixed | 3.4 | 25.0 | 7.4 | 299 | WDF | cliff |
| 99 | Fixed | 3.1 | 9.0 | 2.9 | 354 | WDF | intertidal |
| 102A | Fixed | 1.2 | >1.9 | >1.6 | 3/183 | WDF | cliff |
| 102B | Fixed | 1.4 | 3.7 | 2.6 | 340 | WDF | intertidal |
| 114 | Multistorey | 6.5 | >51.0 | >7.8 | 75 | WDF | cliff/intertidal |
| 145 | Fixed: mud-filled | 5.5 | 11.0 | 2.0 | 23 | PDF | cliff |
| 167A | Fixed | 2.5 | <21.0 | <8.4 | ? | WDF | intertidal |
| 167B | Fixed | 1.8 | 4.5 | 2.5 | 294 | WDF | intertidal |
| 234 | Fixed | 1.3 | 3.5 | 2.7 | 054 | WDF | intertidal |
| 235A | Fixed | 1.7 | 7.3 | 4.3 | 299 | WDF | intertidal |
| 235B | Fixed | 1.3 | 5.6 | 4.3 | 067 | WDF | intertidal |
| 244 | Fixed | 2.8 | 22.8 | 8.1 | 047 | WDF | intertidal |
| 251 | Fixed | 1.28 | 5.2 | 4.1 | 99/279 | WDF | cliff |
| 271 | Fixed | 3.4 | 21.0 | 6.2 | 068 | WDF | intertidal |
| 271.5 | Fixed | 5.7 | >27.4 | >4.8 | 050 | WDF | cliff |
| 274A | Fixed | 3.9 | >14.0 | >3.6 | 065 | WDF | cliff |
| 274B | Meandering | 3.5 | >20.4 | >5.8 | 064 | WDF | cliff |
| 274C | Meandering | 1.8 | 39.6 | 22.0 | 109 | WDF | cliff |
| 291 | Meandering | 2.5 | 89.0 | 35.6 | 140 | WDF | intertidal |
| 293A | Fixed | 2.4 | <18.7 | <7.8 | ? | WDF | cliff |
| 293B | Fixed | 2.3 | 33.0 | 14.3 | 036 | WDF | intertidal |
| 295 | Fixed | 5 | 31.0 | 6.2 | 078 | WDF | intertidal |
| 302 | Fixed | 3.6 | 22.0 | 6.1 | 076 | WDF | intertidal |
| 307 | Meandering | 2.3 | 147.0 | 63.9 | 015 | WDF | intertidal |
| 314 | Fixed | 1.4 | <5.6 | <4.0 | ? | PDF | intertidal |
| 320A | Meandering | 3 | 28.0 | >9.3 | 057/237 | WDF | cliff |
| 320B | Fixed | 4 | 36.0 | 9.0 | 222 | WDF | intertidal |
| 326 | Fixed | 1.4 | 13.0 | 9.3 | 194 | WDF | intertidal |
| 328 | Fixed | 3.6 | 20.0 | 5.6 | 073 | WDF | intertidal |
| 347 | Fixed | 1.3 | 10.0 | 7.7 | 097/277 | WDF | cliff |
| 348 | Fixed | 3.3 | 13.0 | 3.9 | 124 | WDF | intertidal |
| 352 | Meandering | 3.4 | 72.0 | 21.2 | 340 | PDF | intertidal |
| 366 | Fixed | 1.4 | <3.8 | <2.7 | ? | PDF | cliff |
| 369 | Fixed | 1.2 | <4.3 | <3.6 | 098/278 | PDF | cliff |
| 379 | Fixed | 1 | <3.1 | <3.2 | ? | PDF | cliff |
| 382 | Fixed: Mud-filled | 4 | 45.0 | 11.3 | 335 | PDF | intertidal |

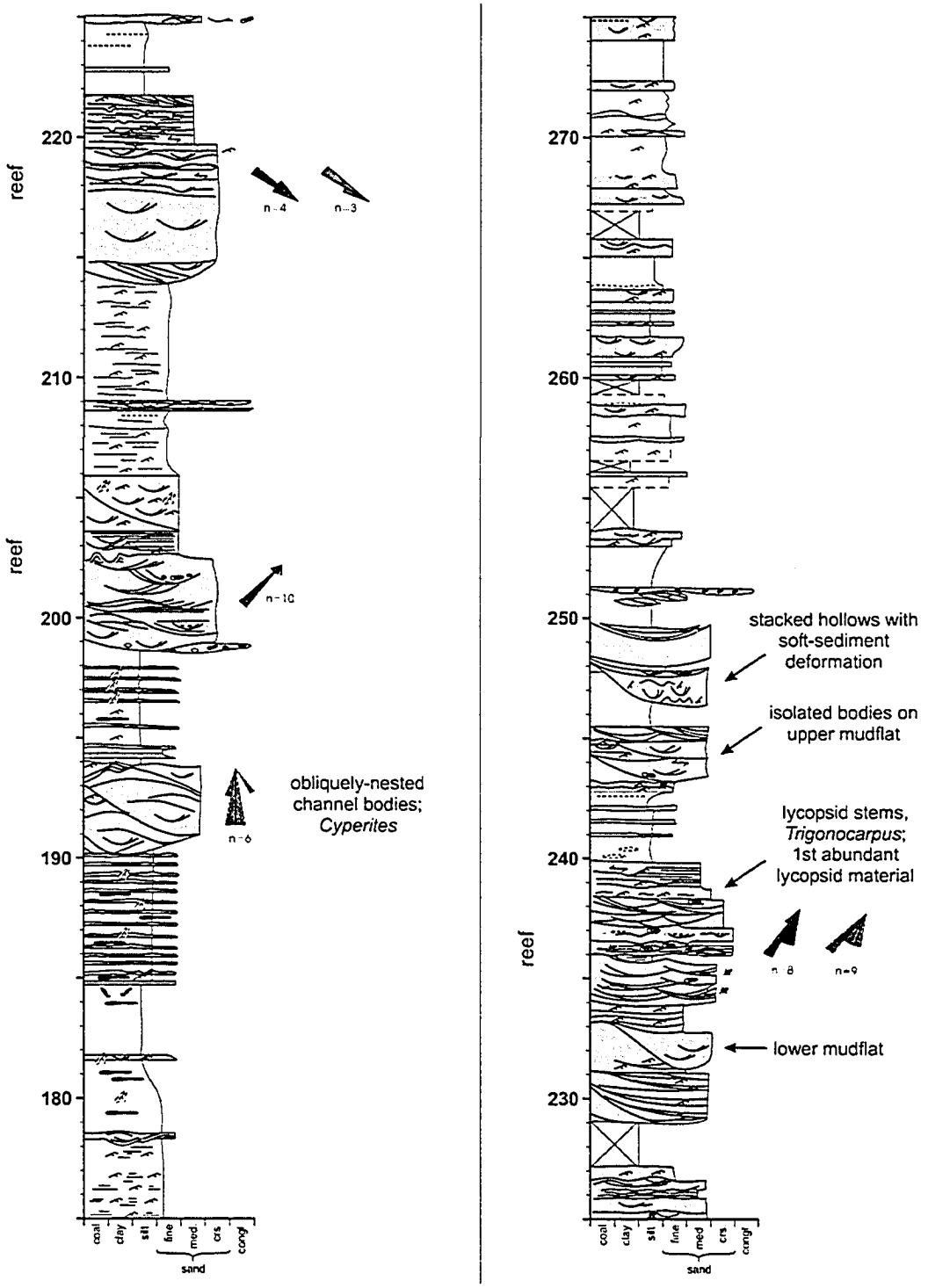
| Stratigraphic Position | Type | Thickness (m) | Width (m) | Width/ Thickness | Paleoflow | Facies Association | Exposure |
|---|---|---|---|---|---|---|---|
| 383 | Fixed | 4.5 | 22.0 | 4.9 | 347 | PDF | intertidal |
| 384 | Fixed | 2.6 | <15.4 | <5.9 | ? | PDF | intertidal |
| 386 | Meandering | 6.1 | 72.0 | 11.8 | 64 | PDF | intertidal |
| 398 | Fixed | 1.9 | <11.2 | <5.9 | ? | PDF | intertidal |
| 405 | Meandering | 1.7 | <160.0 | <94.1 | ? | PDF | intertidal |
| 419 | Fixed | 4 | 15.0 | 3.8 | 047 | PDF | intertidal |
| 419.5 | Fixed | 4.8 | 27.0 | 5.6 | 041 | PDF | intertidal |
| 436 | Fixed | 1.4 | 3.6 | 2.6 | 007 | PDF | cliff |
| 459 | Fixed | 1.5 | 4.0 | 2.7 | 055/235 | PDF | cliff |
| 464 | Fixed | 1.4 | 14.0 | 10.0 | 140 | PDF | intertidal |
| 465A | Fixed | 2.4 | 6.0 | 2.5 | 066 | PDF | intertidal |
| 465B | Fixed | 1.3 | <8.4 | <6.5 | ? | PDF | intertidal |
| 469 | Fixed | 1.1 | 4.0 | 3.6 | 090/270 | PDF | cliff |
| 470 | Fixed | 2.8 | <56.0 | <20.0 | ? | PDF | intertidal |
| 480 | Fixed | 3.2 | 29.0 | 9.1 | 345 | PDF | intertidal |
| 494A | Meandering | 2.6 | 85.0 | 32.7 | 206 | PDF | intertidal |
| 494B | Meandering | 4.8 | 108.0 | 22.5 | 139 | PDF | intertidal |
| 494C | Meandering | 5.6 | >123.0 | >22.0 | 134 | PDF | intertidal |
| 498 | Fixed | 1.9 | <12.6 | <6.6 | ? | PDF | intertidal |
| 499A | Meandering | 2.6 | 32.0 | 12.3 | 069 | PDF | intertidal |
| 499B | Fixed | 2.2 | 43.0 | 19.5 | 020 | PDF | intertidal |
| 535 | Fixed | 1.3 | 3.2 | 2.5 | 273 | PDF | intertidal |
| 541A | Fixed | 1.4 | <25.2 | <18.0 | ? | PDF | intertidal |
| 541B | Fixed | 1.5 | 5.0 | 3.3 | 086 | PDF | intertidal |
| 553 | Fixed: Distal Distrib. | 1.5 | 17.0 | 11.3 | 111 | PDF | intertidal |
| 569 | Fixed: Distal Distrib. | 4.3 | 58.0 | 13.5 | 129 | PDF | intertidal |
| 581 | Multistorey | 9.2 | >114.0 | >12.4 | 111 | PDF | cliff/intertidal |
| 583 | Fixed | 2.5 | 19.0 | 7.6 | 312 | PDF | cliff |
| 591 | Meandering | 5.6 | 196.0 | 35.0 | 180 | PDF | intertidal |
| 598 | Fixed | 4 | 25.0 | 6.3 | 056 | PDF | intertidal |
| 611 | Fixed | 1.8 | 13.0 | 7.2 | 170 | PDF | intertidal |
| 619 | Fixed | 5 | 62.0 | 12.4 | 087 | WDF | intertidal |
| 648 | Meandering | 10.5 | >403.0 | >38.4 | 177 | PDF | cliff/intertidal |
| 705 | Multistorey | 7.4 | >60.0 | >8.1 | 082 | PDF | cliff |
| 765A | Fixed | 1.8 | 7.1 | 3.9 | 089 | WDF | cliff |
| 765B | Fixed | 1.8 | 6.0 | 3.3 | 089 | WDF | cliff |
| 765C | Fixed | 1.3 | 3.6 | 2.8 | 089 | WDF | cliff |
| 849 | Fixed | 7.5 | <61 | <8.1 | ? | WDF | intertidal |
| 886 | Fixed | 2.5 | 8.5 | 3.4 | 089 | PDF | cliff |
| 887 | Fixed | 2.5 | 6.3 | 2.5 | 089 | PDF | cliff |
| 912 | Fixed | 1.2 | 9.0 | 7.5 | 110 | PDF | cliff |

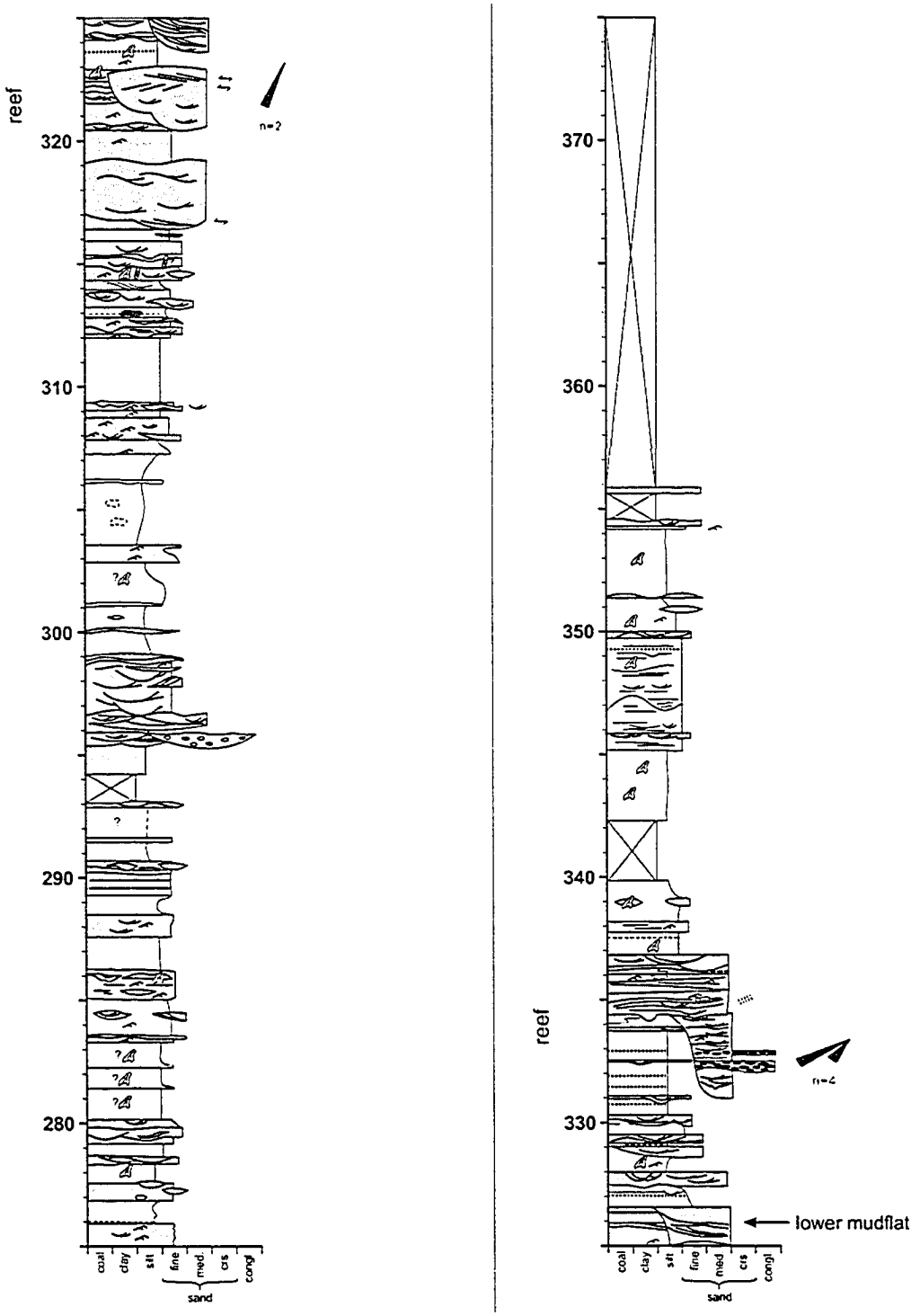
## APPENDIX 6: THE LITTLE RIVER MEASURED SECTION

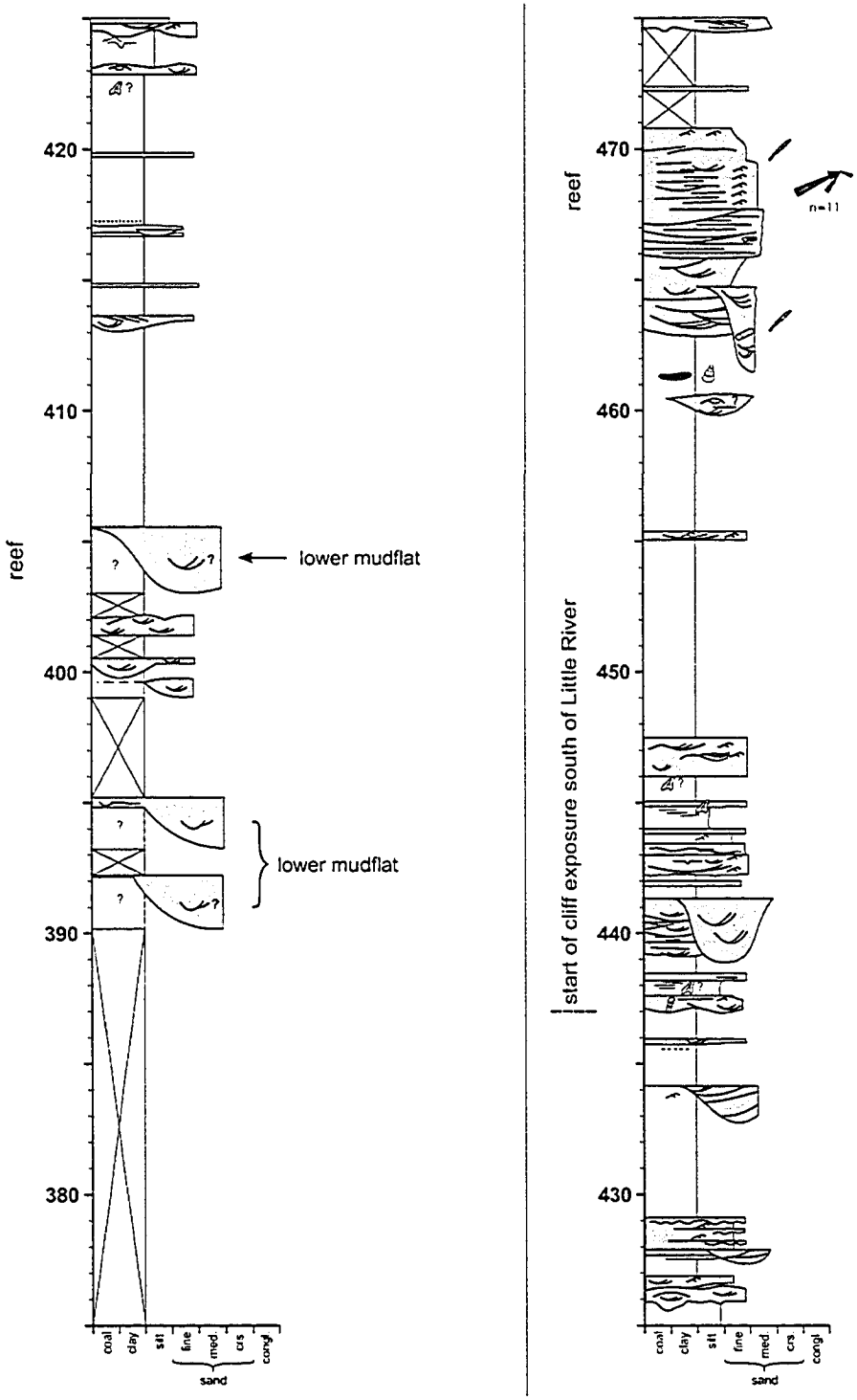
Sedimentological log of the measured type section near Little River, from South Reef to the lowest coal bed (Coal 45 of Logan, 1845) of the overlying coal-bearing strata of the Joggins Formation, approximately coinciding with the start of the continuous cliff section south of Little River (from Calder *et al.*, submitted).

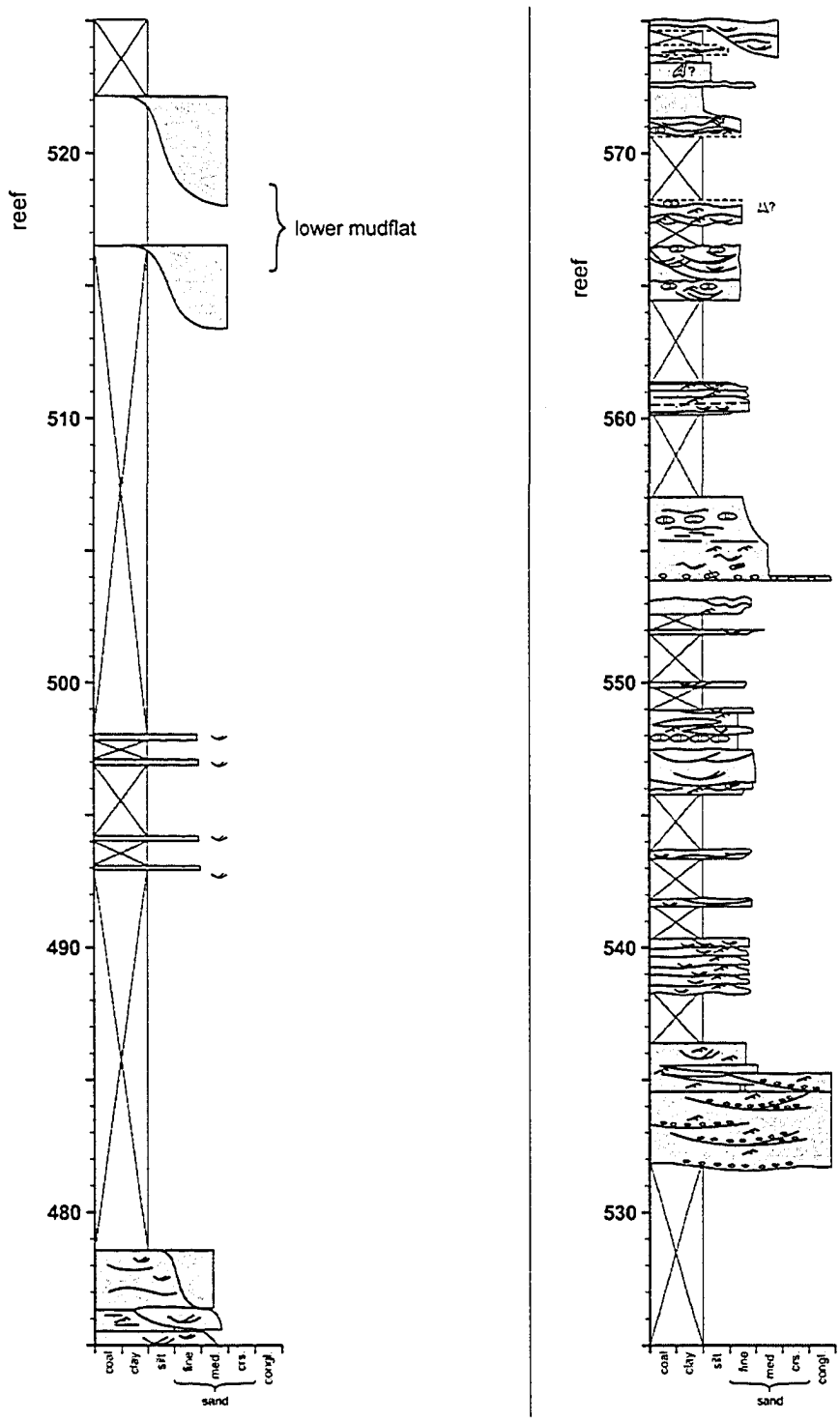

headland
South Reef
20
10
0
lower mudflat
Little River Formation
Boss Point Formation
coal
clay
silt
fine
med
crs
congl
sand
reef
reef
70
60
50
40
30
n-2
coal
clay
silt
fine
med
crs
congl
sand

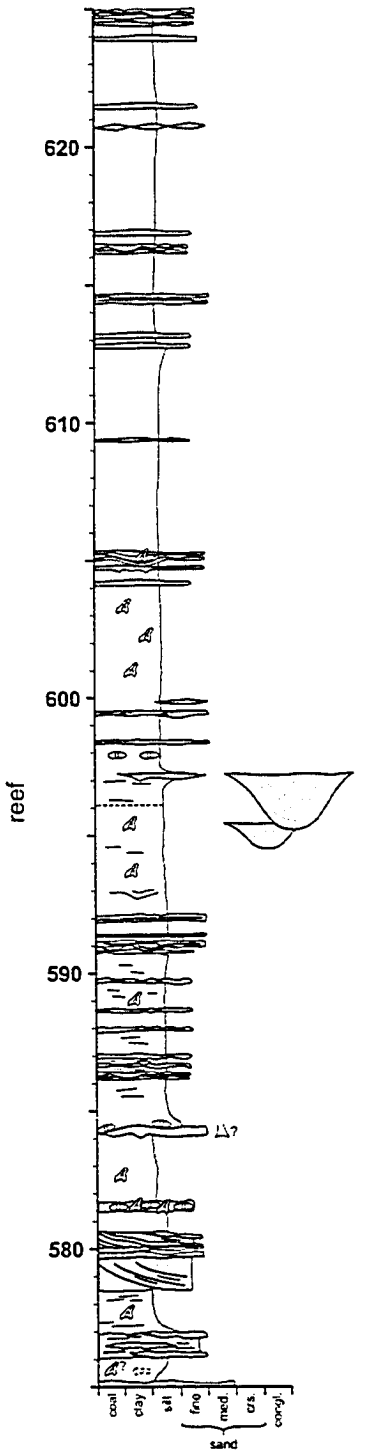

120
110
100
90
80
headland
reef & headland
reef
laterally stacked
channel bodies
n=6
mounded barform
n=11
n=2
feldspathic granules
n=32
coal
clay
silt
fine
med
crs.
congl.
sand
170
160
150
140
130
reef
reef
n=7
n=2
obliquely nested
channel bodies

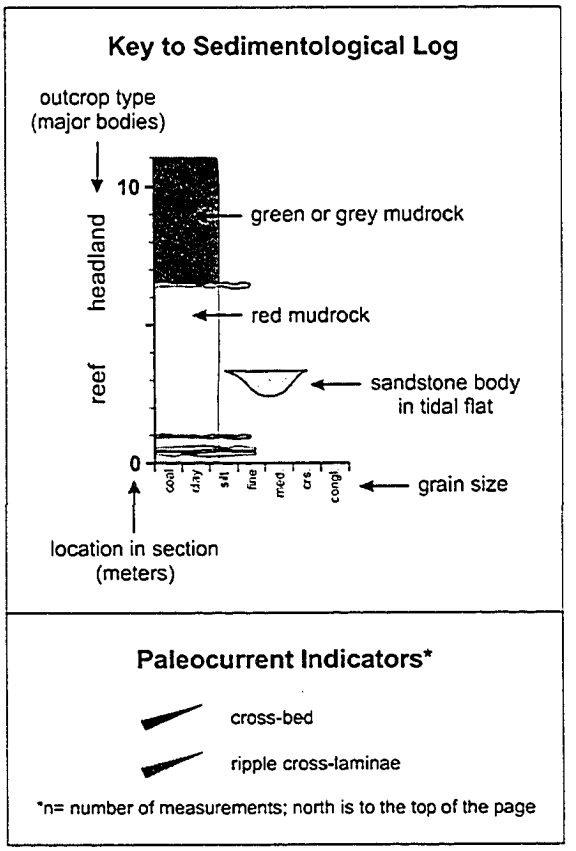

reef
220
210
reef
200
190
180
n=4
n=3
n=10
n=6
obliquely-nested
channel bodies;
Cyperites
coal
clay
silt
fine
med
crs
congl
sand
270
260
250
240
reef
230
stacked hollows with
soft-sediment
deformation
isolated bodies on
upper mudflat
lycopsid stems,
Trigonocarpus;
1st abundant
lycopsid material
n=8
n=9
lower mudflat
coal
clay
silt
fine
med
crs
congl
sand

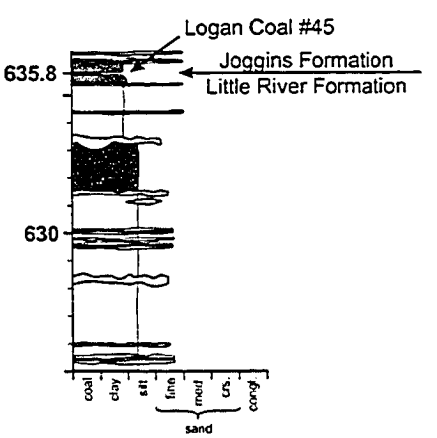

reef
320
310
300
290
280
n=?
coal
clay
silt
fine
med.
crs
congl
sand
370
360
350
340
330
reef
lower mudflat
coal
clay
silt
fine
med
crs
congl
sand

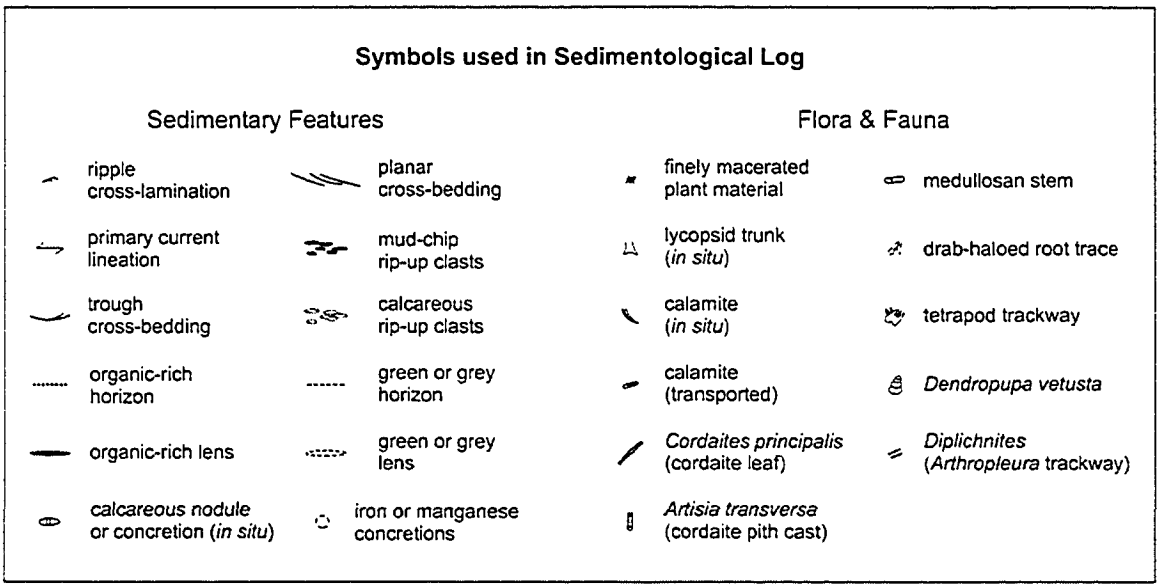

reef
420
410
400
390
380
lower mudflat
lower mudflat
coal
clay
silt
fine
med
crs
congl
sand
start of cliff exposure south of Little River
reef
470
460
450
440
430
n=11
coal
clay
silt
fine
med
crs
congl
sand


reef
520
510
500
490
480
lower mudflat
coal
clay
silt
fine
med
crs
congl
sand
reef
570
560
550
540
530
coal
clay
silt
fine
med
crs
congl
sand


620
610
600
590
580
reef
coal
clay
silt
fine
med
crs.
congl.
sand


Key to Sedimentological Log
outcrop type
(major bodies)
10
headland
reef
0
green or grey mudrock
red mudrock
sandstone body
in tidal flat
coal
clay
silt
fine
med
crs
congl
grain size
location in section
(meters)
Paleocurrent Indicators*
cross-bed
ripple cross-laminae
*n= number of measurements; north is to the top of the page


Logan Coal #45
Joggins Formation
Little River Formation
635.8
630
coal
clay
silt
fine
med
crs.
congl
sand


Symbols used in Sedimentological Log
Sedimentary Features
ripple cross-lamination
planar cross-bedding
primary current lineation
mud-chip rip-up clasts
trough cross-bedding
calcareous rip-up clasts
organic-rich horizon
green or grey horizon
organic-rich lens
green or grey lens
calcareous nodule or concretion (in situ)
iron or manganese concretions
Flora & Fauna
finely macerated plant material
medullosan stem
lycopsid trunk (in situ)
drab-haloed root trace
calamite (in situ)
tetrapod trackway
calamite (transported)
Dendropupa vetusta
Cordaites principalis (cordaite leaf)
Diplichnites (Arthropleura trackway)
Artisia transversa (cordaite pith cast)

## APPENDIX 7: OVERSIZE VERSIONS OF FIGURES 94 & 95

Versions of Figures 94 & 95 printed on tabloid-sized paper are included in the rear pocket of the thesis.

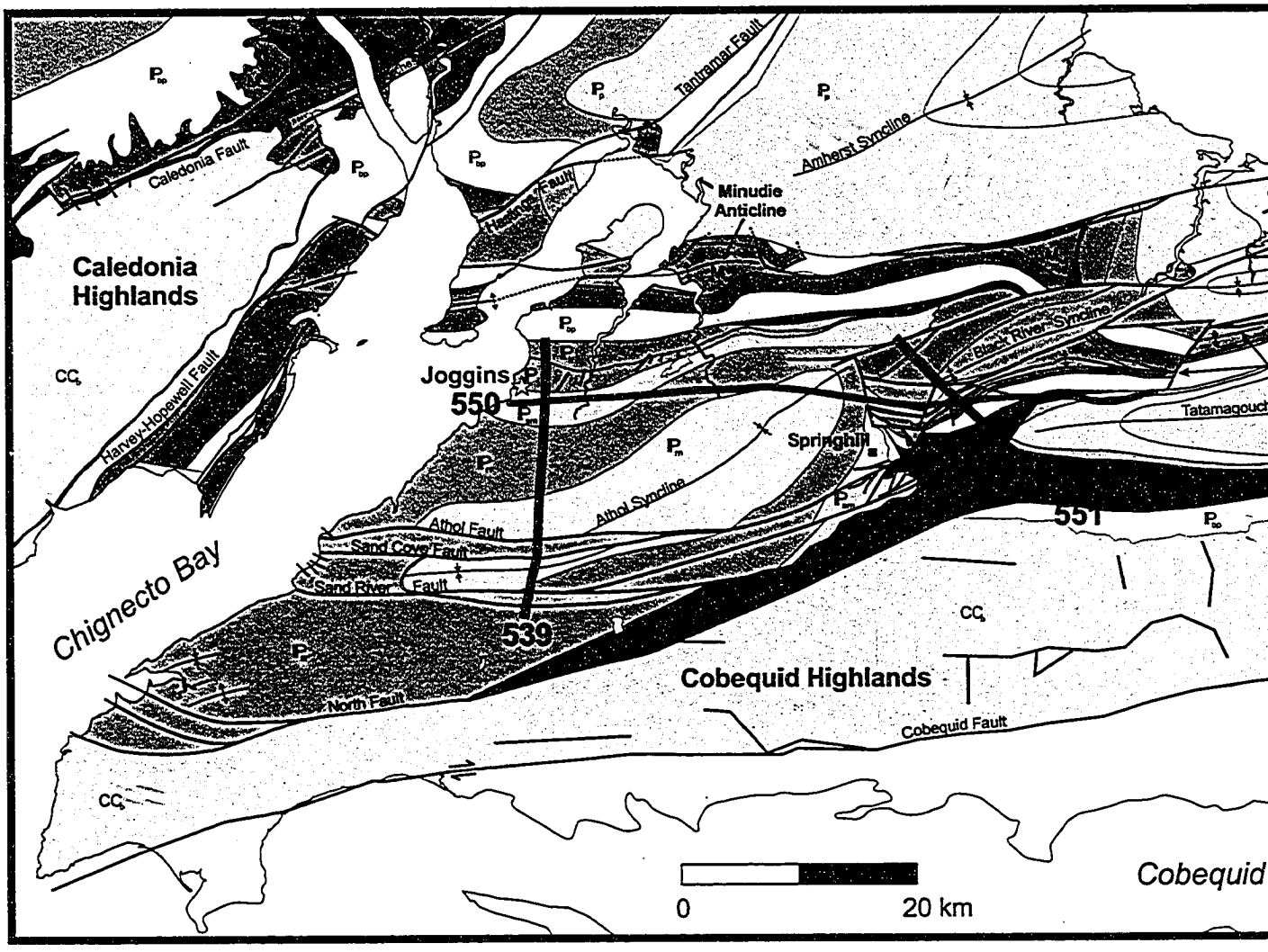
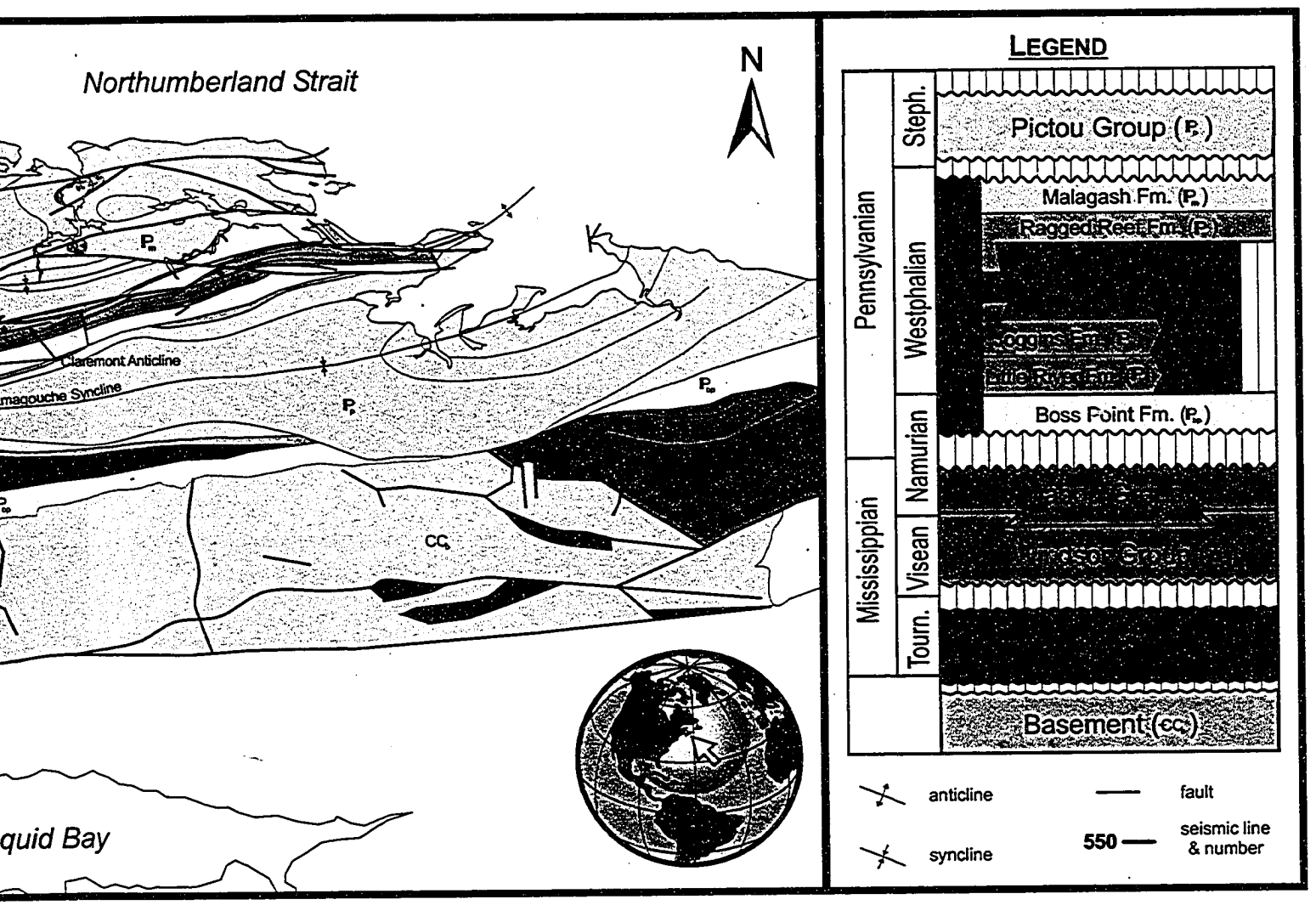
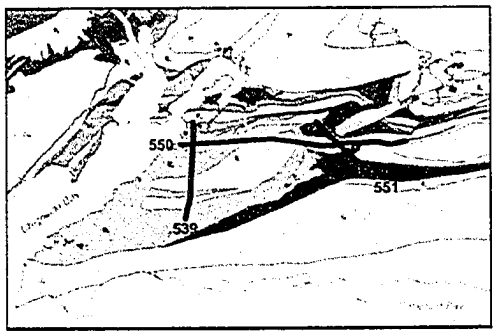
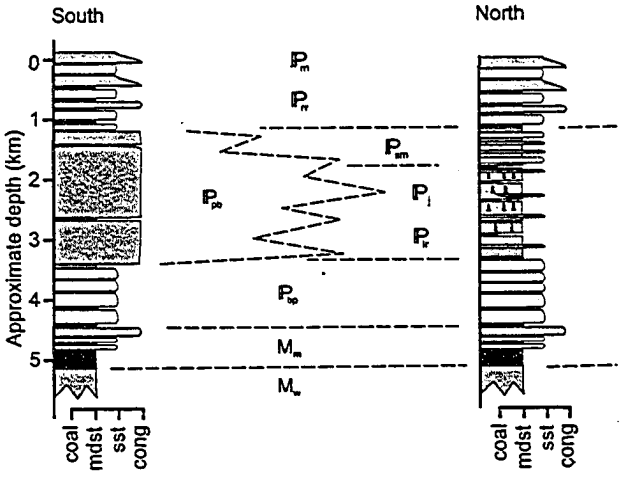

Caledonia Fault
Caledonia Highlands
Harvey-Hopewell Fault
Chignecto Bay
Tantramar Fault
Amherst Syncline
Minudie Anticline
Hastings Fault
Joggins
550
Black River Syncline
Springhill
Tatamagouch
551
Athol Fault
Sand Cove Fault
Sand River Fault
Athol Syncline
539
North Fault
Cobequid Highlands
Cobequid Fault
0
20 km
Cobequid

Figure 94


Northumberland Strait
N
Claremont Anticline
LEGEND
Pictou Group (P)
Malagash Fm. (P)
Boss Point Fm. (P)
Basement (CC)
Pennsylvanian
Mississippian
Steph.
Westphalian
Namurian
Visean
Tourn.
anticline
syncline
fault
550
seismic line & number

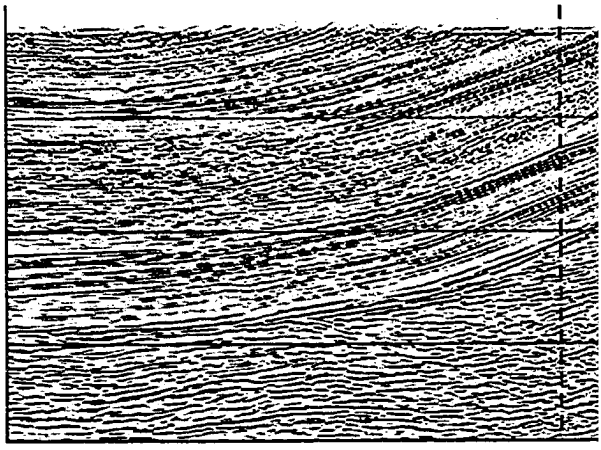


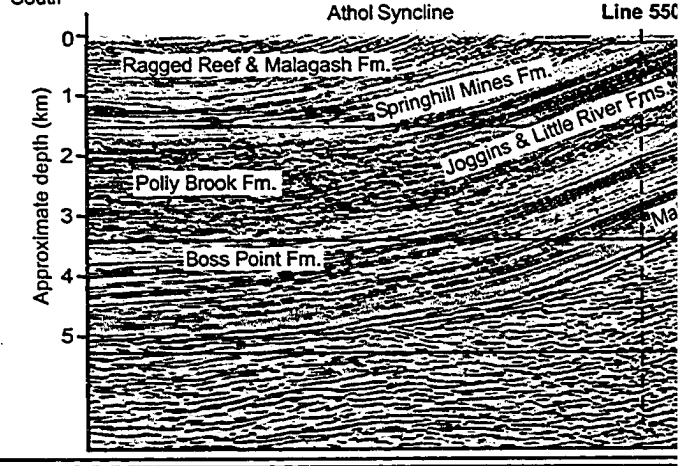

Schematic stratigraphic columns for seismic line 539




A

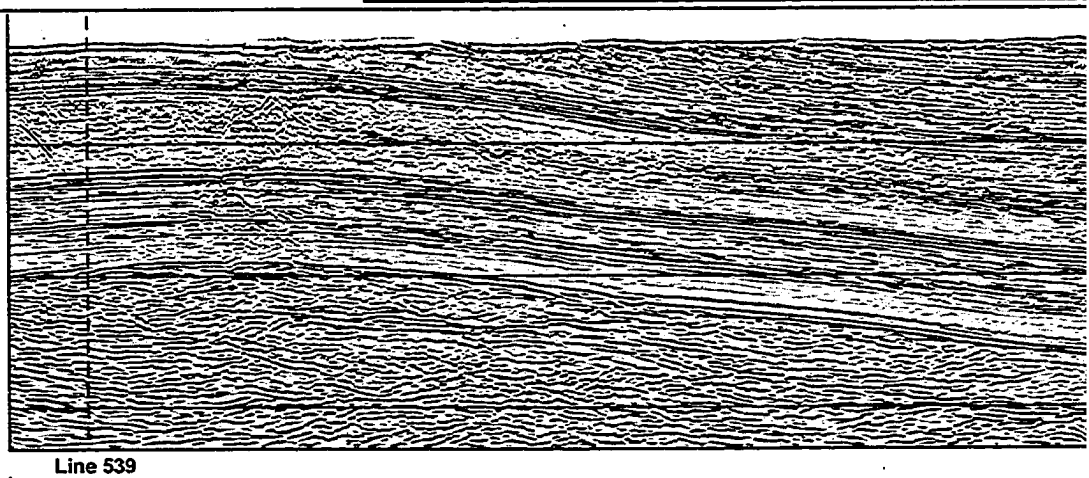
Line 539






B

Line 550



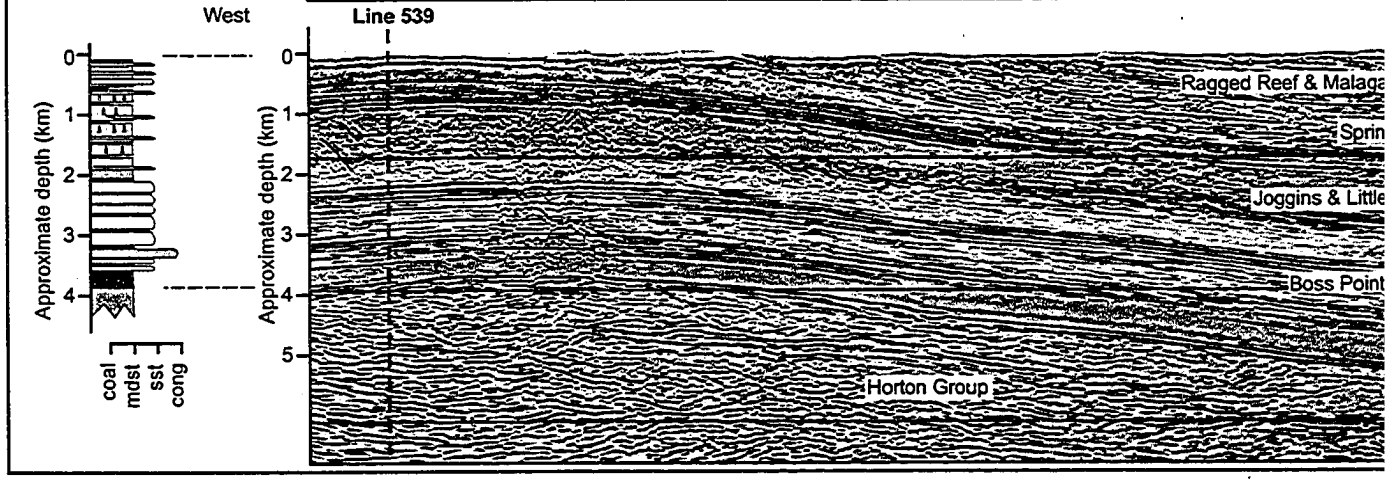
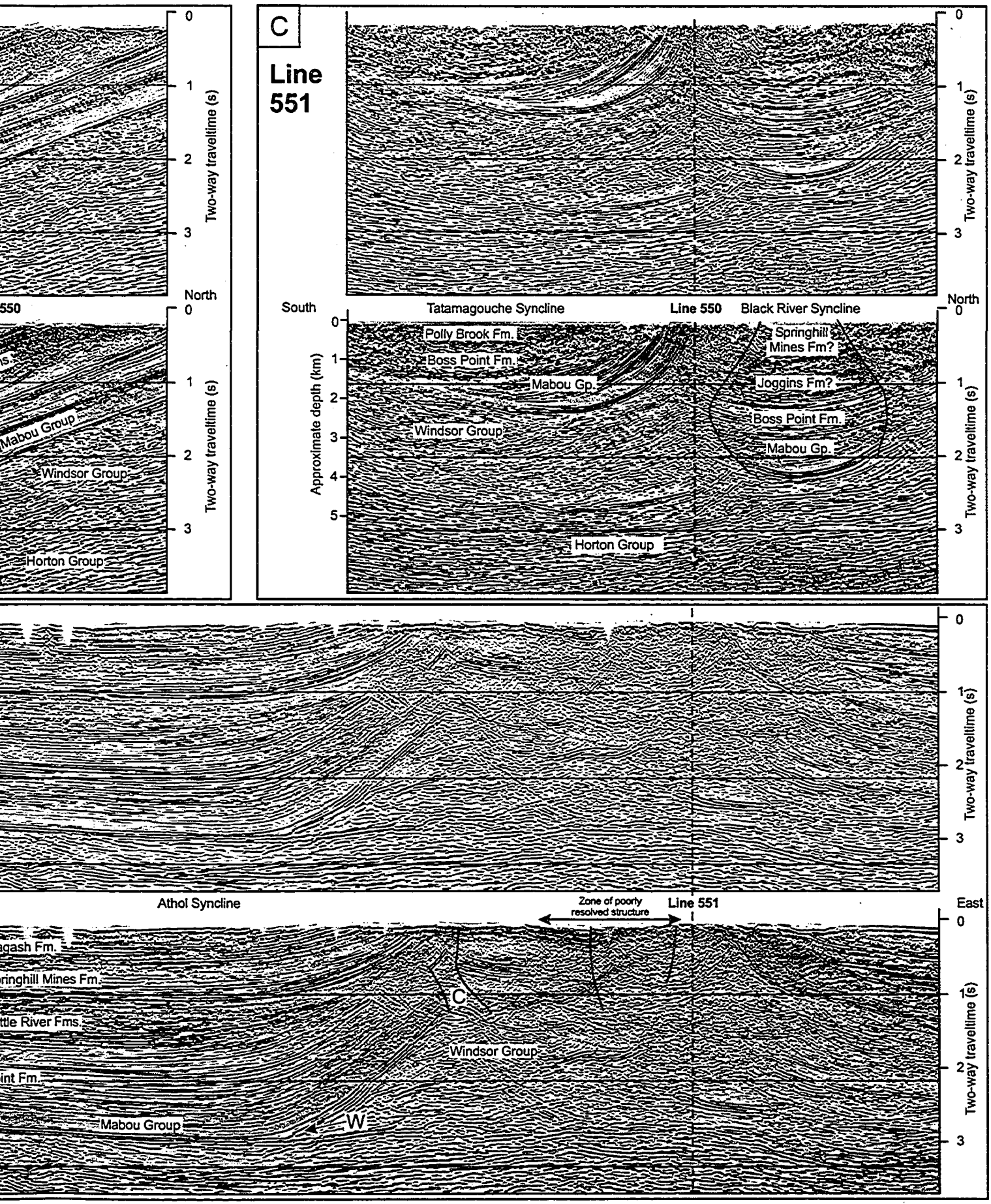


Figure 95


C
Line 551
Two-way traveltime (s)
North
550
Mabou Group
Windsor Group
Horton Group
South
Tatamagouche Syncline
Line 550
Black River Syncline
Approximate depth (km)
Polly Brook Fm.
Boss Point Fm.
Mabou Gp.
Windsor Group
Horton Group
Springhill Mines Fm?
Joggins Fm?
Boss Point Fm.
Mabou Gp.
Athol Syncline
Zone of poorly resolved structure
Line 551
East
agash Fm.
pringhill Mines Fm.
ttle River Fms.
int Fm.
Mabou Group
Windsor Group
C
W