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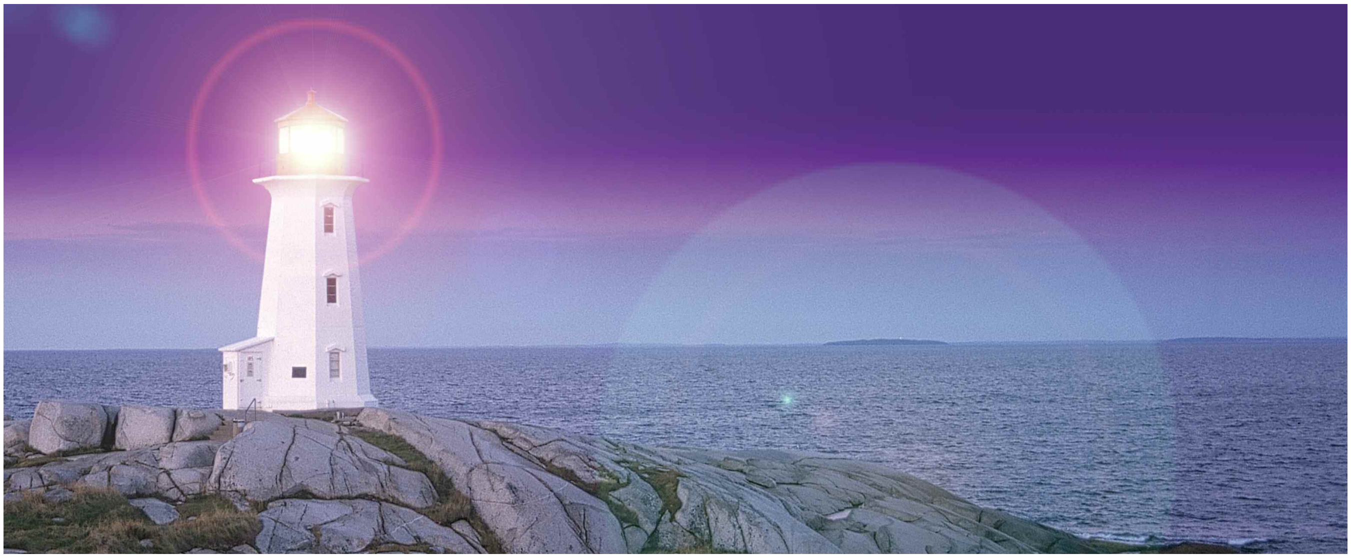

Field Trip B2

The Joggins Cliffs of Nova Scotia: Lyell & Co's "Coal Age Galapagos"

J.H. Calder, M.R. Gibling, and M.C. Rygel

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The Joggins Cliffs of Nova Scotia: Lyell & Co's "Coal Age Galapagos"

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THE JOGGINS CLIFFS OF NOVA SCOTIA: CHARLES LYELL & CO'S "COAL AGE GALAPAGOS"

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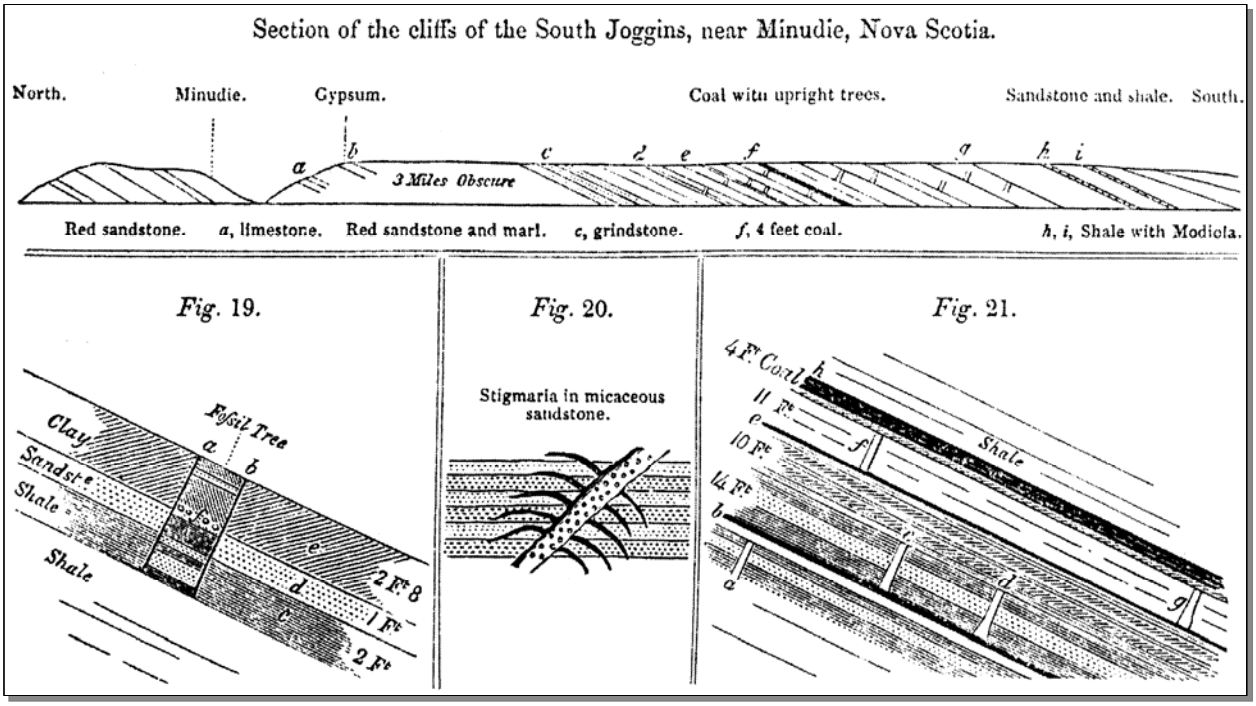


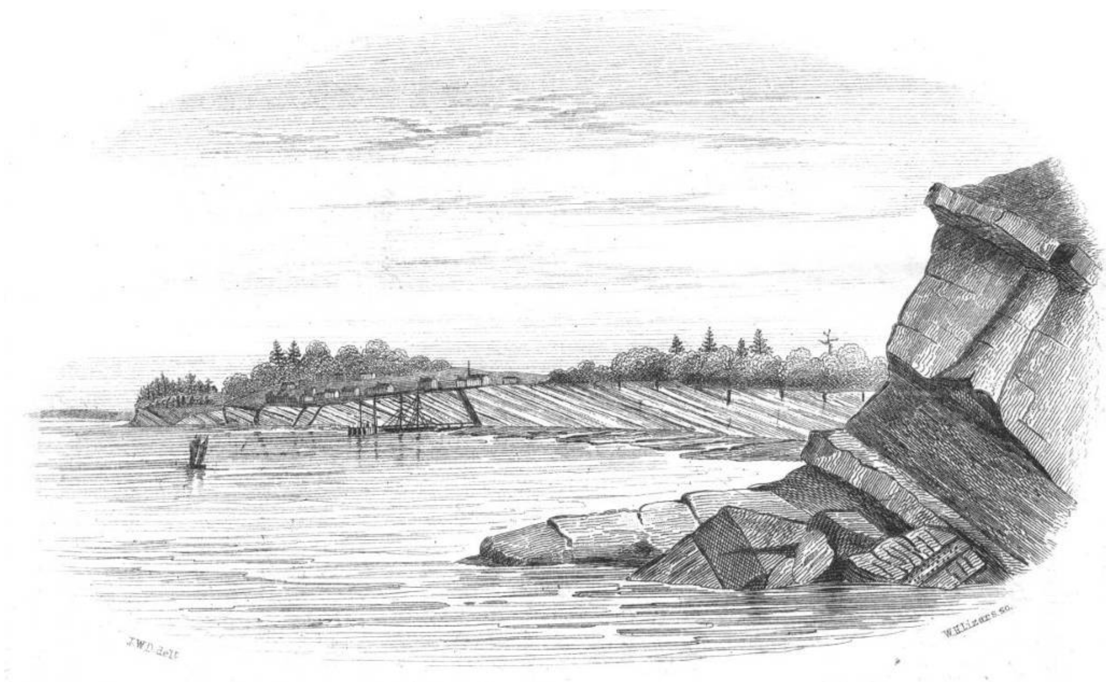
from Lyell (1845)

PREFACE

This guidebook was designed for the 2005 Geological Association of Canada-Mineralogical Association of Canada meeting in Halifax, Nova Scotia. Much of the information contained in this guidebook was adapted from recent work by Davies et al. (submitted), Calder et al. (submitted), and Rygel (2005), which contain fuller accounts of the Joggins section.

ACKNOWLEDGEMENTS

We are most grateful to Don Reid and Brian Hebert for their unselfish interest in the cliffs of Joggins and in sharing their fossil discoveries, through us, with the world. We would like to thank as well our colleagues who have worked with us at the cliffs and who have co-authored the papers upon which this field guide draws.



from Dawson (1855)

SAFETY

The Joggins section is a spectacular exposure of Carboniferous strata, but there are some very real hazards at this location. Joggins experiences the world's highest tides, and many exit routes are flooded as much as two hours before the high tide. Please plan your trip around the low tide; tide tables are available online at the Fisheries and Oceans Canada website (http://www.lau.chs-shc.dfo-mpo.gc.ca/english/Canada.shtml). Try to stay on sandy areas of the tidal flat and avoid muddy areas where you could get stuck during a rising tide. The intertidal areas can be very slippery, avoid damp rocks and especially those with a coating of green algae. Stay back from the cliffs as much as possible, rock falls are a common occurrence – particularly in the spring. Hard hats are recommended, as are warm clothes and, rain gear, and extra water. Study field boots are also suggested, the distance covered on this trip will be ~2.5 km over irregular terrain. Never climb the cliffs, they are unstable and a fall could be fatal. If trapped by the rising tide, try and find a spot on the cliffs where the face looks stable, climb up the talus above the high tide level.

COLLECTION AND PROTECTION OF FOSSILS

Joggins is a protected site designated under the Special Places Protection Act of the Province of Nova Scotia and excavation of fossil material from the cliffs is prohibited. Although all fossils in Nova Scotia are the property of the Province, it has been past practice to allow collection of common fossils found in beach stones. The ability to distinguish the 'common' from the 'significant', however, is the issue. Nor does size matter! Virtually all of the important paleontological discoveries over the years, including Lyell and Dawson's first discovery of tetrapods, have been made from material fallen from the cliffs. Should you find a vertebrate or other unusual fossil, please bring it to the attention of the trip leader, Nova Scotia Museum (902 424 6451), Fundy Geological Museum (902 254 3814), NS Dept of Natural Resources (902 424 2778) or staff at the Joggins Fossil Centre.

ABSTRACT

The Joggins cliffs of Nova Scotia are widely regarded as the world's best exposure of coal-bearing Pennsylvanian strata. The section is superbly exposed in several kilometers of sea cliffs and a broad wave-cut platform, both of which are constantly hewn and renewed by the world's highest tides along the Bay of Fundy. The section came to prominence largely through the research of Sir Charles Lyell and Sir William Dawson commencing in the 1840s, and figured prominently in the arguments of Darwin's *On the Origin of Species*. For this reason, the section has come to be known as a "Coal Age Galapagos." Drawing upon Lyell's knowledge of the modern earth's surface, it quickly became apparent to Dawson and Lyell that the Joggins strata represented ancient landscapes. Now as then, multiple horizons of standing trees entombed in the strata (some of them atop coal seams), spreads of charcoal from wildfires, and the world's earliest known reptiles and land snails are particularly remarkable features of the section. Recent sedimentological and paleontological work points to the presence of restricted-marine faunal assemblages, and a series of parasequence-dominated cycles. These cycles reflect a tectonically controlled architectural style generated in a rapidly subsiding basin modulated by glacioeustatic events. The wealth of historic and current research at this classic section are the foundation for its future nomination as a World Heritage Site.

LOCATION & ACCESS

To reach Joggins by road, leave Route 302 at Maccan, turning west (right if travelling south from Amherst via Nappan) on Route 242. Proceed 20 km, crossing bridges spanning the Maccan River and the River Hebert, continuing through the village of River Hebert to Joggins. Proceed along the Main Street, turning right onto Hardscrabble Road towards Lower Cove; park at the bridge crossing Little River and proceed to the left (southward and up section) along the shore. Alternatively, follow signage from Main Street leading to the designated parking area off Hardscrabble Road and descend the steps at Bell's Brook; proceed to the right (northward and down section). Care should be taken when visiting the section, as the extreme tidal range submerges most exit routes within two hours of high tide.

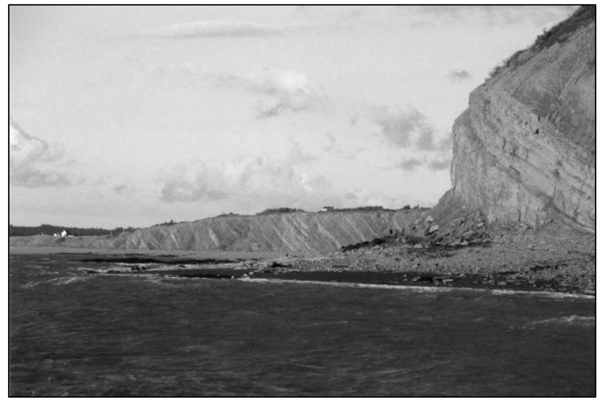


Figure 1: The lower 600 m of the Joggins Formation.

INTRODUCTION

The Joggins fossil cliffs are among the world's most remarkable and historic stratigraphic sections (Fig. 1). The cliffs extend from Minudie in the north past Joggins village to Spicers Cove, a distance of 50 km, and border a broad tidal platform along Chignecto Bay where the world's highest tides continually hew Carboniferous strata of the Cumberland Basin. Sir Charles Lyell (1871, p. 410) proclaimed that the section represented the world's best natural exposure of the Carboniferous coal measures, a view that is still widely accepted (Gibling, 1987; Falcon-Lang and Calder, 2004).

Early accounts by Jackson and Alger (1828), Brown and Smith (1829), and Gesner (1836) first brought the Joggins section to the attention of the likes of Charles Lyell. Lyell visited Joggins during his second visit to North America in 1842 and was deeply impressed by the spectacular geological features (Lyell, 1845; Scott, 1998). In the following year, Joggins hosted William Logan, the head of the newly constituted Geological Survey of Canada, who recorded a 14,570 foot (4,441 m), virtually continuous section along Chignecto Bay (Logan, 1845; Rygel and Shipley, in press). Lyell would return nearly a decade later, and during that trip with Dawson would make one of the most noteworthy fossil discoveries in the history of paleontology: that of tetrapods entombed within the upright trees (Lyell and Dawson, 1853). Subsequent investigations by Dawson over the next several decades would yield the skeletal remains of the earliest amniote, the reptile *Hylonomus lyelli* (Dawson, 1878).

In many ways, Joggins was to Lyell and his colleagues what the Galapagos Islands were to

Research Area	Author(s)
Topical accounts	Scott (2001); Falcon-Lang and Calder (2004); Falcon-Lang et al. (2004a)
Sedimentology and stratigraphy	Smith (1991); Davies and Gibling (2003); Calder et al. (submitted); Davies et al. (submitted); Rygel (2005)
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; 2003a; 2003c; 2003b; 2004); Falcon-Lang and Scott (2000); Falcon-Lang et al. (2004b);
Fauna	Archer et al. (1995) ; Reisz (1997); Holmes et al. (1998); Hebert and Calder (2004); Falcon-Lang et al. (2004b); Chamberlain (2004); Hunt et al. (2004); Tibert and Dewey (submitted)
Age assessment	Dolby (1991); Utting (1995)
Coal and source rocks	Hower (2000); Calder et al. (in press)
History of geologic research	Rygel and Shipley (in press); Falcon-Lang and Calder (submitted)

Table 1: Significant contributions to our understanding of the Joggins Formation in the past 15 years.

Darwin (Calder, 2003). Lyell's early research at Joggins, following the earlier success of his *Principles of Geology* (Lyell, 1830) and Dawson's pioneering paleoecological studies in the following decade (Falcon-Lang and Calder, submitted), was pivotal in establishing the stratigraphic record at Joggins as an archive of Earth's evolving landscape. Joggins is mentioned several times in Charles Darwin's (1859) *On the Origin of Species*, and featured in the 1860s evolution debate. The existence of the earliest known land snail, tauntingly referred to as that "miserable little *Dendropupa*" by Bishop Sam Wilberforce was gleefully summoned to chide Darwin and his "bulldog" Thomas Huxley during the debate. The cliffs have provided the world's best example of terrestrial life from the Pennsylvanian "Coal Age" preserved in its environmental context (Falcon-Lang and Calder, 2004), including some of the world's best preserved fossil lycopsid forests, the earliest known true reptile (*Hylonomus lyelli*), and the first land snail (*Dendropupa vestusta*). In 2004, Joggins was proposed for Canada's list of World Heritage nominations (Falcon-Lang and Calder, 2004).

Over the past 15 years, the natural laboratory of the Joggins cliffs - renewed constantly by the tides - has experienced a surge of scientific interest (Table 1). 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. Despite the importance of the Joggins cliffs, until recently the only formal stratigraphic log available has been the detailed written descriptions of Logan (1845) and Dawson (1854). Later workers have remeasured shorter segments, and Ryan and Boehner (1994) recast Logan's log as a simplified graphic log. Since 1996, the cliff and foreshore section (1551.3 m thick) from South Reef to south of Bell's Brook, corresponding to Divisions 4 and 5 of Logan's section, was measured bed-by-bed with centimeter-scale resolution (Calder *et al.*, submitted; Davies *et al.*, submitted). This detailed measured section of the redefined Joggins Formation (Appendix) and newly defined Little River Formation (Calder *et al.*, submitted), provides a framework for sedimentological and paleontological discoveries at this classic Carboniferous locality.

GEOLOGICAL SETTING

The Pennsylvanian Joggins Formation was deposited in the Cumberland Basin of Nova Scotia, a fault-bounded depocenter within the regional Maritimes Basin (Fig. 2). Strata of the Maritimes Basin accumulated in successive phases of subsidence and inversion, that began with the closing of the Iapetus Ocean during the Acadian Orogeny (mid-Devonian) and continued through phases of the Alleghanian Orogeny into the early Permian, when Laurasia and Gondwana finally amalgamated to form the supercontinent of Pangea (Fig. 3; Calder, 1998). The Maritimes Basin fill is

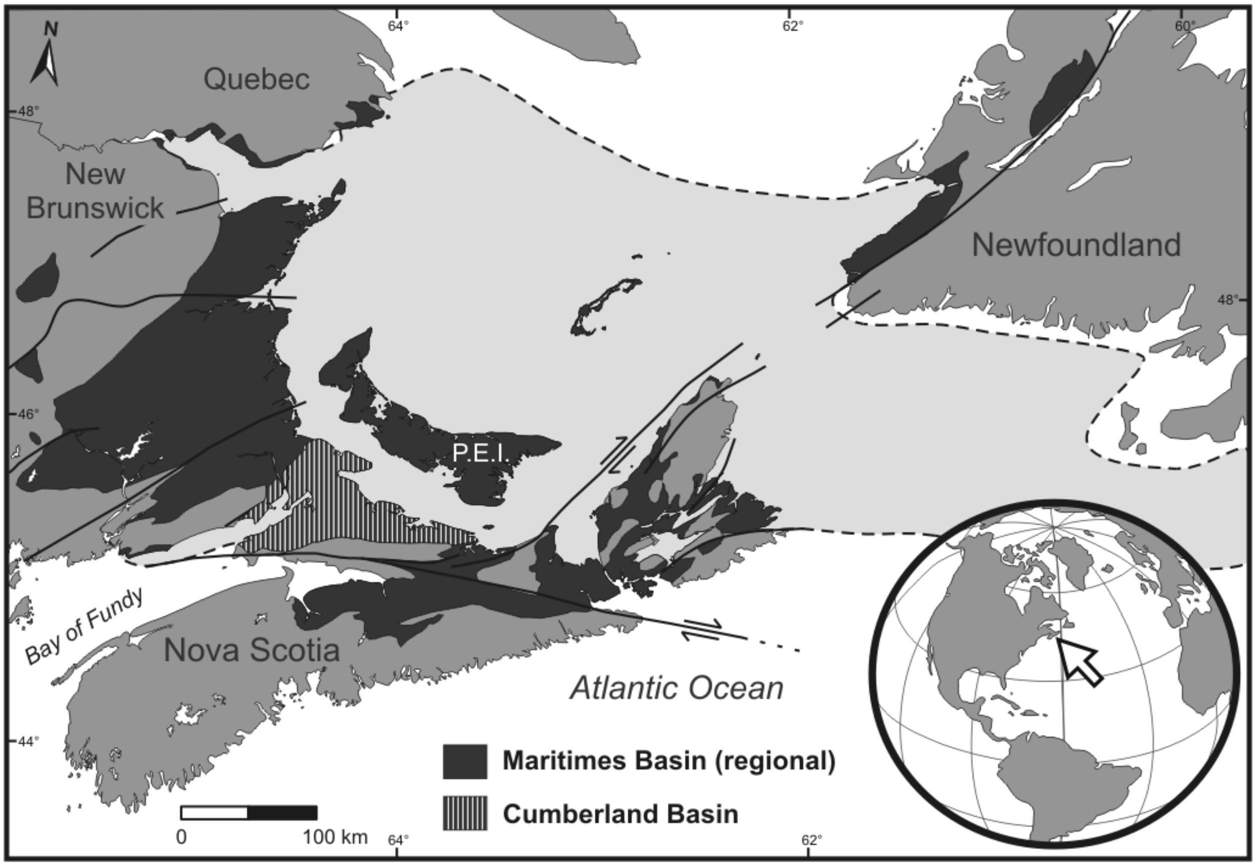


Figure 2: Map showing the extent of the Maritimes Basin (after Gibling et al., 1992).

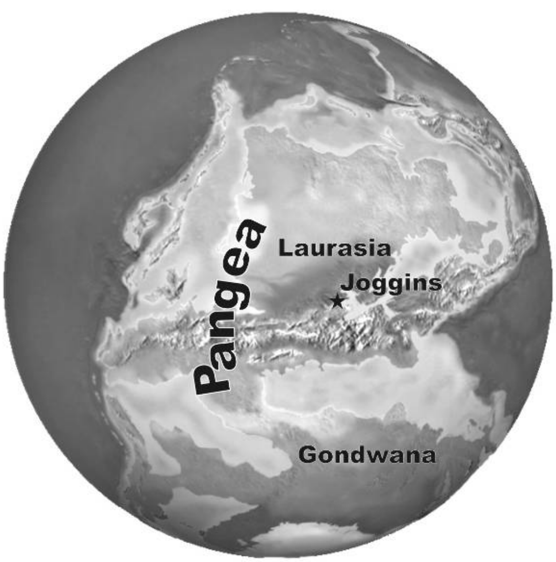


Figure 3: Pennsylvanian paleogeography (after http://jan.ucc.nau.edu/~rcb7/globaltext2.html).

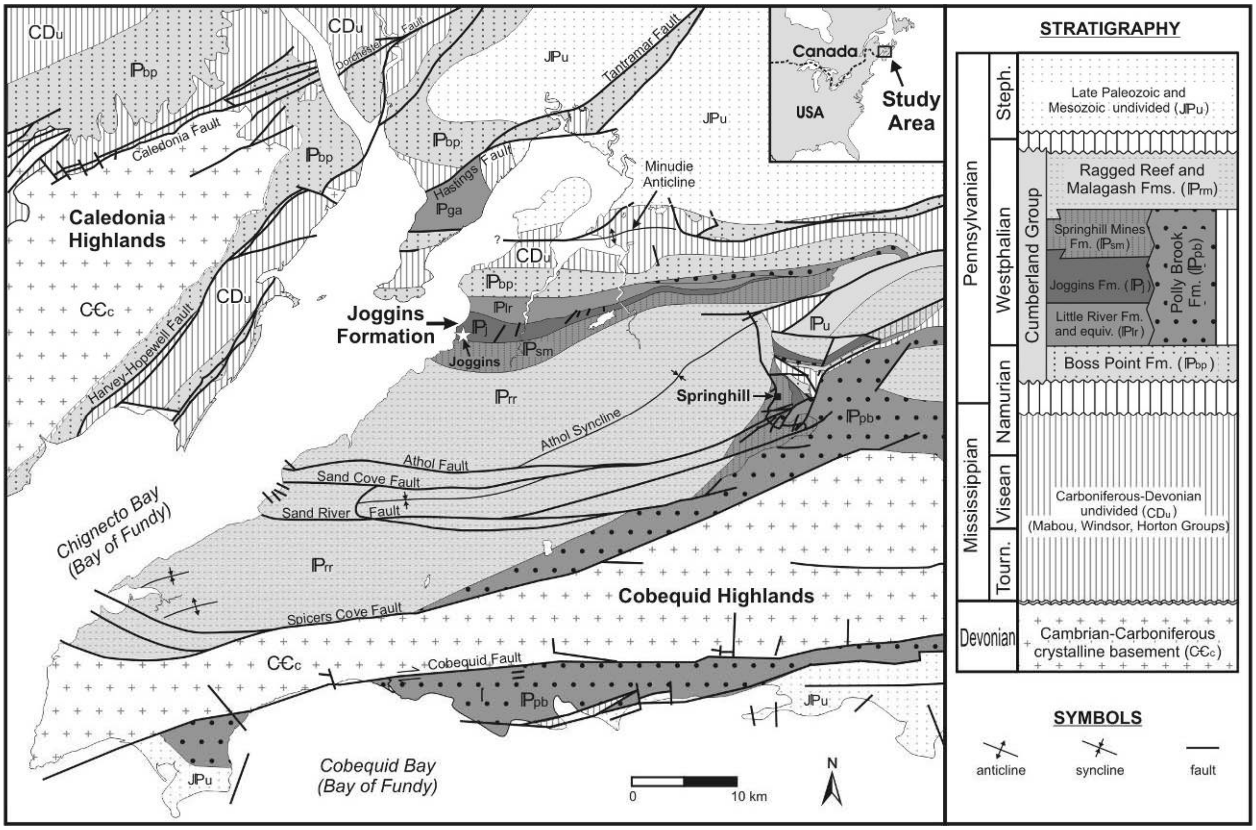


Figure 4: Map of the western Cumberland Basin from Rygel (2005); based on the work of Ryan et al. (1990a; 1990b), Keppie (2000), New Brunswick Department of Natural Resources and Energy (2000), and St. Peter (2001).

as much as 10 km thick under the Gulf of St. Lawrence and covers basement rocks of ancestral North America (the Grenville Province) and the accreted Avalon and Meguma Terranes - an area that extends from western New Brunswick east to the Grand Banks, and from mainland Nova Scotia north to Newfoundland (Fig. 2). Where individual depocenters can be recognized, they have historically been termed "basins" in their own right; one of these is the Cumberland Basin, home to the Joggins Formation. Detailed accounts of the history of the Maritimes Basin are given in Bell and Howie (1990), Williams (1995), Calder (1998), and Pascucci et al. (2000).

Tectonics of the Cumberland Basin

The fault-bounded Cumberland Basin is a 3,600 km^2 depocenter that covers much of northwestern Nova Scotia and parts of southern New Brunswick (Fig. 4; Ryan *et al.*, 1987). Situated between the once formidable Caledonia and Cobequid Highland Massifs, the margins of the fault-bounded 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 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 timing and magnitude of fault motion in the Cumberland Basin is poorly understood, the 8 km of Carboniferous basin fill resting atop the Avalonian basement attests to significant fault-induced subsidence during this time. Many of the bounding faults have a complex history of motion including both dip-slip and strike-slip motion, but dextral transpression is generally recognized as the overall sense of motion (Webb, 1963; Nance, 1987; Browne and Plint, 1994).

In addition to motion along the basin-bounding faults, Carboniferous subsidence in the Cumberland Basin was also produced by several phases of halokinetic subsidence caused by withdrawal of the underlying Mississippian-aged evaporites (Waldron and Rygel, 2005). The first phase occurred in the eastern part of the basin during the late

Mississippian; the second phase occurred in the western part of the basin and created much of the accommodation generated during deposition of the Early Pennsylvanian coal-bearing units (Waldron and Rygel, 2005).

The Joggins section crops out along the northern limb of the Athol Syncline – the dominant structural feature in the western Cumberland Basin. This 25-km-wide by 75-km-long syncline lies between the salt-cored Minudie Anticline to the north, the Black River diapir to the east, and the Athol-Sand Cove Fault Zone to the south (Calder, 1994). Thinning of stratal units against the bounding diapiric structures indicates that halokinesis was syndepositonal and that the syncline represents a large minibasin similar to those described from the Gulf of Mexico and other offshore areas with good seismic coverage (Waldron and Rygel, 2005).

Stratigraphy of the Cumberland Basin

Along the southern shore of Chignecto Bay over 4,500 m of Carboniferous strata are continuously exposed in a gently dipping coastal section on the northern limb of the Athol Syncline (Figs. 4, 5). The evaporite-dominated cycles of the Windsor Group form the core of the Minudie Anticline (diapir) and represent only a small portion of the 2-3 km thickness of salt that was probably deposited in this part of the basin (Waldron and Rygel, 2005). Although not exposed, the Windsor Group probably sits atop several thousand meters of the late Devonian-early Mississippian Horton and/or Fountain Lake Groups (Waldron and Rygel, 2005). The fluvio-lacustrine Shepody Formation and the conglomerates of the Claremont Formation flank the diapir; together these units comprise the Mabou Group (Mississippian), a unit that thickens into subsurface minibasins in the eastern half of the basin. 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 C to earliest Langsettian). The transition into the redbeds of the Little River Formation 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).

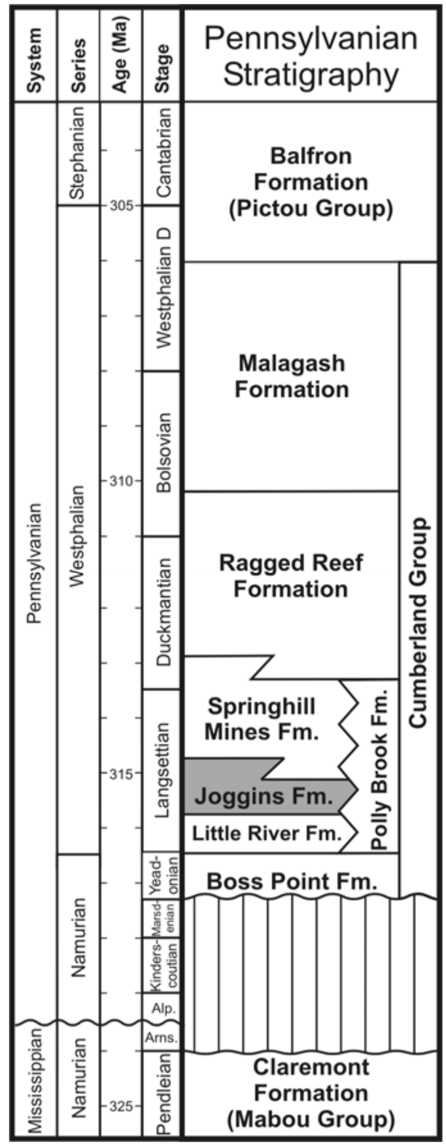


Figure 5: Details of Pennsylvanian stratigraphy in the Cumberland Basin (from Davies et al., submitted)

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, 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

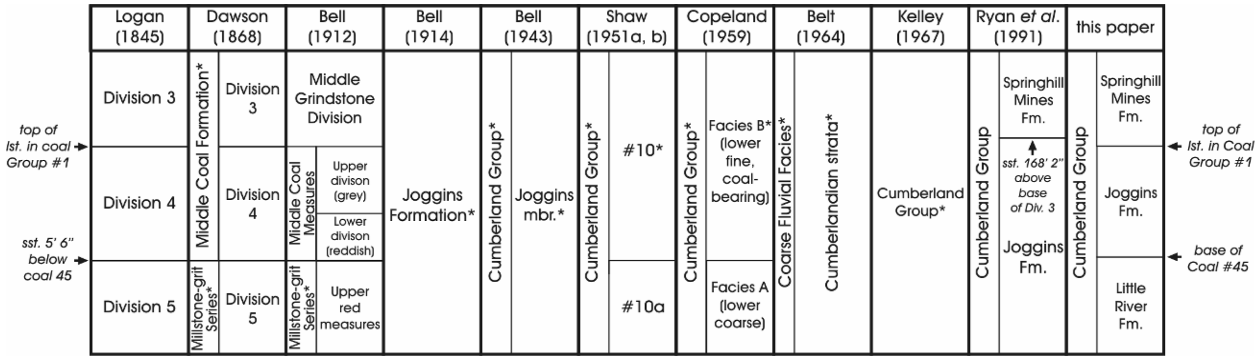


Figure 6: Comparative stratigraphic chart to show the evolution of nomenclature for the Joggins Formation and associated strata in the Cumberland Basin. Vertical axis is approximately scaled to the thickness of the units. Chart refers only to major stratigraphic revisions that directly affected the coastal section. Asterisks denote units that are partially shown (from Davies et al., submitted).

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 Westphalian D) in the center of the Athol Syncline are erosional remnants of the 1.5 to 4-km-thickness of late Pennsylvanian-Permian sedimentary rocks that once covered the now exposed Pennsylvanian sections (Ryan and Zentilli, 1993).

THE JOGGINS FORMATION

Age

Historically, the age of the Joggins Formation has been given as Duckmantian (Bell, 1943; Hacquebard and Donaldson, 1964; from Davies *et al.*, submitted). More recently, the Joggins Formation has been dated on the basis of comprehensive palynological sampling as Langsettian (approximately 315 million years old; Dolby, 1991; numerical dates of Menning *et al.*, 2000), however the Namurian-Westphalian boundary is extremely difficult to resolve in the Maritimes Basin in the absence of open 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 is still more vexing due to the paucity of the floral and palynological records; however, it can be framed as late Namurian to early Langsettian (Utting et al., 2005). The persistence of late Namurian floral elements underscores the proximity of 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).

The Measured Section

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 (in press) set out more fully the history of stratigraphic work as it pertains to the coastal section. Aspects pertinent to the Joggins cliffs are outlined in Figure 6. Despite its magnificence, 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. 4), which were an active, fault-bounded upland during Joggins deposition. In proposing a stratigraphic framework, every researcher since Logan has wrestled with this difficult background.

Although measured at the base of the accessible cliff, the section reproduced in the Appendix represents the exposed cliff face more broadly and records lateral changes in thickness of channel bodies and crevasse splays evident at the time of measurement. Figure 7 shows meterage for distinctive beds that can bee seen in the airphotograph (Fig. 8) as resistant bodies long known

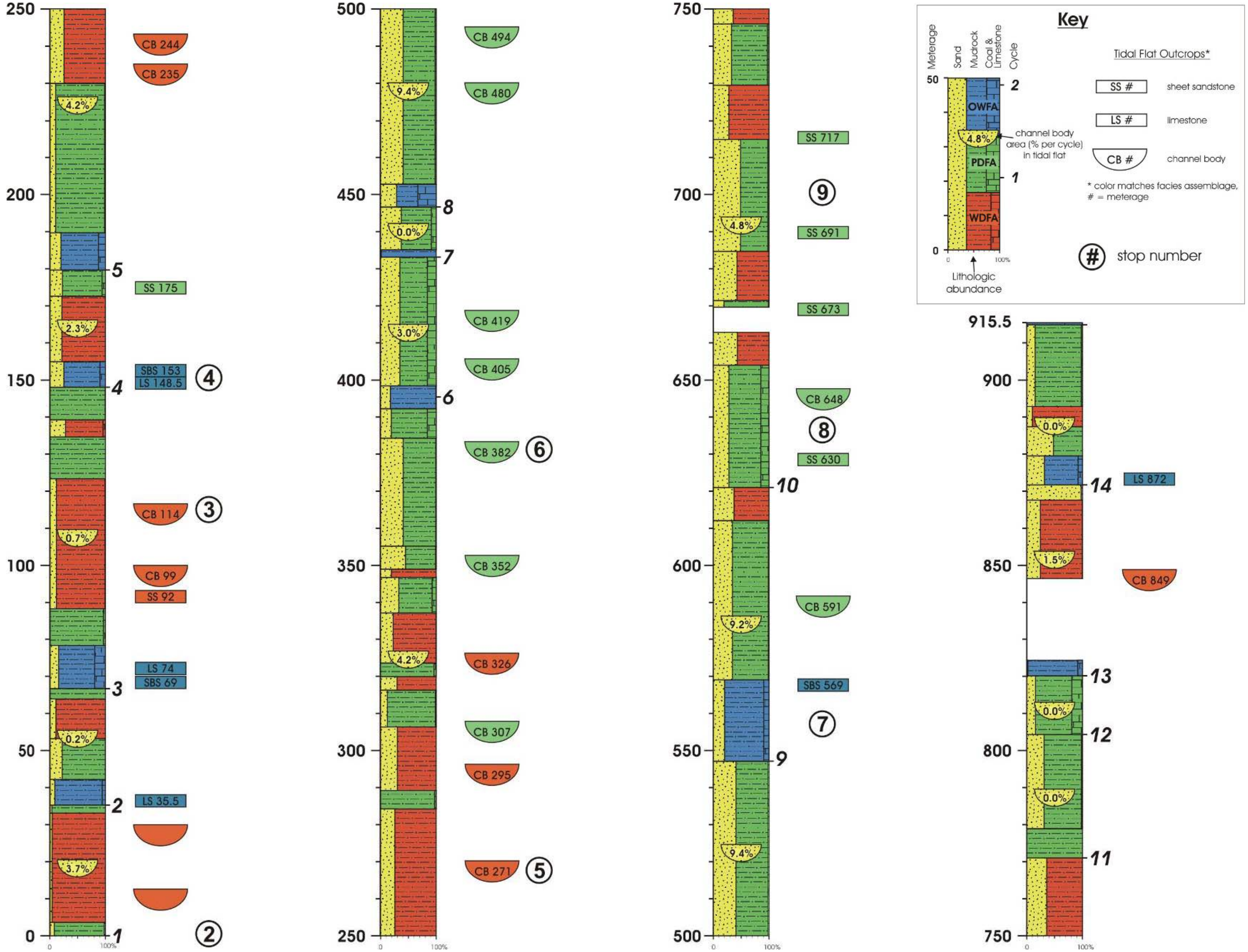


Figure 7: Simplified measured section of the Joggins Formation, meterage values correspond to reefs on Figure 8 (from Rygel, 2005).

Figure 8: Labeled airphotograph showing cycles and the stratigraphic position of prominent "reefs" in the tidal flat (from Rygel, 2005).

	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, submitted)
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	33	46	0
Channel bodies/ 100 m of section	13.0	8.7	0

Table 2: Summary of facies associations in the Joggins Formation (from Rygel, 2005).

in the local vernacular as “reefs.” Fine-grained beds, limestones and sharp-based sandstones are generally continuous across the outcrop belt, but the numerous lensoid channel bodies exposed only on the foreshore are not represented in the measured section. Red and drab intervals are 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.

Overview of Facies and Cycles

The section is divided into 14 cycles (Figs. 7, 9), the bases of which are marked by limestone, coal or fossiliferous shale. The cycles are divided in turn into stratal intervals that belong to the Open Water, Poorly Drained, and Well Drained Facies Associations (Table 2; Davies and Gibling, 2003), the main features of which are summarized briefly below. In the cycles, the three associations typically succeed each other upwards, although the Open Water Facies Association is not represented in some cycles.

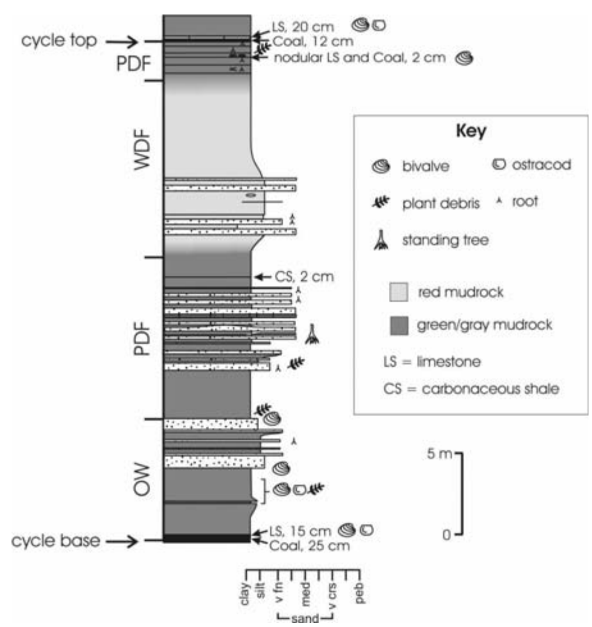


Figure 9: Simplified measured section of Cycle 2 (35 to 67 m) of the Joggins Formation showing the facies succession in a typical cycle (from Rygel, 2005).

Open Water Facies Association

This association represents major flooding events, some of which appear to have inundated most of the Cumberland Basin. Especially good examples in the lower part of the formation (Cycles 2-4) commence with a thin coal overlain by a dark limestone up to 1 m thick (Figs. 10, 11), which is overlain by several meters of grey siltstone capped abruptly or gradationally by sandstone. The limestones are resistant to erosion and stand out on the foreshore. They are locally termed “clam coals” because of their organic content and the abundance of bivalves. Accessory to the bivalves are ostracods, spirorbids, arthropods, disarticulated fish and plant fragments. The overlying siltstones are laminated and platy weathering, giving the strata a stratified appearance and they contain discoidal siderite nodules. The siltstones contain bivalves and ostracods (generally confined to discrete levels), as well as drifted plant material. Agglutinated foraminifera were obtained from some samples (Archer *et al.*, 1995).

Capping the siltstones are sharp-based, sheet-like sandstones a few meters thick, which extend across the cliff and foreshore and are characterized by planar bedding and a flaggy appearance. In a few instances, they comprise overlapping mounds up to ~100 m in apparent width. The sandstones contain unidirectional ripple cross-lamination, local mud drapes, and lineated plane beds, with wave ripples and rare hummocky cross-stratification indicating wave activity. Trace fossils include delicate grazing and walking traces (Archer et al., 1995) and, less commonly, resting traces (e.g. of limulids). A few channel bodies cut the planar sandstones, with which they are evidently closely associated. The topmost coarser beds contain roots, which mark the re-establishment of subaerial conditions after the initial flooding event.

The association represents the establishment across the basin of a restricted-marine gulf, perhaps similar to the modern Baltic Sea in its partially enclosed nature and variable but generally low salinity (Grasshoff, 1975). Open-marine faunal elements have not been observed, but the presence of certain taxa of bivalves, ostracods, foraminifera and trace fossils suggest at least brackish conditions (Bell, 1914; Duff and Walton, 1973; Archer et al., 1995; Skilliter, 2001; Tibert and Dewey, submitted). Strontium isotope data from fish material also suggest marine influence

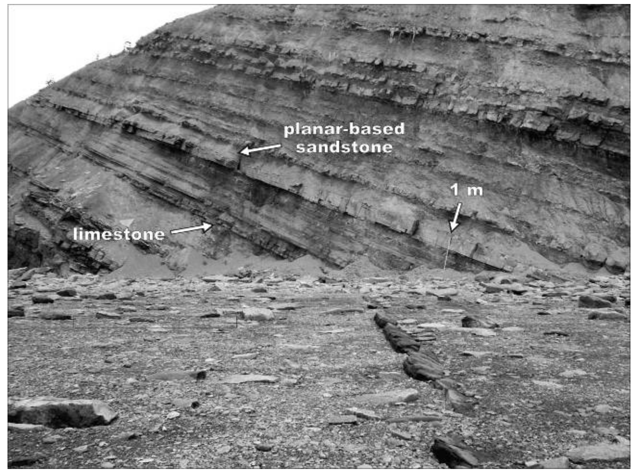


Figure 10: Limestone and planar-based sandstone at the base of cycle 4.

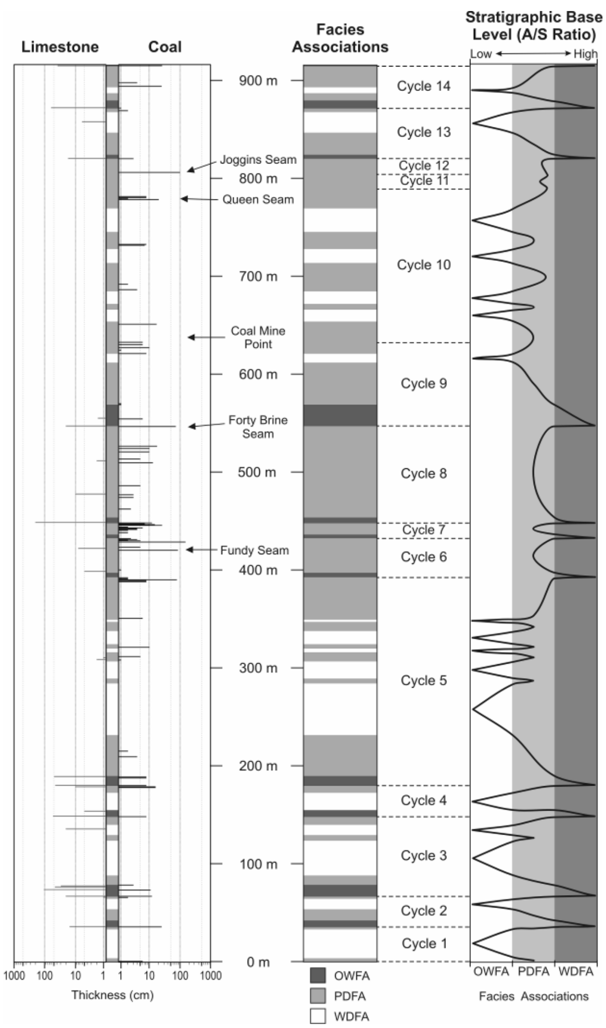


Figure 11: Summary log for the Joggins Formation, to show cycles, facies associations, position and thickness of coal and limestone beds, and relative base-level curve (from Davies et al., submitted).

(Calder, 1998), although mineralogical and geochemical data from some bivalve shells are consistent with a freshwater setting (Brand, 1994). During some flooding events at cycle bases, the presence of a basal coal suggests that peat formation initially kept pace with rising water level until the rate of sea-level rise exceeded that of peat accumulation, after which the area was transformed into a shallow bay where faunal-concentrate layers accumulated.

The upward change to siltstone indicates the re-establishment of detrital supply to the basin and renewed advance of the coastal plain as the rate of sea-level rise decreased. Progradation culminated in shallow-water sands that represent thin shorefaces and small delta lobes derived from the associated channels. Wave activity was prominent, but sedimentological evidence for tidal influence is restricted to mud drapes at a few levels (Skilliter, 2001). Drifted lycopsid plants predominate in the basal limestones, whereas overlying siltstones and sandstones contain a mixed suite of drifted gymnosperms (cordaitaleans), sphenopsids (primarily calamiteans), pteridosperms and putative progymnosperms (Falcon-Lang, 2003b, 2005). The high proportion of progymnosperms and gymnosperms suggests that the basin floor was almost entirely drowned, greatly reducing the area of coastal swamps. Under these conditions, elements of the upland vegetation (Falcon-Lang and Scott, 2000) brought to the ocean by rivers were preferentially concentrated in the siltstones (a megafloral equivalent of the "Neves Effect" of Chaloner, 1958). The presence of stigmarian roots at multiple horizons within some limestones points to near emergent, shallow conditions.

Poorly Drained Floodplain Association & Fossil Lycopsid Forests

Joggins is justifiably famous for this association, which contains the spectacular fossil forest horizons (Fig. 12). Sandstone and green/grey mudstone (commonly intensively rooted), are accompanied by coal, carbonaceous shale and minor limestone, with siderite nodules. Bivalves and ostracods are generally less common than in the open-water association. The association includes thin grey intervals with carbonaceous shales that separate redbeds near cycle tops from coal and limestone at the base of the next cycle.

Most of the Coal Groups (marked on the section in the Appendix) lie within the poorly drained association which includes the main economic seams of the formerly worked Joggins-Chignecto Coalfield: most notably the Fundy (coal 29a), Forty Brine (coal 20), Kimberly (coal 14), Queen (Coal 8) and Joggins (coal 7) seams. The bituminous coals are sulphur-rich (Copeland, 1959; Skilliter, 2001) with prominent mudstone partings and locally high concentrations of Zn, Pb and As (Hower et al., 2000).

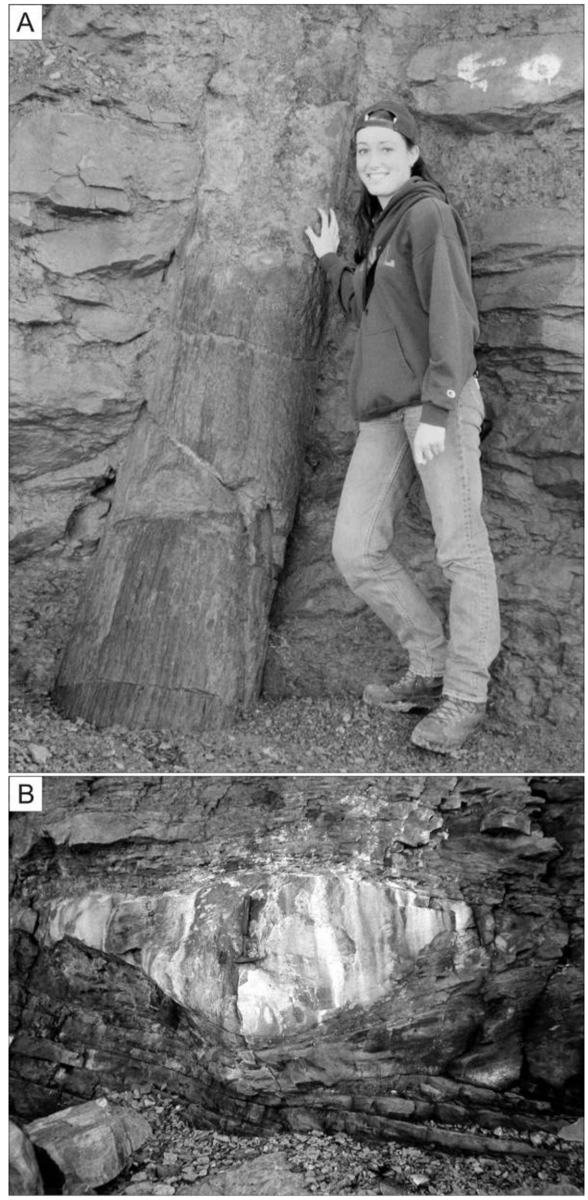


Figure 12: Common features of the poorly drained floodplain: A) standing lycopsid from cycle 8 and B) centroclinal cross strata infilling a scour developed around a lycopsid in the upper "Fundy fossil forest" (Stop 6).

The coals represent planar (groundwater-fed) mires that were flood-prone (Hower et al., 2000; Calder et al., in press); ubiquitous mudstone partings and interbedded bivalve-bearing limestones in some seams testify that the coals developed at or near base level. Thin poorly drained intervals at cycle tops represent incipient drowning of the coastal zone prior to the main manifestations of transgression. Several economic seams cap heterolithic units or channel bodies, suggesting that the precursor peat accumulated in freshwater settings following abandonment of a local distributary. These thick coals may be the updip equivalent of marine flooding events, and the high sulphur levels of many coals suggest that sulphate-rich, marine waters influenced the peats, probably after the mires were drowned by sea-level rise. Many drab mudstones are hydromorphic paleosols that formed under variable redoxymorphic conditions, and red and red/grey mottled intervals testify to episodes of soil formation under oxidizing conditions (Smith, 1991). The 595-612 m interval of Cycle 9 contains stratified red and grey mudstone without coal or invertebrate fossils, suggesting that oxidized mud was washed into clastic-dominated lakes.

Especially prominent are sheet-like, heterolithic units of sandstone and mudstone, several meters thick, that extend across the cliffs and foreshore and contain many entombed erect trees. Splendid examples include two forested intervals below the Fundy Seam (404-420 m; Calder et al., in press), two intervals just below the Forty Brine Seam (539-546 m) and the lower reef just north of Coal Mine Point (628-630 m). Charles Lyell was struck by the preserved height of the trees, which he estimated to be up to 7.6 m tall (Lyell, 1842, 1843), although the maximum height observed over the past three decades has been 6 m (Calder *et al.*, in press). Vegetation includes abundant, *in situ* lycopsids and sphenopsids with a compression macrofloral record comprising cordaitalean gymnosperms, pteridosperms, ferns and putative progymnosperms (Falcon-Lang, 1999; Calder *et al.*, in press; R.H. Wagner pers. comm.). Many standing trees are bordered by scour fills of sandstone up to 2 m thick with centroclinal (inward dipping) cross-stratification, and suites of large sandy mounds (vegetation shadows) are common (Rygel *et al.*, 2004).

Within this association, Lyell and Dawson made their remarkable discovery of tetrapods and land snails within erect trees of a fossil lycopsid forest preserved within the lower reef ("Lesser Reef of Coal Mine Point" of Dawson, 1882) at Coal Mine Point (Lyell and Dawson, 1853). Dawson's subsequent investigations at the site confirmed the tree-stump fauna to be a diverse terrestrial biota, now known to include eleven tetrapod genera replete with coprolites, and a variety of invertebrates including land snails (*Dendropupa*), millipedes, and arthropod fragments (Carroll *et al.*, 1972). Charcoal fragments are abundant within and adjacent to some trunks, testifying to wildfires that swept the forests and may have been instrumental in hollowing out the trunks (Falcon-Lang, 1999). Regarding their initial discovery, Lyell and Dawson (1853) postulated that the creature to which the bones belonged may, therefore, either have been washed in after death, or may, when creeping on the surface, have fallen into the open pit caused by the decay of the tree, or it may have crept into some crevice in the trunk before it was finally buried in the mud and sand.

The heterolithic units are closely associated with narrow, fixed channel bodies up to 5.5 m thick. A few much larger channel bodies are also present in the association. One large channel body at 580 m has incised 9 m through rooted grey mudstone and contains two vertically stacked storeys. This body is interpreted as a small paleovalley fill based on its incised nature and multistorey architecture. In both the poorly drained and well drained floodplain associations, the term paleovalley is used only to describe the geomorphic form of these bodies, and not to imply any genetic relationship to changes in relative sea level (see Type 1 vs. Type 2 paleovalleys of Dalrymple *et al.*, 1994). The major sandstone "reef" at Coal Mine Point (637-648 m) is a channel body that contains trough cross-beds, and a spectacular example of *Diplichnites* (large trackways attributed to the arthopod *Arthropleura*; Ferguson, 1975). Coal Mine Point represents a meandering river that advanced over bayfills, much as the modern Atchafalaya River of Louisiana advanced rapidly once it had filled Atchafalaya Bay (Tye and Coleman, 1989).

The strata were deposited in wetlands akin to those of the modern Mississippi Delta (Dawson, 1868; Coleman and Prior, 1980; Tye and Coleman, 1989), although the geomorphic form of the coastal system is not known. Small distributary channels traversed the coastal plain and brought sand and mud to the adjacent fresh to brackish bays during repeated flood events, depositing characteristically heterolithic sediment as interdistributary crevasse splays and bay fills. These repeated sedimentation events entombed the standing trees and created scour hollows and vegetation shadows around the trunks (Rygel *et al.*, 2004; Calder *et al.*, in press). At the level of the upper Fundy forest, thin sandstone sheets can be traced from the margins of channel bodies on the tidal platform (419 m level in Fig. 7) into scour fills around standing trees exposed in the cliffs.

Well Drained Floodplain Association

This predominantly redbed association comprises red mudstone and sandstone, with minor grey mudstone, rare coal and ostracod-bearing limestone (Davies and Gibling, 2003; Davies *et al.*, submitted). Although not highly fossiliferous, these strata have recently yielded some unusual fossil discoveries. Cycle 4 contains an especially thick redbed interval.

Single storey channel bodies are narrow and up to 7.5 m thick with an aggradational style of filling; and in places several bodies lie at the same stratigraphic level in the cliffs. Most are associated with heterolithic sheets of sandstone and mudstone that typically thin away from the channel bodies and represent levee and crevasse splay complexes. The channels are filled with grey and red sandstone and mudstone, with local conglomerates composed of reworked carbonate (paleosol) fragments. Within Cycles 1 and 3, some large multistorey channel bodies are composed of many smaller channel fills, suggesting that the bodies are small dryland paleovalleys. The red muds are poorly stratified and contain scattered calcareous nodules, although petrocalcic horizons are not observed. Standing trees (preserved as poorly preserved stump casts <1-m-tall) rooted in discontinuous gleyed horizons attest to the presence of localized wet areas on the otherwise well drained floodplain (Fig. 13). Additionally, narrow hollow fills with abundant roots below them mark the former positions of trees, since decayed (Rygel *et al.*, 2004). Charcoal and other floral remains in channel bodies are dominated by cordaitaleans, with minor pteridosperms, sphenopsids and lycopsids - the minor constituents typically confined to channel-margin situations

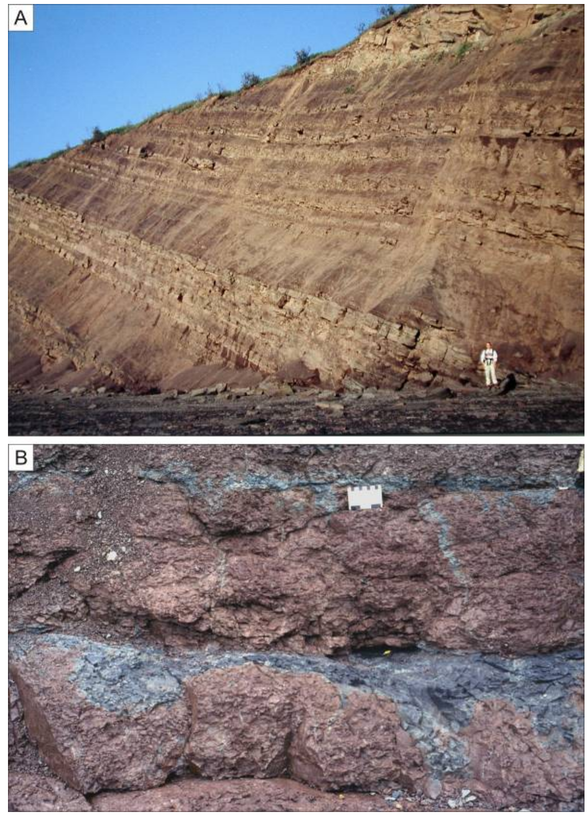


Figure 13: A) WDF strata containing red, oxidized mudrock, crevasse splay sandstones, and channel bodies. B) Localized gleyed horizons record wet areas within the well drained floodplain.

(Falcon-Lang, 1999; Falcon-Lang and Scott, 2000; Falcon-Lang, 2003c). One group of channel bodies at 270-274 m, known informally as the "Hebert beds," contains abundant charcoal as well as tetrapod material, shells up to 23 cm long of the unionoid bivalve *Archanodon*, and the land snail *Dendropupa* (Falcon-Lang *et al.*, 2004b; Hebert and Calder, 2004), and other channel bodies have yielded large arthropod trackways (*Diplichnites*).

The association represents the alluvial plain of a seasonal dryland traversed by suites of narrow channels that probably had an anastomosing planform, as indicated by multiple, narrow channels at similar levels connected by sheet sandstones ("ribbon tiers" of Kraus and Wells, 1999). The setting may have resembled that of the Channel Country of Australia with its dryland anastomosing systems and waterholes (Gibling *et al.*, 1998). The red floodplain muds are immature, cumulative paleosols that formed under a humid seasonal climate (Smith, 1991). The abundance of cordaitalean charcoal in some dryland channels suggests that the seasonally dry floodplains were covered with a fire-prone and ecologically stressed assemblage dominated by gymnosperms (Falcon-Lang, 2003c; Falcon-Lang *et al.*, 2004b). Riparian (channel-margin) settings permitted the local growth of vegetation more akin to the wetlands, and wildfires were common, perhaps promoted by elevated levels of atmospheric oxygen (Berner *et al.*, 2003). The unusual biota preserved within the Hebert beds suggest that the parent channels served as a waterhole where organisms continued to flourish during seasonal low-stage flow or more prolonged droughts.

Underlying redbeds of the Little River Formation record still drier conditions, with formation of calcareous soils and a paucity of *Stigmaria* (Calder *et al.*, submitted), suggesting conditions that were too dry for established lycopsid forests.

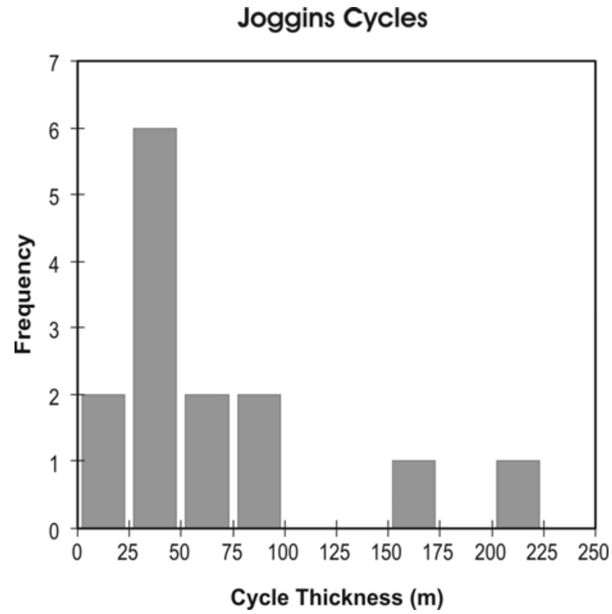


Figure 14: Histogram of cycle thicknesses (from Rygel, 2005).

FORMATION-SCALE TRENDS

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 (11.6 and 8.9 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 (Figs. 7, 8), the measured section reveals that the amount of sandstone in floodplain sediments stays relatively constant above the 230 m level (Fig. 7). 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 (Rygel, 2005). Airphoto 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 (Figs. 7, 8).

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 (Figure 14). Facies distribution was used to construct a relative base-level curve for the formation (Fig. 7; Davies *et al.*, submitted). Unfortunately, the lack of firm biostratigraphic boundaries and absolute dates for the section precludes detailed regional correlation and the determination of cycle durations and precise accumulation rates.

Relatively straightforward 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 sharp-based sandstones that cap open-water deposits contain good trace fossil assemblages. 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. 7), 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 association), with only thin intervals of open-water 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 occurrence of open-water facies above the Forty Brine Seam (Skilliter, 2001), with limestones, mud drapes, good 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 thick interval of alternate poorly drained and well drained deposits without open-water facies and limestones (Cycles 10-12). Prominent sets of 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. 7). 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. 7): 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.*, 2004). In contrast, shoreface and delta-lobe sands of the open-water facies association are relatively thin, and dryland alluvial plains of the well drained facies association include numerous thin beds of sand occurring as levees, splays, and small channels.

Sequence Stratigraphy

Many Carboniferous cycles (or cyclothems) reflect sea-level fluctuations in the order of 100 m in amplitude caused by the accumulation and melting of ice sheets in high southern latitudes (Crowley and Baum, 1991; Maynard and Leeder, 1992; Soreghan and Giles, 1999). Glacioeustasy in Carboniferous basins has commonly generated stacked Exxon-type sequences with prominent sequence boundaries, valley fills, maximum flooding surfaces and systems tracts (Hampson *et al.*, 1999; Gibling *et al.*, 2004). Such expressions of glacioeustasy may be modified under conditions of unusually rapid subsidence, as at Joggins, where the record of sea-level fall may be suppressed and the record of sea level rise may be strongly augmented, rendering the basin susceptible to basin-wide flooding events marked by faunal horizons.

At Joggins in the western Cumberland Basin, rapid subsidence probably reflects the extensional basin setting, coupled with active withdrawal of Windsor Group salt (Waldron and Rygel, 2005). In consequence, the Joggins cycles display what we consider to be a “tectonically controlled architecture” dominated by multiple flooding surfaces (Davies and Gibling, 2003), including coal and fossiliferous limestone at cycle bases that mark important episodes of sea-level rise. The overlying strata lack clear evidence for sea-level fall such as profound valley incision or well developed paleosols, although sharp-based shoreface and delta-lobe sandstones may reflect in part modest falls of sea-level (Plint, 1988). Large channel bodies appear to represent distributary channels, meandering rivers, and small valleys or gullies within a coastal plain setting, rather than profound basinward facies shifts that could have emplaced proximal (braided or low-sinuosity) river deposits over marine deposits. Small valley fills in Cycles 2 and 3 appear to lie within redbed intervals, and need not imply basinward shifts of facies belts linked to base-level lowering. The Joggins cycles may record glacial-interglacial transitions, manifested in an equatorial setting, periods of varied subsidence rate as faults moved and salt migrated, and/or variations in sediment flux.

In the absence of sequence boundaries, the Joggins cycles can be categorized as parasequence sets, composed of numerous thin parasequences and bounded by flooding surfaces marked by limestones, coals and carbonaceous shales. Thin drab intervals at cycle tops mark retrogradational parasequence sets that culminated in profound flooding at the start of the overlying cycle. As coastal rivers readvanced, thick progradational parasequence sets accumulated where tropical wetland deposits filled marine embayments, until a dryland alluvial plain was established. Thereafter, alluvial redbeds accumulated, flooding surfaces become fewer and less prominent, and trends of pro-, retro- or aggradation are difficult to establish.

Because subsidence was so rapid, a remarkably complete record of environments and the organisms that inhabited them is preserved in the Joggins cycles. In particular, prolonged periods of wetland conditions, during which sedimentation kept pace with subsidence, promoted the repeated generation and burial of forests.

SELECTED FIELD STOPS

Stop 1: Overview of the Little River Formation.

The strata exposed in Lower Cove between "South Reef" of the Boss Point Formation and the lowest coal of the Joggins Formation comprise the newly defined Little River Formation; a unit that corresponds almost exactly to Logan's (1845) Division 5. This 635.8-m-thick unit is bounded by regionally important stratigraphic surfaces and is traceable inland for 30 km from its Lower Cove type section. 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.

Facies analysis indicates that these strata represent the deposits of a well drained floodplain dissected by relatively flashy, shallow rivers. The presence of several well indurated petrocalcic horizons indicates pronounced rainfall seasonality and greater soil longevity than in the overlying Joggins Formation. Plant remains consist of abundant sphenopsid stems and *Cordaites* leaves, with less common pycnoxylic coniferopsid wood of *Dadoxylon*-type, medullosan pteridosperm axes, and rare lycopsid trunk compressions. Invertebrate remains are common and include shells of the land snail *Dendropupa vestusta* and 23-cm-wide trackways of the trackways of giant millipede-like *Arthropleura*. The only record of vertebrate life consists of a set of large tetrapod footprints provisionally assigned to the ichnogenus *Pseudobradypus* (Calder *et al.*, submitted). The xeric conditions and pronounced dry season recorded by the Little River Formation provide limiting constraints to the interpretation of seasonal drylands in the succeeding Joggins Formation, which records a gradual shift to wetter conditions with peat formation and flooding events near base level.

A complete account of the sedimentology, stratigraphy, and paleoecology of the Little River Formation accompanies the measured section presented in Calder et al (submitted).

Stop 2: Contact between the Little River and Joggins Formations

The upper contact of the formation is placed at the base of the stratigraphically lowest coal bed (No. 45 of Logan 1845), which coincides with the base of the revised Joggins Formation (Davies et al., submitted). Given that the Little River Formation lacks coal and bivalve-bearing limestone beds, the two defining hallmarks of the overlying

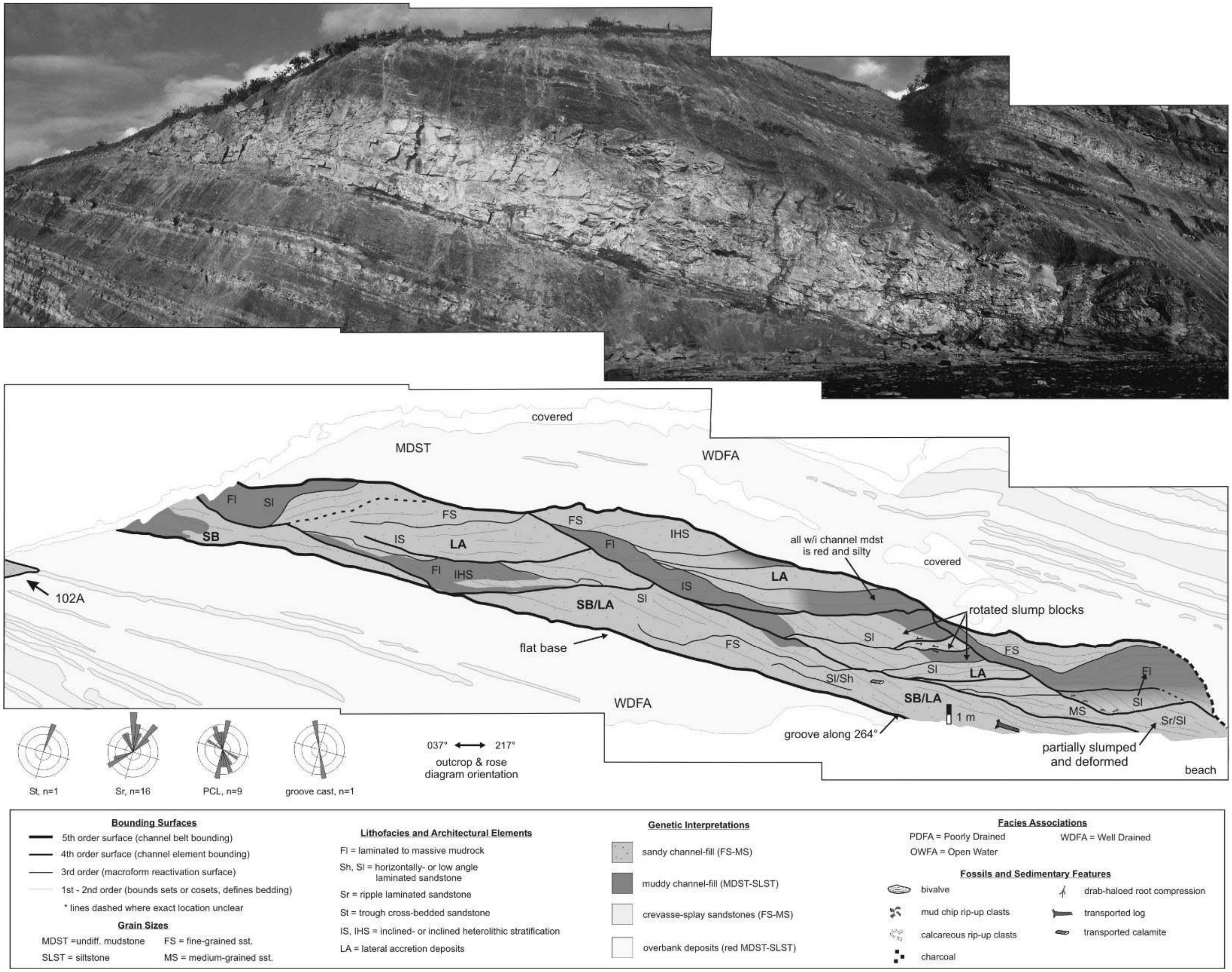


Figure 15: View of Stop 8, the multistorey channel body at 114 m (from Rygel, 2005).

Joggins Formation (Ryan et al. 1991), this coal represents an important stratigraphic surface marking the transition from the predominantly dryland conditions of the Little River Formation to the bays, wetlands, and seasonal drylands of the overlying Joggins Formation.

To the east, the formation interfingers with, or onlaps against, the polymictic conglomerates of the Polly Brook Formation (Ryan et al., 1990). It is probable that the Grand Anse Formation of New Brunswick represents a facies of the Little River Formation, but determining their exact correlation is problematic because the lower contact of the Grand Anse section is in faulted contact with the Boss Point Formation, and the upper contact is in faulted contact with the Windsor Group (Calder et al., submitted).

Stop 3: Multistorey channel body in Cycle 3 (114 m)

This 6.5 m thick channel body represents the largest of the multistorey "paleovalley" deposits within the well drained floodplain (Fig. 15). The base of these bodies consists of a flat 6^{th} order (channel belt-bounding) surface that forms a well defined channel margin that is visible on the airphotograph (Fig. 8). Within these bodies, numerous channel elements are defined by concave-up 5^{th} order (channel bounding) surfaces. These smaller channels averaged 3.5 m deep and 13 m wide and were much smaller than the valleys within which they flowed. Because these features do not mark a basinward shift in facies or pass into well developed paleosols in the overbank areas, the term paleovalley is used only to describe the paleogeomorphology of these incised drainages, not to imply that they necessarily formed in response to sea level fall (Rygel, 2005).

Internally, multistorey channel bodies in the well drained floodplain generally contain inclined- and inclined heterolithic strata organized into lateral- and downstream-accretion with gravel bars, sandy bedforms, abandonment fills present locally. Channel body 114 has slump blocks that record failure of the adjacent muddy channel deposits. The channel fill consists of very fine- to medium-grained sandstone to red or green clayey siltstone. Ripple cross-laminae, trough cross-beds, horizontal and low-angle laminae, laminated and rooted mudrock are the most common alluvial lithofacies.

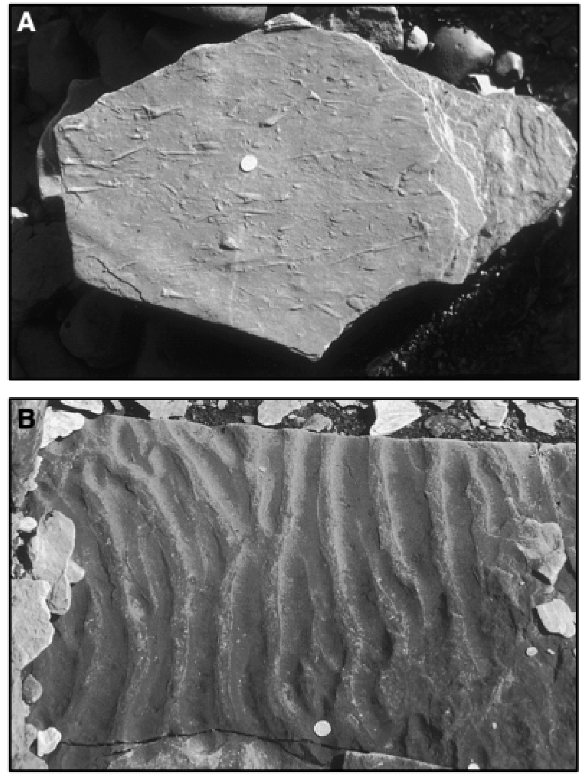


Figure 16: Common features of planar based-sandstones in the open water facies association: A) tool marks and B) truncated wave ripples (from Davies and Gibling, 2003).

Erosional surfaces are commonly overlain by a pebble-sized lag of mud rip-up clasts. The multistorey bodies lower in the section contain *in situ* vegetation, fragments of the land snail *Dendropupa*, pedogenic carbonate nodules, and carbonate rhizoconcretions cored by gymnospermous roots (Falcon-Lang *et al.*, 2004b). Fragmented plant remains within these bodies are dominated by a dryland assemblage consisting of pteridosperms, cordaites, and sphenopsids (Falcon-Lang, 2003c, his Facies 1).

Stop 4: Sharp-based sandstones in cycle 4 (115 to 148 m)

Occurrences of the open water facies association at the base of cycles 3 and 4 provide a good overview of the lithologies typically seen in these deposits: carbonaceous limestones, laminated shales, and the sharp-based sandstones (Fig. 16) which are the focus of this stop. As described by Davies and Gibling (2003)and Davies et al. (submitted), these sheet-like sandstones are as much as a meter thick, extend across the cliff and foreshore, and are characterized by planar bedding and a flaggy appearance. In cycle 4, these beds comprise overlapping mounds up to ~100 m in apparent width. The sandstones contain unidirectional ripple cross-lamination, local mud drapes, and lineated plane beds, wave ripples, ball-and-pillow structures (Stop 7), and rare hummocky cross-stratification indicating wave activity. Trace fossils include delicate grazing and walking traces (Archer et al., 1995). A few channel bodies cut the planar sandstones, with which they are closely associated. The topmost coarser beds contain roots, which mark the re-establishment of subaerial conditions after the initial flooding event.

These beds represent the sandy deposits at the terminal end of river-generated delta lobes. These beds are commonly associated with shallow channels indicating that they were either emplaced as mouth bar deposits and/or were generated by hyperpycnal flows that brought sandy sediment into deeper waters. In some cases, these beds may have been emplaced by storms that generated geostrophic flows that transferred sediment from the shorelines to deeper water.

Stop 5: Seasonal dryland waterhole of the "Hebert beds" (270-275 m)

These beds represent the deposits of an anastomosed drainage network within a seasonally dry alluvial plain. The channel bodies contain an unusual fossil assemblage (Figs. 17-19) and are interpreted as an alluvial waterhole deposit that formed following drought-induced cessation of channel flow. Fossil plant remains (including abundant charcoal) indicate that the waterhole was surrounded by hydrophilic lycopsids and sphenopsids and that much of the rest of the alluvial plan was covered by fire-prone cordaite vegetation (Figure 18).

The most striking faunal remains within these beds are those of the large unionoid freshwater bivalve *Archanodon* – which is locally preserved in life position. Remains of the terrestrial gastropod *Dendropupa* are commonly found clustered around fossil plant detritus, indicating that they 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 bears close similarity to the seasonal drainages and waterholes of present-day central and northern Australia. Please see Hebert and Calder (2004) and Falcon-Lang et al. (2004b) for more information on these beds.

Stop 6: The "Fundy Fossil Forests" (403-420 m)

These fossil forests sit atop the thickest cycle and beneath the first thick coal in the Joggins Formation (Coal 32). This interval illustrates the sedimentological context of the numerous lycopsid-calamite forests and their profound impact on sedimentation. At times, large scours filled with centroclinal-cross strata are exposed in this interval – showing how these fossil forests caused both local erosion and sediment accumulation (Rygel *et al.*, 2004). Short-term (seasonal?) precipitation flux is suggested by the heterolithic nature of the entombing sediments and the presence of charred lycopsid remains – charcoal generated by lightning-lighted wildfires.

Calder et al. (in press) described this interval in detail and noted that lycopsids range in diameter from 0.25 to 0.50 m, are as much as 5 to 6 m tall, and can be spaced as closely as 1.1 m. Compression flora associated with the forests consists of both mire (lycopsids) and extramire (sphenopsids, ferns, progymnosperms, pteridosperms, and gymnosperms) types.

Faunal remains from the Fundy forests includes a tetrapod ichnofacies consisting of *Pseudobradypus 'rex,' Limnopus vagus*, *Ornithoides trifudus*, and *Matthewichnus velox*. *Pseudobradypus 'rex'*, a provisional name, may represent the top predator of the Joggins ecosystem: a 1 to 2-m-long heavily built temnospondyl or crocodile-like loxommatid. Siderite concretions above coal 29 appear to be the source of two articulated tetrapod skeletons: a *Dendrerpeton* (Holmes *et al.*, 1998) and the other a partial anthracosaur (A. Milner, pers. comm.).

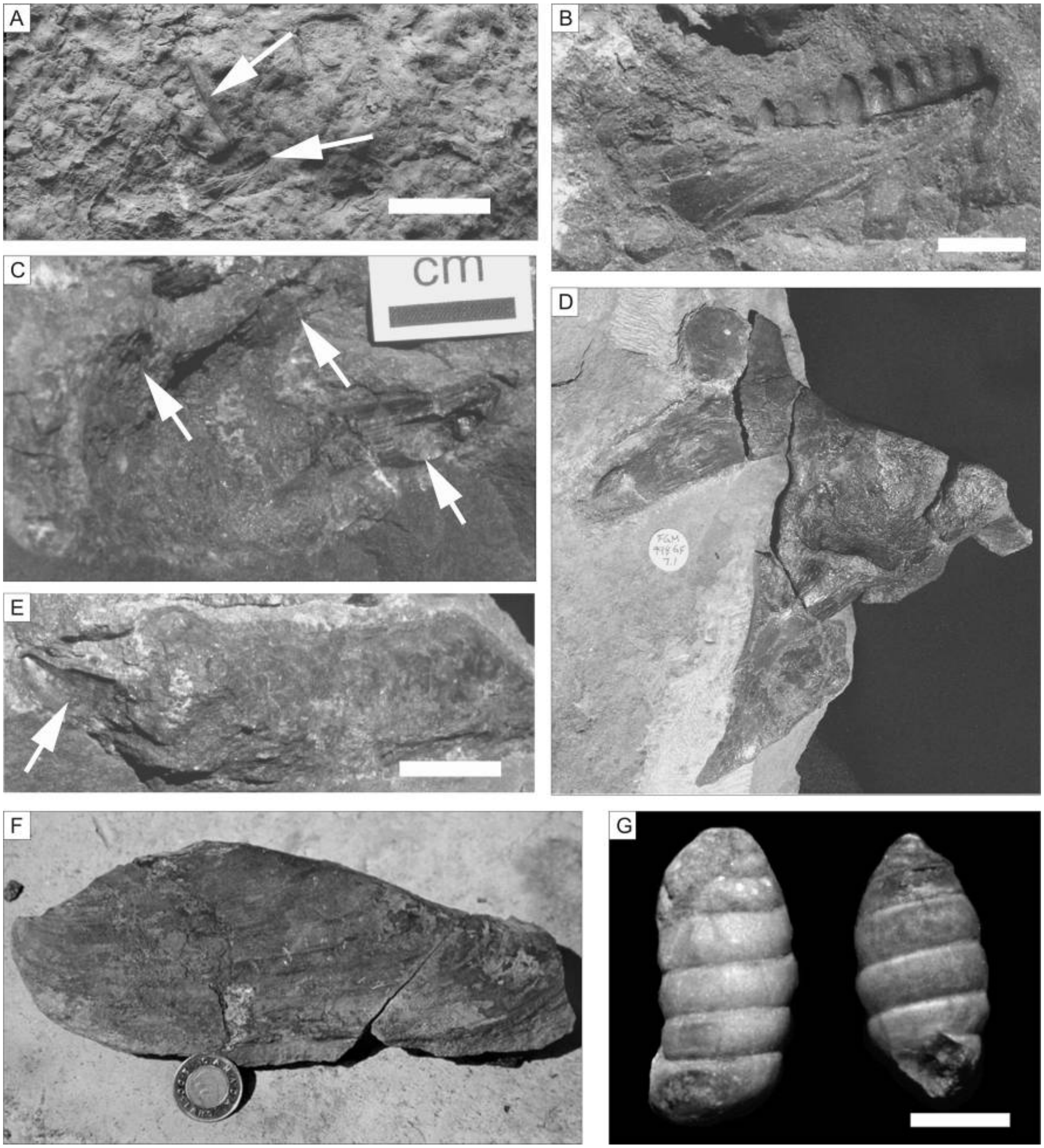


Figure 17: Examples of faunal material from Hebert beds. A) Basal lag of channel body 5 containing elongate rhizoconcretions (upper centre, arrowed) and a microsaur jaw (lower centre, arrowed), FGM000GF19, scale = 2 cm diameter, B) Enlargement of microsaur jaw shown in Fig. 8A, scale = 7 mm, FGM000GF19, 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. F) *Archanodon westoni* unionoid bivalve from channel body 274C, this articulated specimen is similar to the one extracted from life position in IS bedsets, coin = 27 mm diameter, FGM998GF70. G) Two specimen s of *Dendropupa vetusta* land snail, scale = 3 mm, NSM002GF031.189. Figure after Falcon-Lang et al. (2005).

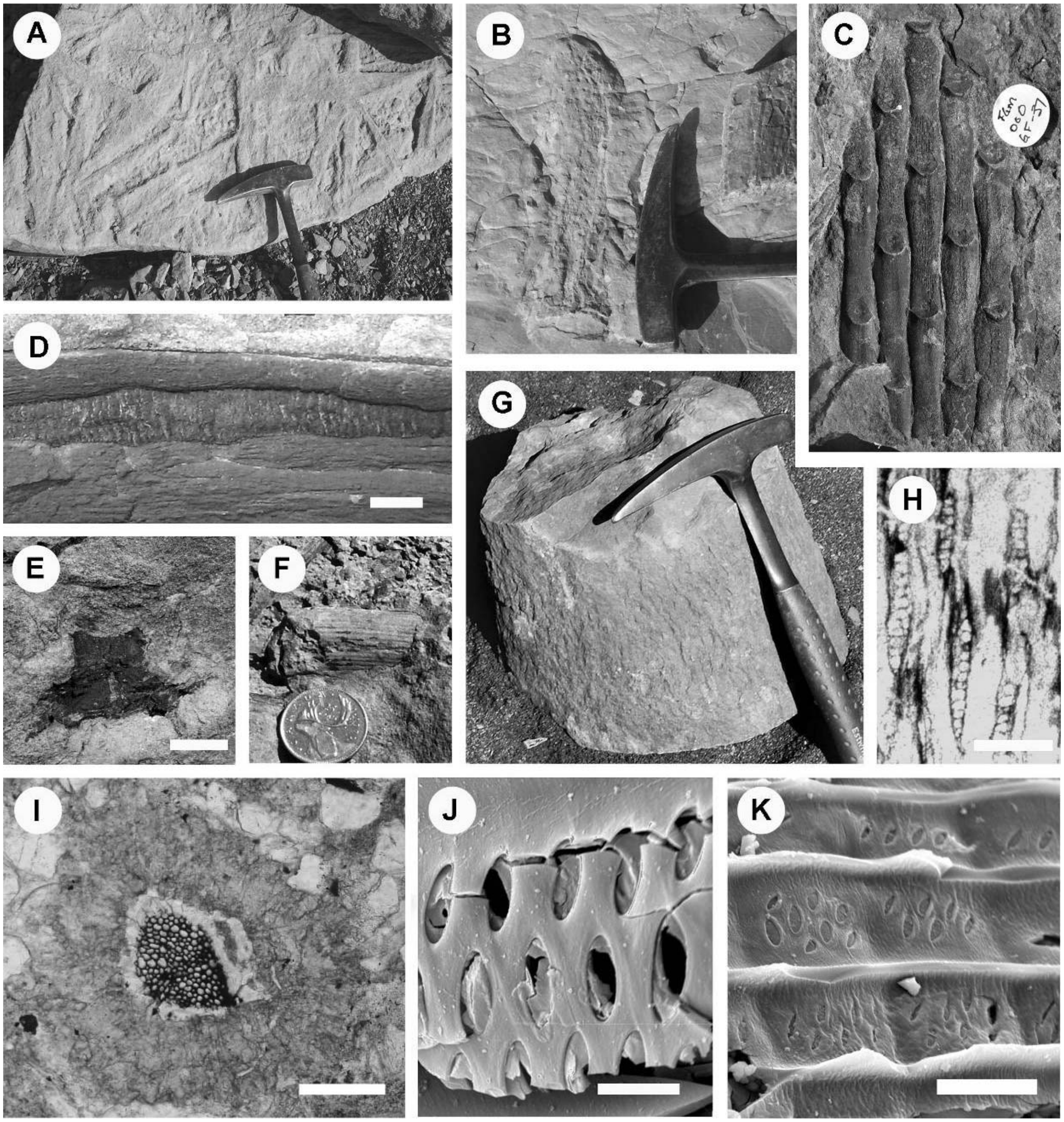


Figure 18: Fossil plants in and adjacent to the Hebert beds; (A, C-F, H-K) allochthonous and (B, G) autochthonous; all from Falcon-Lang et al. (2004). A) Abundant impressions of *Cordaites principalis* leaves, not collected, hammerhead for scale = 15 cm long. B) *Stigmaria ficoides* root cast, not collected. 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. K) Charred *D. materiarium* cordaite wood showing araucarioid cross-field pitting; SEM image, NSM003GF029.003, scale = 40 µm.

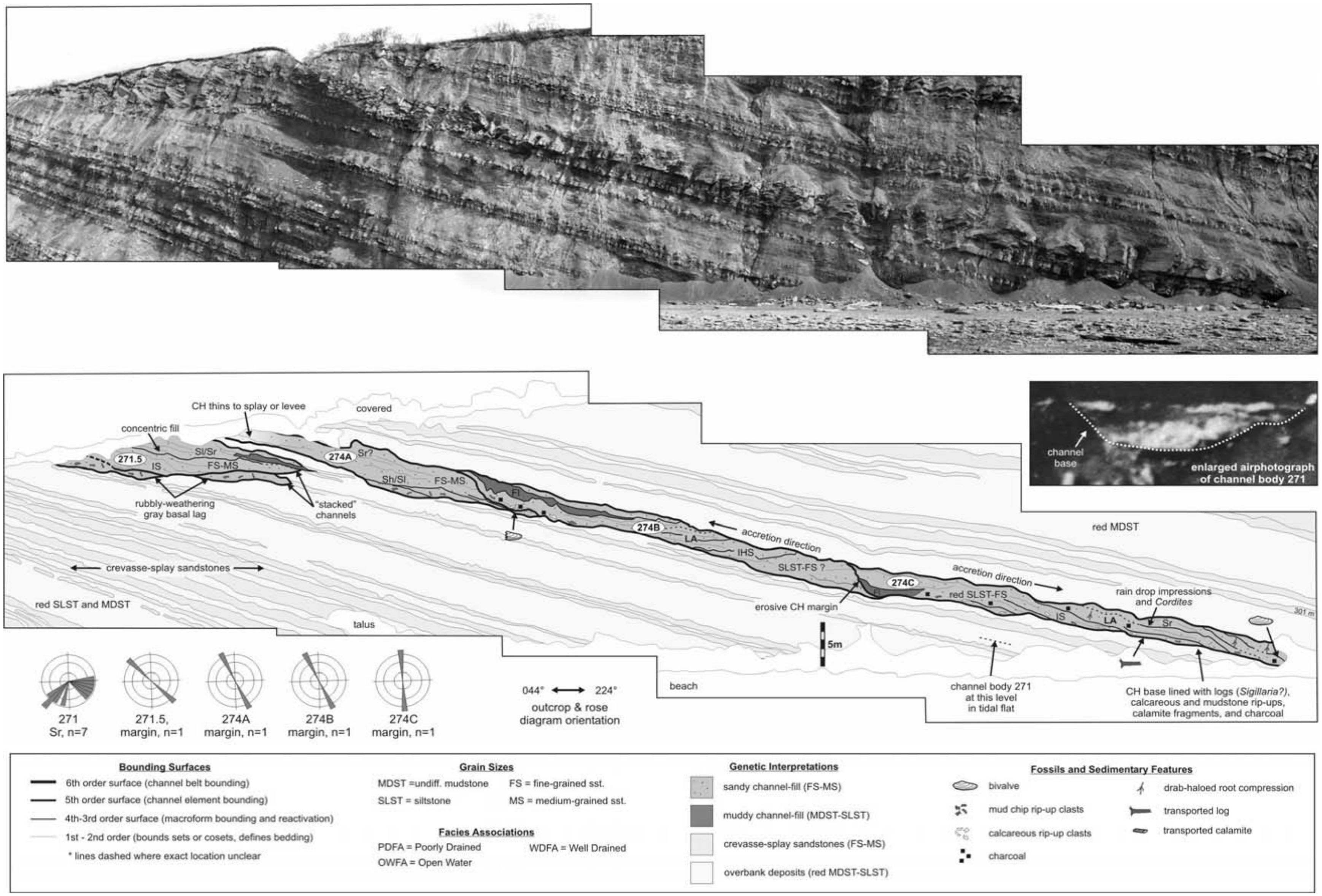


Figure 19: Photograph and interpretive tracing of the "Hebert beds," a series of fixed (271 and 271.5) and meandering (274A-C) channel bodies within the well drained facies association of cycle 5. Enlarged airphotograph of channel body 271 presented at the same scale as the cliff photograph. (from Rygel 2005; after Falcon-Lang et al., 2004).

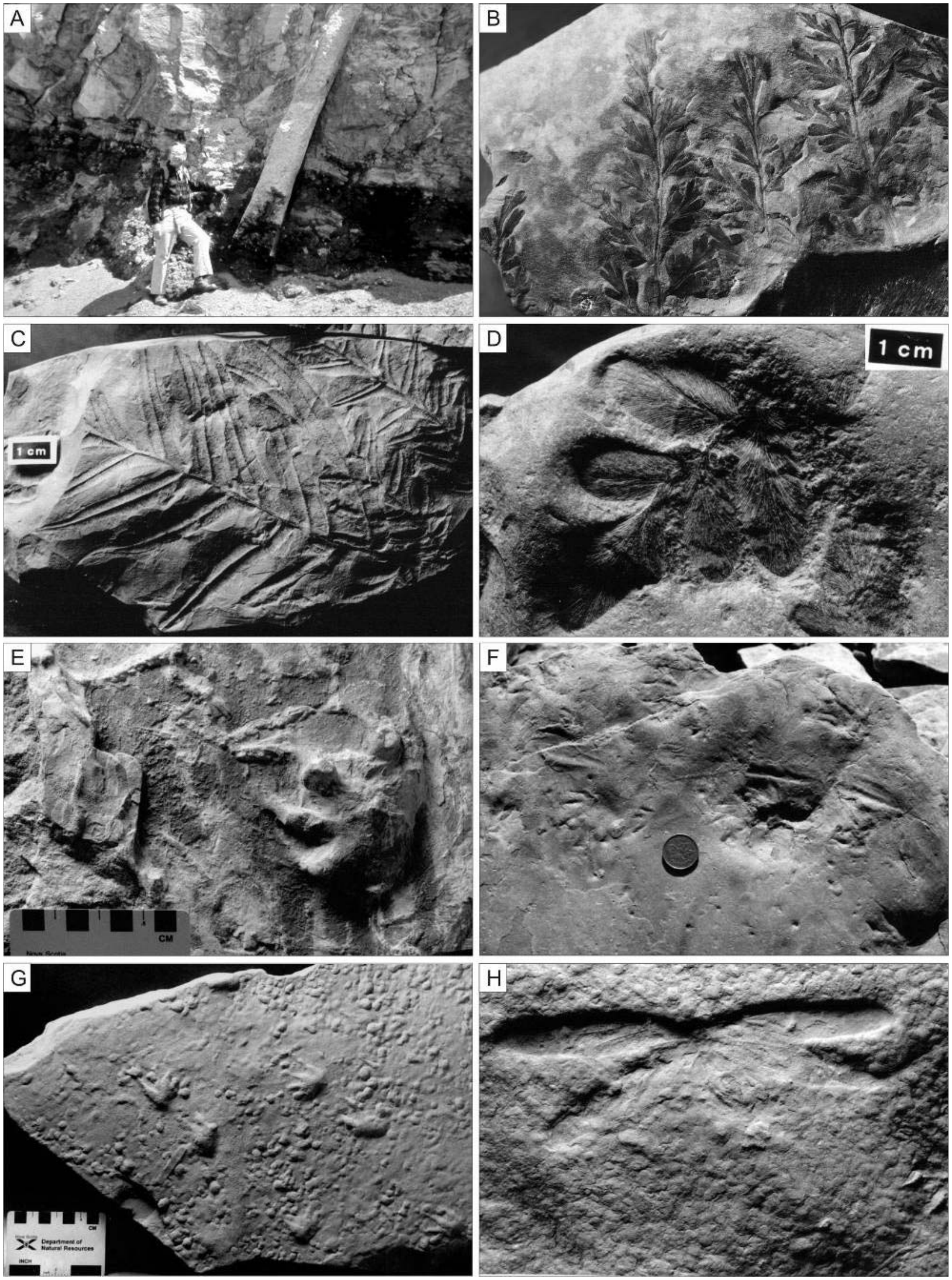


Figure 20: Biota of the "Fundy Fossil Forests" from Calder et al. (in press). A) Standing lycopsid. B) *Adiantites,* C) *Alethopteris,* D) *Neuropteris,* E) *Pseudobradypus 'rex'* , F) *Dromillopus,* G) *Limnopus,* and H) *Megasecoptera.*

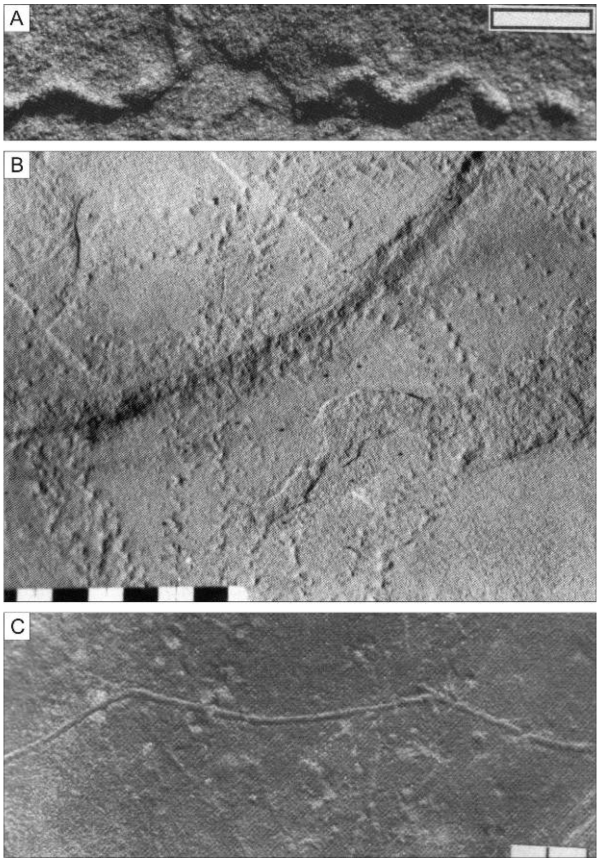


Figure 21: Invertebrate trace fossils from the open water facies above the Forty Brine Coal. A) *Cochlichnus*, B) *Kouphichnium*, and C) *Treptichnus* (scale gradations in cm; all from Archer et al., 1995).

Stop 7: Open water facies above the Forty Brine Coal (548-570 m)

The open water interval above the Forty Brine Seam was the subject of a Master's Thesis by D.M. Skilliter (2001) at Boston College. This succession also contains the classic open water lithologies including fossiliferous limestone, carbonaceous limestone, laminated shale, and sharp-based sandstones. The Forty Brine Coal has one of the highest sulphur contents of any coal in the Maritimes; certain parts of the seam exceed 18%. The carbonaceous limestones are locally called "clam coals" in reference to their dark color, bituminous-rich nature, and abundance of the pelecypods *Naiadites carbonarius*, *Naiadites longus*, *Curvirimula sp*., which define its fissility. The overlying sharp-based sandstone represents the "trace fossil bed" identified by Don Reid and described by Archer et al. (1995). Arthropod trackways in this interval include the ichnogenera *Kouphichnus* (made by horseshoe crab-like limulids), *Arenicolites*, *Protichnites*, *Cochlichnus*, *Gordia*, and several others. This unit is cut by a distal distributary channel near the low tide level, indicating that it formed as part of a mouth bar complex. Strata above the Forty Brine coal have the most prominent mud-draped ripples in the section (Skilliter, 2001)

This interval represents the most aerially extensive flooding surface in the basin and can be traced 40 km inland.

Stop 8: Coal Mine Point and Lyell & Dawson's tetrapod-bearing forest (628-650 m)

At this location in 1852 (Fig. 22), Dawson and Lyell discovered the remarkable occurrence of tetrapods and land snails within the casts of erect lycopsid trees (Lyell and Dawson, 1853; Dawson, 1882, 1894). So far over 11 tetrapod and 5 terrestrial invertebrate taxa have been discovered within the trees, the majority of which were found by Sir William Dawson (Carroll et al., 1972; Calder, 1998). Arguably the most famous of these is *Hylonomus lyelli* (Dawson, 1860), which remains the oldest unequivocal terrestrial amniote (Carroll, 1994).

The circumstances surrounding the demise of the tree stump fauna has long been attributed to pitfall into partially buried, hollow stumps (Dawson, 1878; Carroll et al., 1972), however the vast majority of the remains occur near the base of the trees suggesting that the animals were using the hollow trunks as dens or refugia. This is supported by the occurrence of several species within a single tree, the disarticulated nature of the skeletal material, and the presence of coprolites. Fossil charcoal occurs within almost all of the tetrapod-bearing casts, suggesting that fire may have hollowed out the dens and potentially killed the occupants (Scott, 2001).

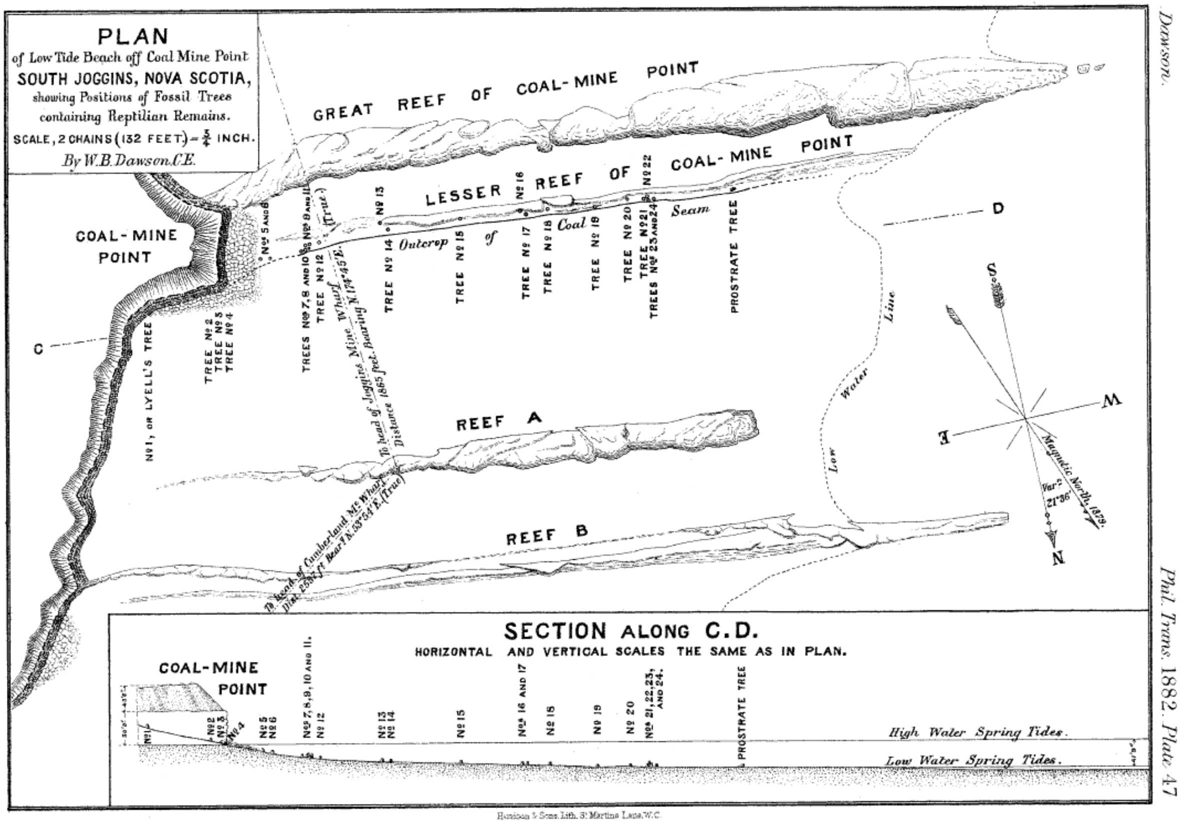


Figure 22: Map of the Dawson's (1882) fossil forest horizon and Coal Mine Point (Stop 8).

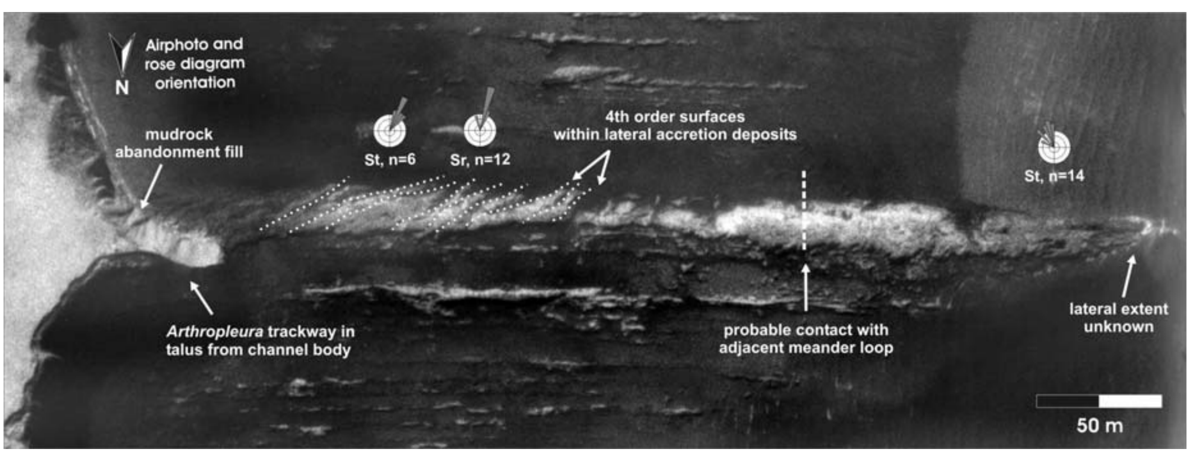


Figure 23: Labeled airphotograph showing Coal Mine Point, a large meandering channel body within poorly drained strata of cycle 10.

Figure 24: Clifftop photograph of Coal Mine Point, arrows point to prominent erosional surfaces within lateral accretion deposits.

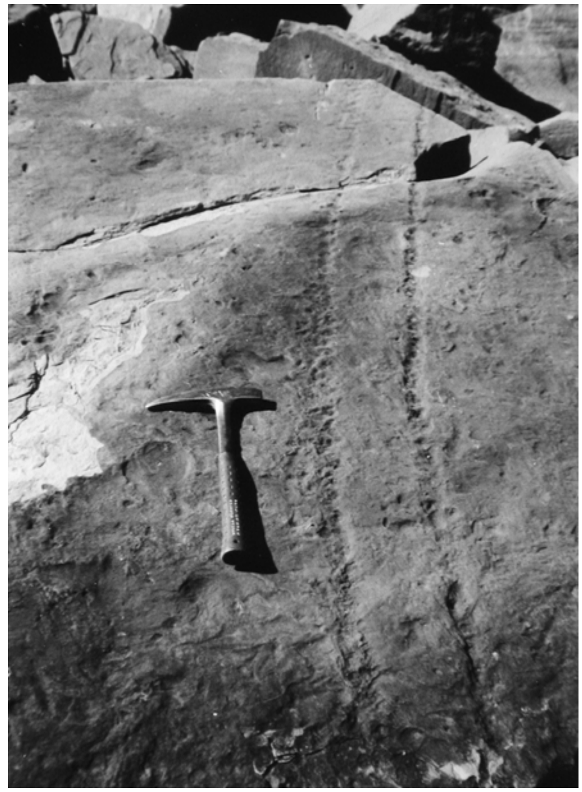


Figure 25: *Diplichnites*, the trackway of the myriapod *Arthropleura*. This talus block fell from the Coal Mine Point channel body.

Overlying the fossil forest is the prominent headland and intertidal "reef" of Coal Mine Point. This 10.5 m thick channel body is organized into lateral accretion deposits which are crosscut by 4^{th} order erosion surfaces that pass through the entire thickness of the body – these intraformational conglomerate-lined surfaces are easily eroded and form the recessed areas on the airphotograph. The channel body is primarily composed of fine-grained sandstone organized into trough cross beds, ripple cross-laminae, and horizontal laminae with primary current lineations. A large talus block just below the headland contains a large trackway of the myriapod *Arthropleura* (Fig. 23).

Stop 9: The calamite grove below Bell's Brook

The package of heterolithic sandstone between 708 and 715 m in the measured section contains numerous *in situ* calamites. These arborescent sphenopsids were able to survive burial by adventitious propagation; evidence of this survival strategy is recorded at the base of some stems where they narrow to a point and attach to a node on another stem. The taphonomy of the calamites and the sedimentology of the entombing sediments indicates that these beds were emplaced at intervals – perhaps closely spaced flood events.

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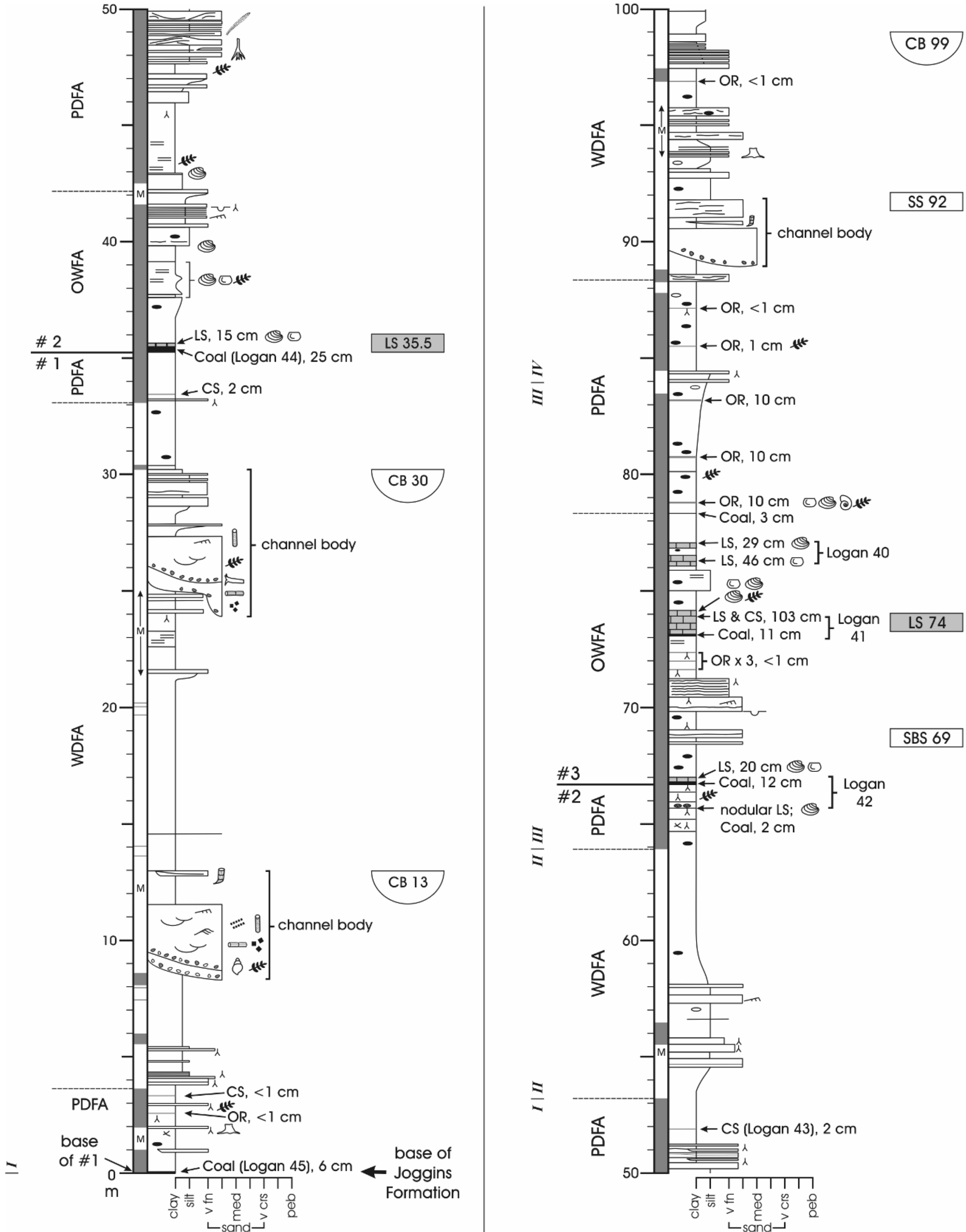
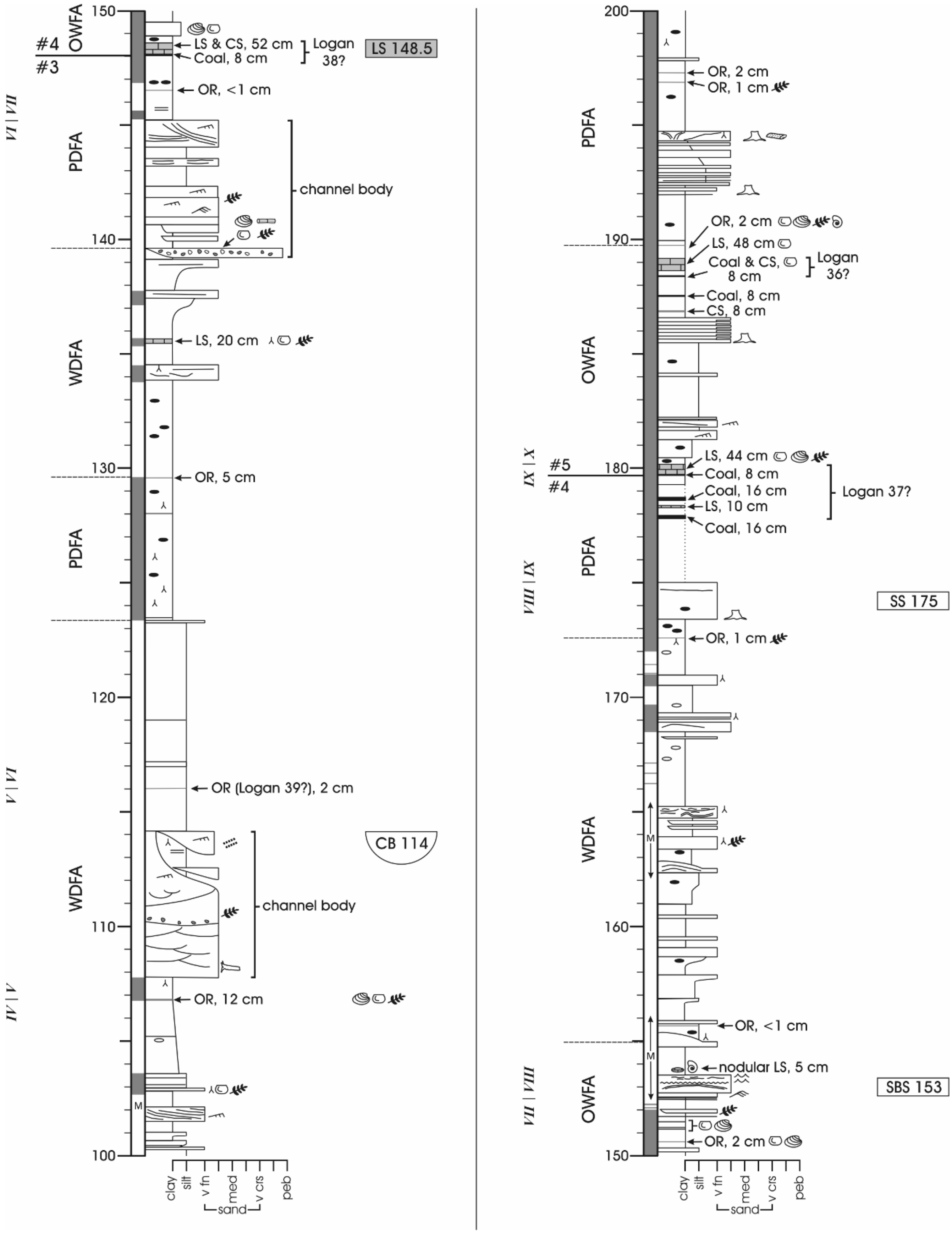
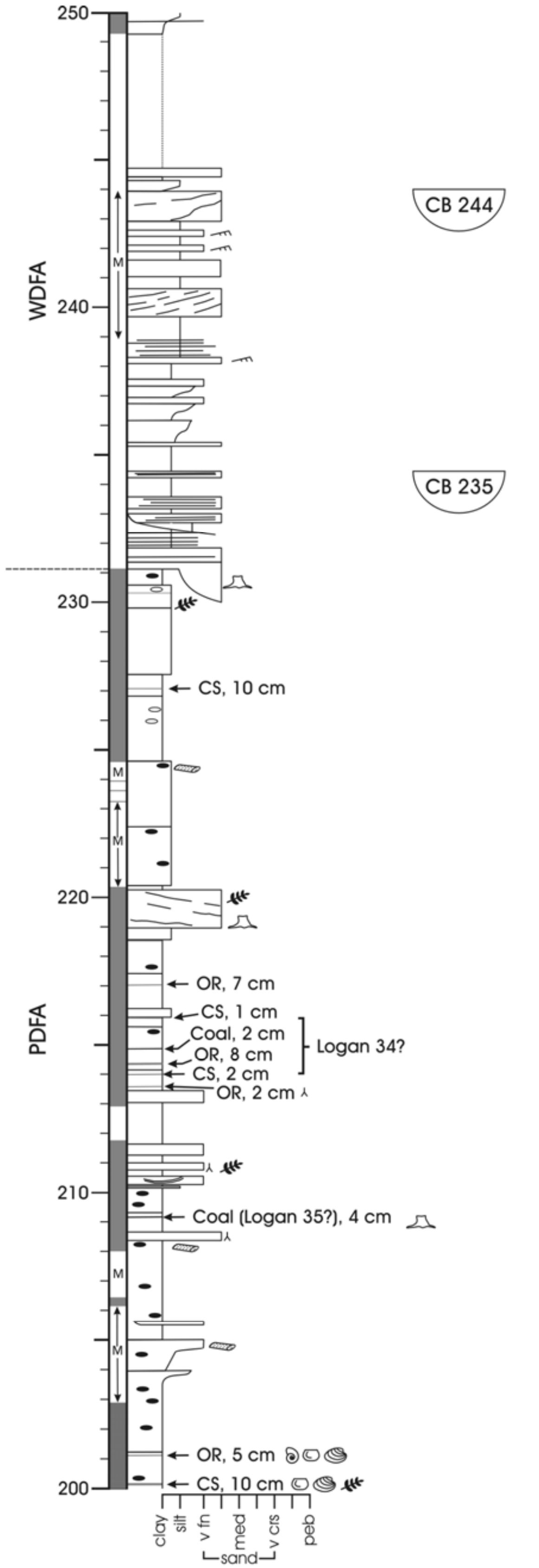
APPENDIX: THE JOGGINS MEASURED SECTION

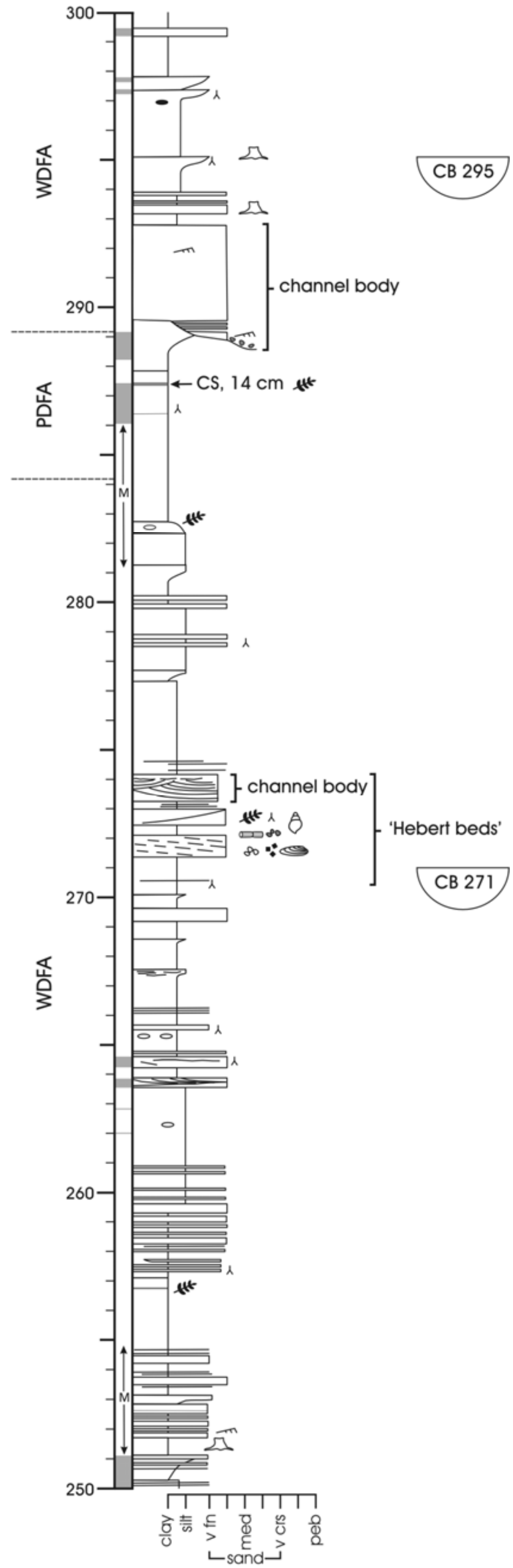
The following eleven pages show the detailed measured section of the Joggins Formation, from the base in the low cliffs at Lower Cove to the formation top south of Bell’s Brook (from Davies *et al.*, submitted). A key to the symbols and features shown on the measured section is provided on pages 41 and 42.

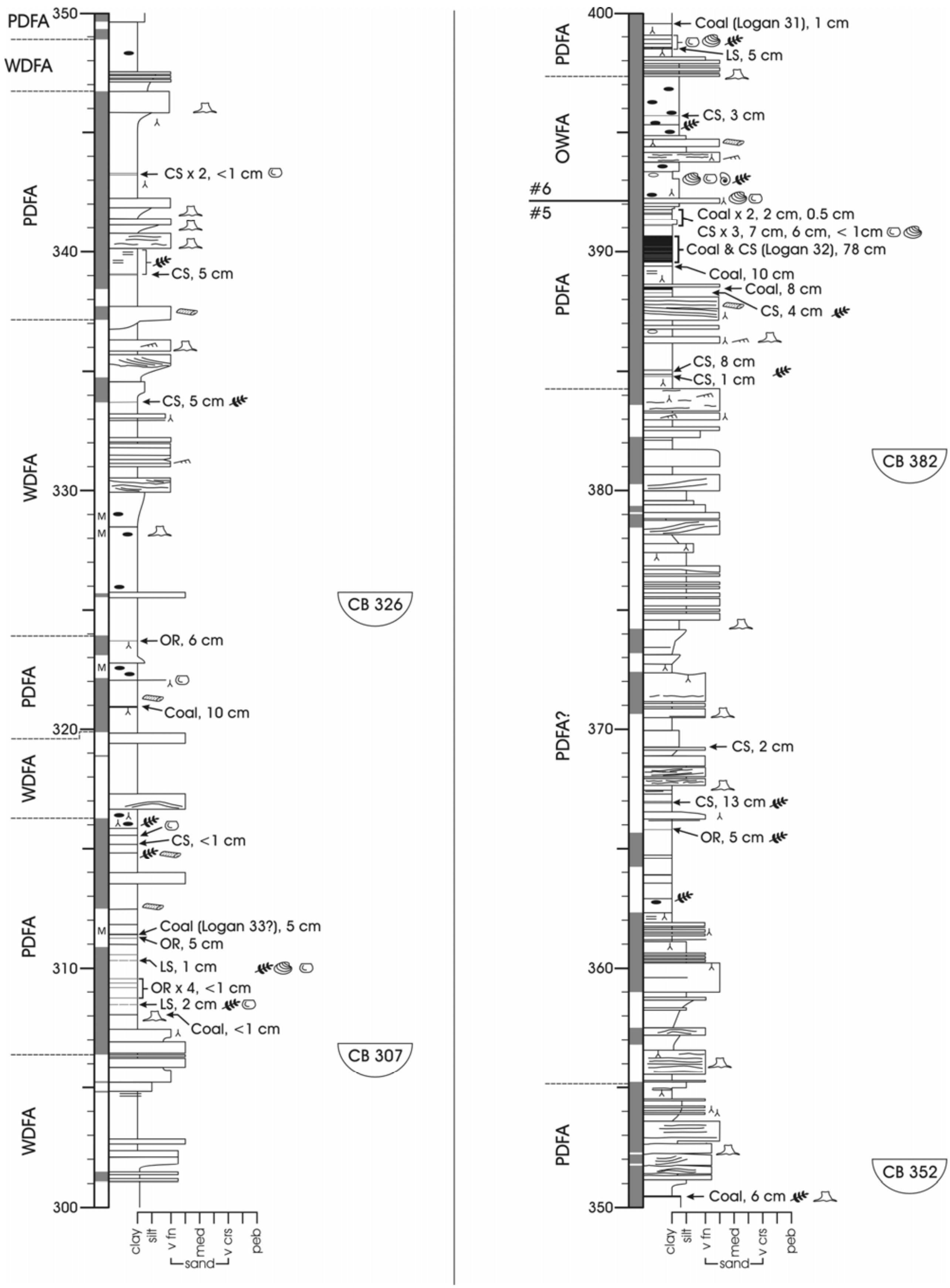


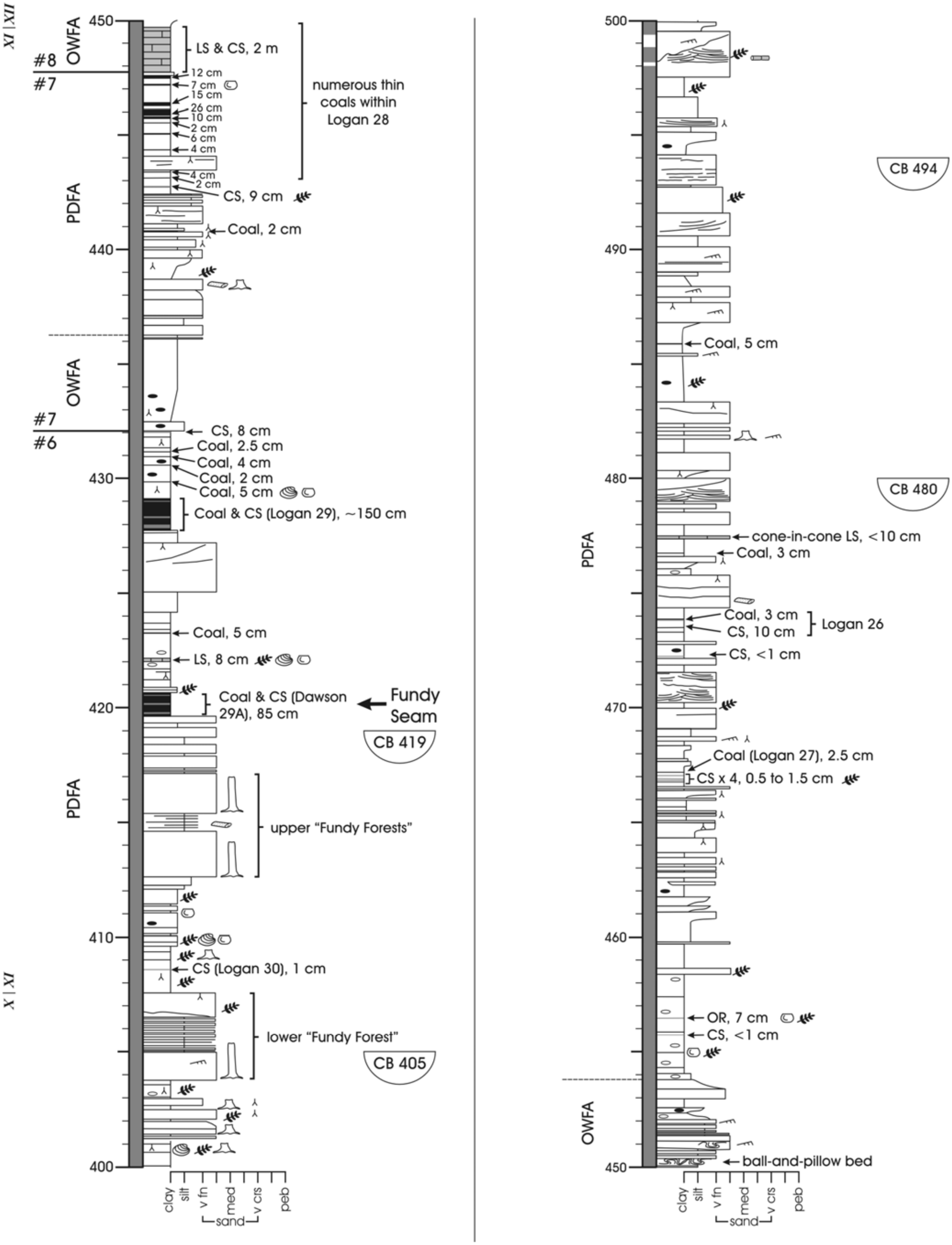
50
PDFA
M
OWFA
40
LS, 15 cm
2
1
Coal (Logan 44), 25 cm
LS 35.5
PDFA
CS, 2 cm
30
CB 30
channel body
M
20
WDFA
M
CB 13
10
channel body
PDFA
CS, <1 cm
OR, <1 cm
M
base of #1
0
m
Coal (Logan 45), 6 cm
base of Joggins Formation
| I
clay
silt
v fn
med
v crs
peb
sand
100
CB 99
OR, <1 cm
WDFA
M
SS 92
90
channel body
OR, <1 cm
OR, 1 cm
III | IV
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
LS, 20 cm
#3
#2
Coal, 12 cm
Logan 42
nodular LS;
Coal, 2 cm
II | III
PDFA
60
WDFA
M
I | II
CS (Logan 43), 2 cm
PDFA
50
clay
silt
v fn
med
v crs
peb
sand

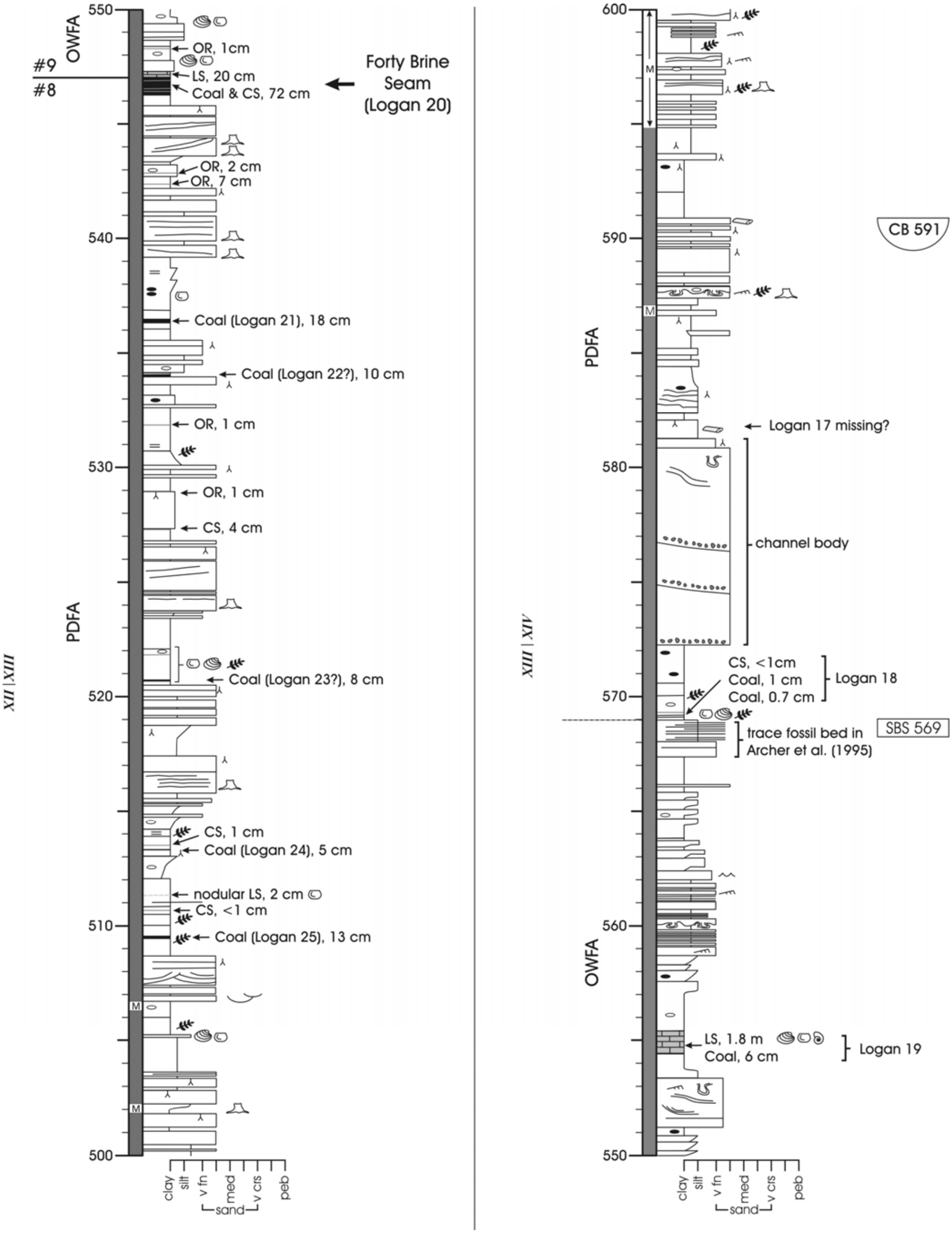

150
OWFA
#4
#3
LS & CS, 52 cm
Coal, 8 cm
Logan 38?
LS 148.5
OR, <1 cm
VI | VII
PDFA
channel body
140
LS, 20 cm
WDFA
130
OR, 5 cm
PDFA
120
V | VI
OR (Logan 39?), 2 cm
CB 114
WDFA
channel body
110
IV | V
OR, 12 cm
M
100
clay
silt
v fn
med
v crs
peb
sand
200
OR, 2 cm
OR, 1 cm
PDFA
190
OR, 2 cm
LS, 48 cm
Coal & CS, 8 cm
Logan 36?
Coal, 8 cm
CS, 8 cm
OWFA
LS, 44 cm
#5
IX | X
#4
180
Coal, 8 cm
Coal, 16 cm
LS, 10 cm
Coal, 16 cm
Logan 37?
PDFA
VIII | IX
SS 175
OR, 1 cm
170
WDFA
M
160
OR, <1 cm
M
nodular LS, 5 cm
VII | VIII
OWFA
SBS 153
OR, 2 cm
150


250
240
230
220
210
200
WDFA
PDFA
M
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
med
v crs
peb
sand

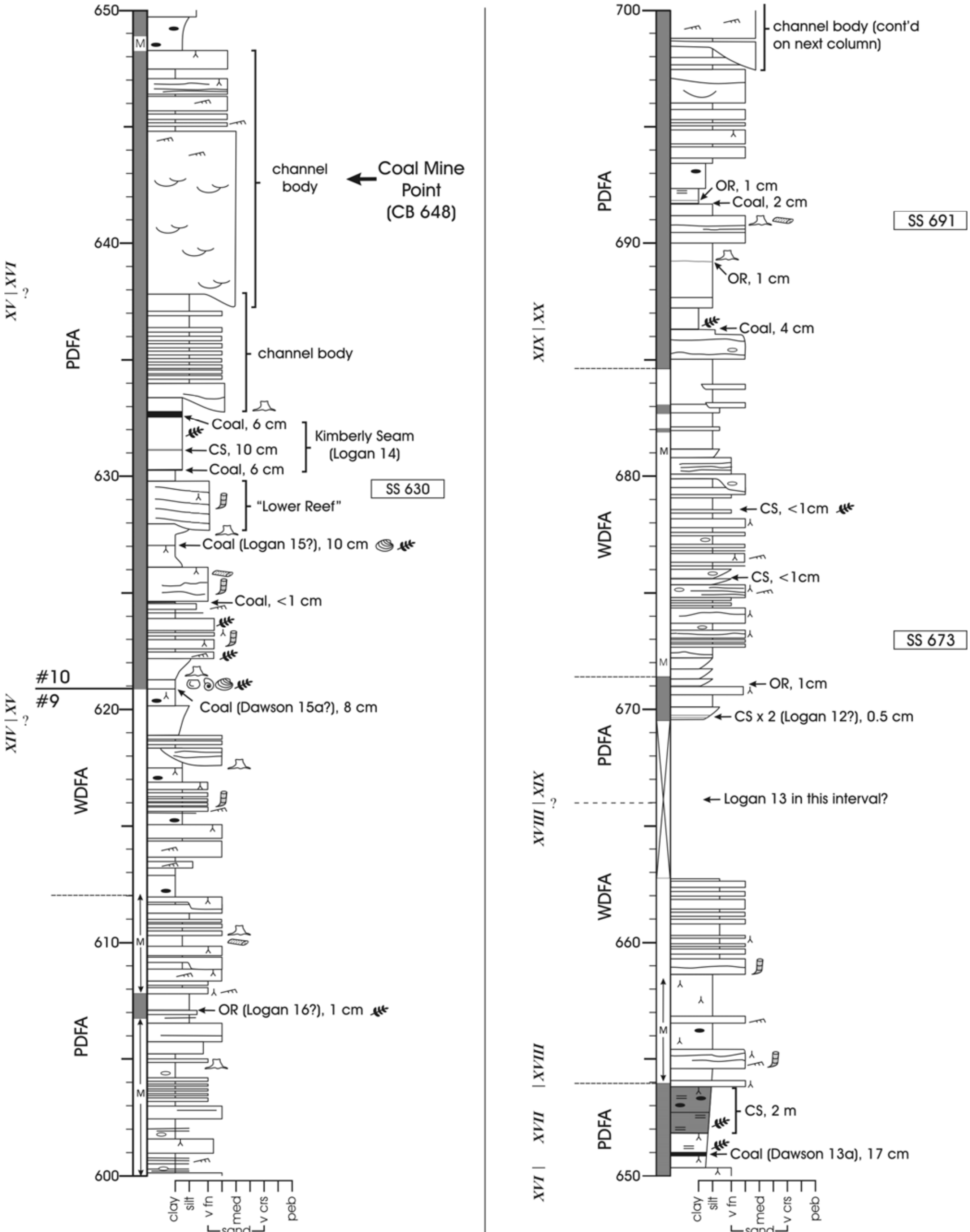

300
290
280
270
260
250
WDFA
PDFA
M
CB 295
channel body
CS, 14 cm
channel body
'Hebert beds'
CB 271
clay
silt
v fn
med
v crs
peb
sand

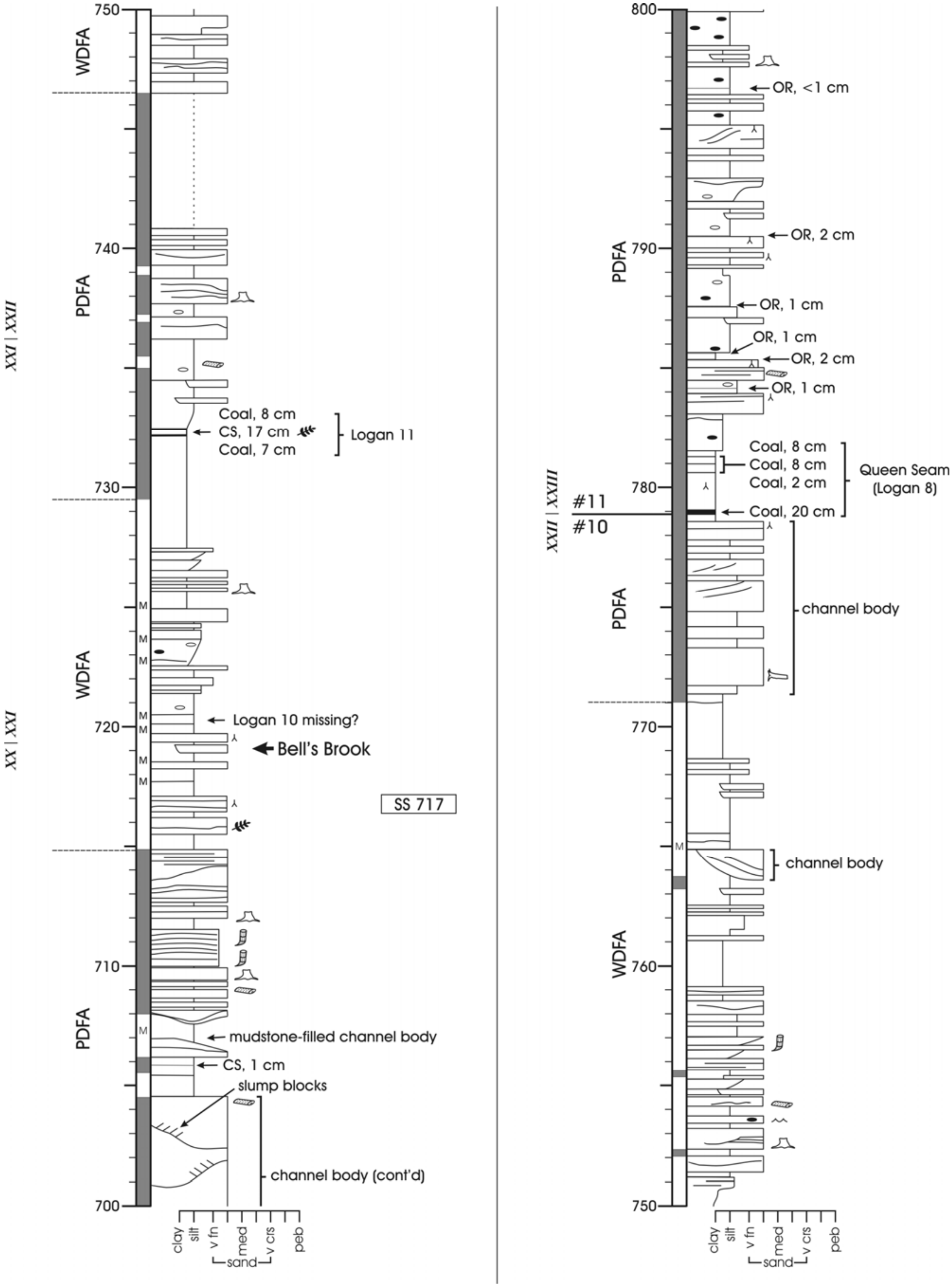

PDFA
WDFA
PDFA
WDFA
PDFA
WDFA
PDFA
WDFA
CS x 2, <1 cm
CS, 5 cm
CS, 5 cm
OR, 6 cm
Coal, 10 cm
CS, <1 cm
Coal (Logan 33?), 5 cm
OR, 5 cm
LS, 1 cm
OR x 4, <1 cm
LS, 2 cm
Coal, <1 cm
CB 326
CB 307
clay silt v fn med v crs peb
sand
PDFA
OWFA
#6
#5
PDFA
PDFA?
PDFA
Coal (Logan 31), 1 cm
LS, 5 cm
CS, 3 cm
Coal x 2, 2 cm, 0.5 cm
CS x 3, 7 cm, 6 cm, < 1cm
Coal & CS (Logan 32), 78 cm
Coal, 10 cm
Coal, 8 cm
CS, 4 cm
CS, 8 cm
CS, 1 cm
CB 382
CS, 2 cm
CS, 13 cm
OR, 5 cm
CB 352
Coal, 6 cm
clay silt v fn med v crs peb
sand


XI | XII
OWFA
#8
#7
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
PDFA
Coal, 2 cm
OWFA
#7
#6
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
PDFA
upper "Fundy Forests"
CS (Logan 30), 1 cm
X | XI
lower "Fundy Forest"
CB 405
450
440
430
420
410
400
clay
silt
v fn
med
v crs
peb
sand
500
490
480
470
460
450
CB 494
Coal, 5 cm
CB 480
PDFA
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
OWFA
ball-and-pillow bed

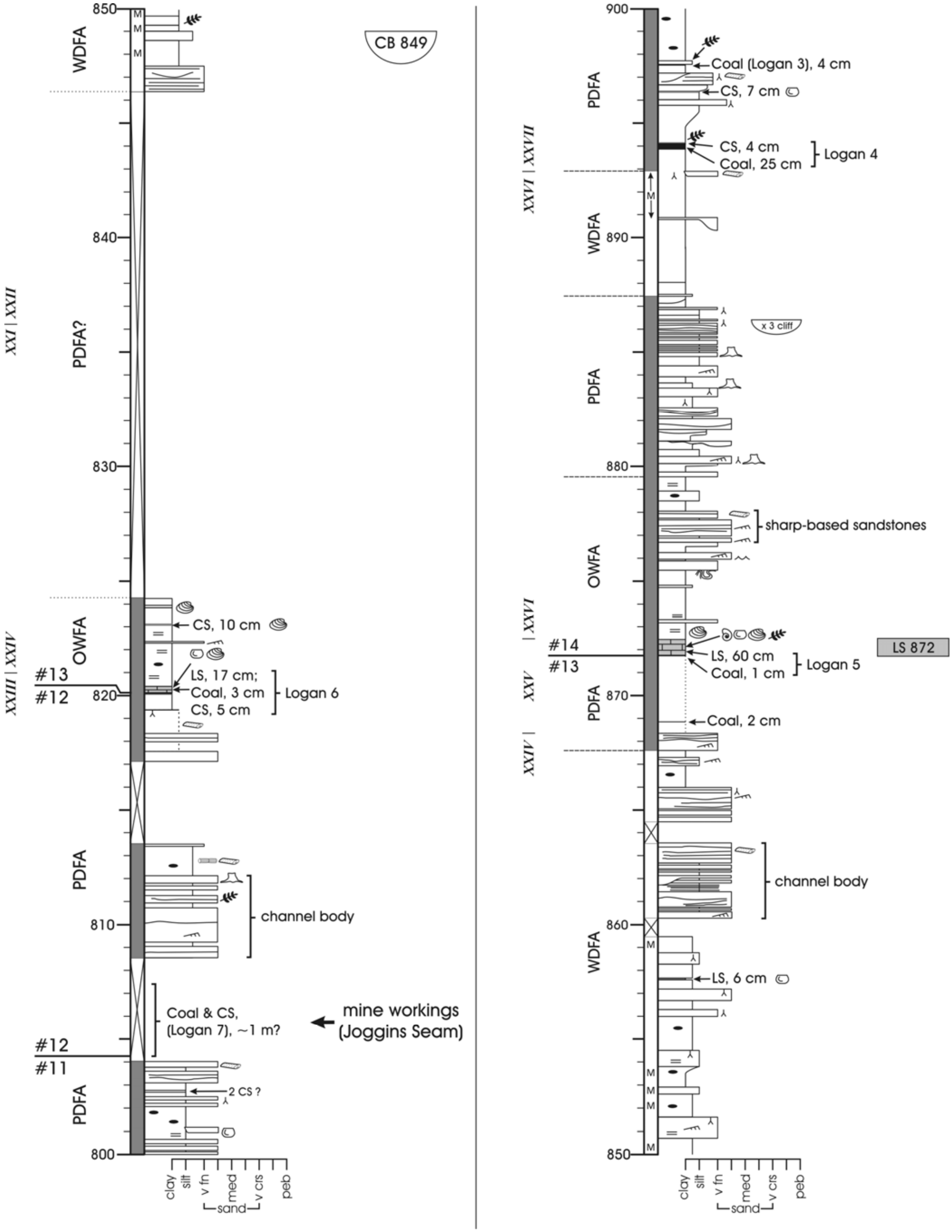


550
OWFA
#9
#8
OR, 1cm
LS, 20 cm
Coal & CS, 72 cm
Forty Brine Seam (Logan 20)
OR, 2 cm
OR, 7 cm
540
Coal (Logan 21), 18 cm
Coal (Logan 22?), 10 cm
OR, 1 cm
530
OR, 1 cm
CS, 4 cm
PDFA
XII | XIII
Coal (Logan 23?), 8 cm
520
CS, 1 cm
Coal (Logan 24), 5 cm
nodular LS, 2 cm
CS, <1 cm
510
Coal (Logan 25), 13 cm
M
500
clay silt v fn med v crs peb
sand
600
M
CB 591
590
PDFA
Logan 17 missing?
580
channel body
XIII | XIV
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
clay silt v fn med v crs peb
sand

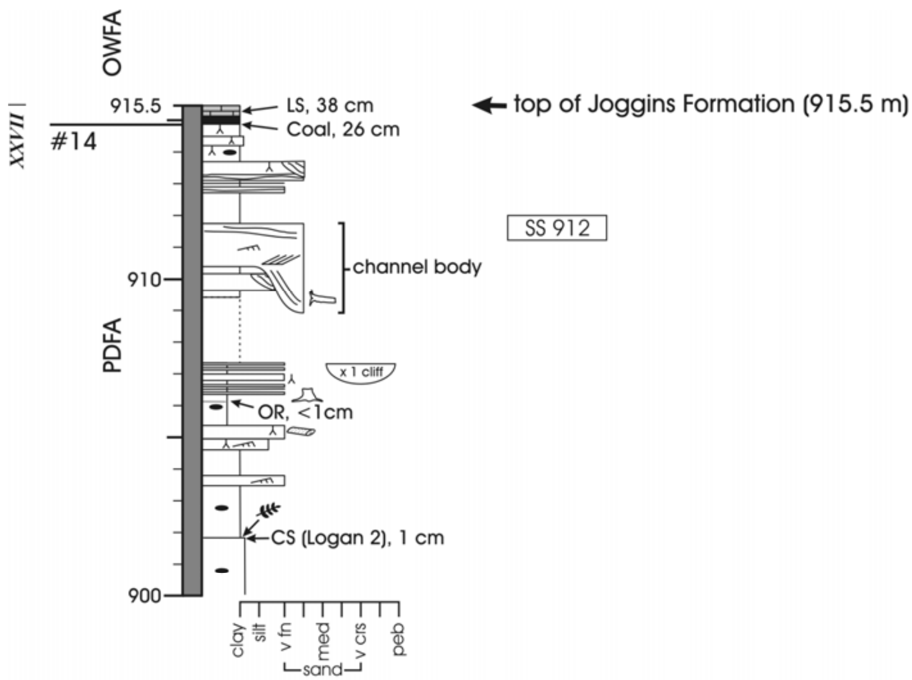

650
640
630
620
610
600
PDFA
WDFA
PDFA
XV | XVI ?
XIV | XV ?
#10
#9
M
channel body
Coal Mine Point (CB 648)
channel body
Coal, 6 cm
CS, 10 cm
Coal, 6 cm
Kimberly Seam (Logan 14)
SS 630
"Lower Reef"
Coal (Logan 15?), 10 cm
Coal, <1 cm
Coal (Dawson 15a?), 8 cm
OR (Logan 16?), 1 cm
clay
silt
v fn
med
v crs
peb
sand
700
690
680
670
660
650
PDFA
WDFA
PDFA
WDFA
PDFA
XIX | XX
XVIII | XIX ?
XVI | XVII | XVIII
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

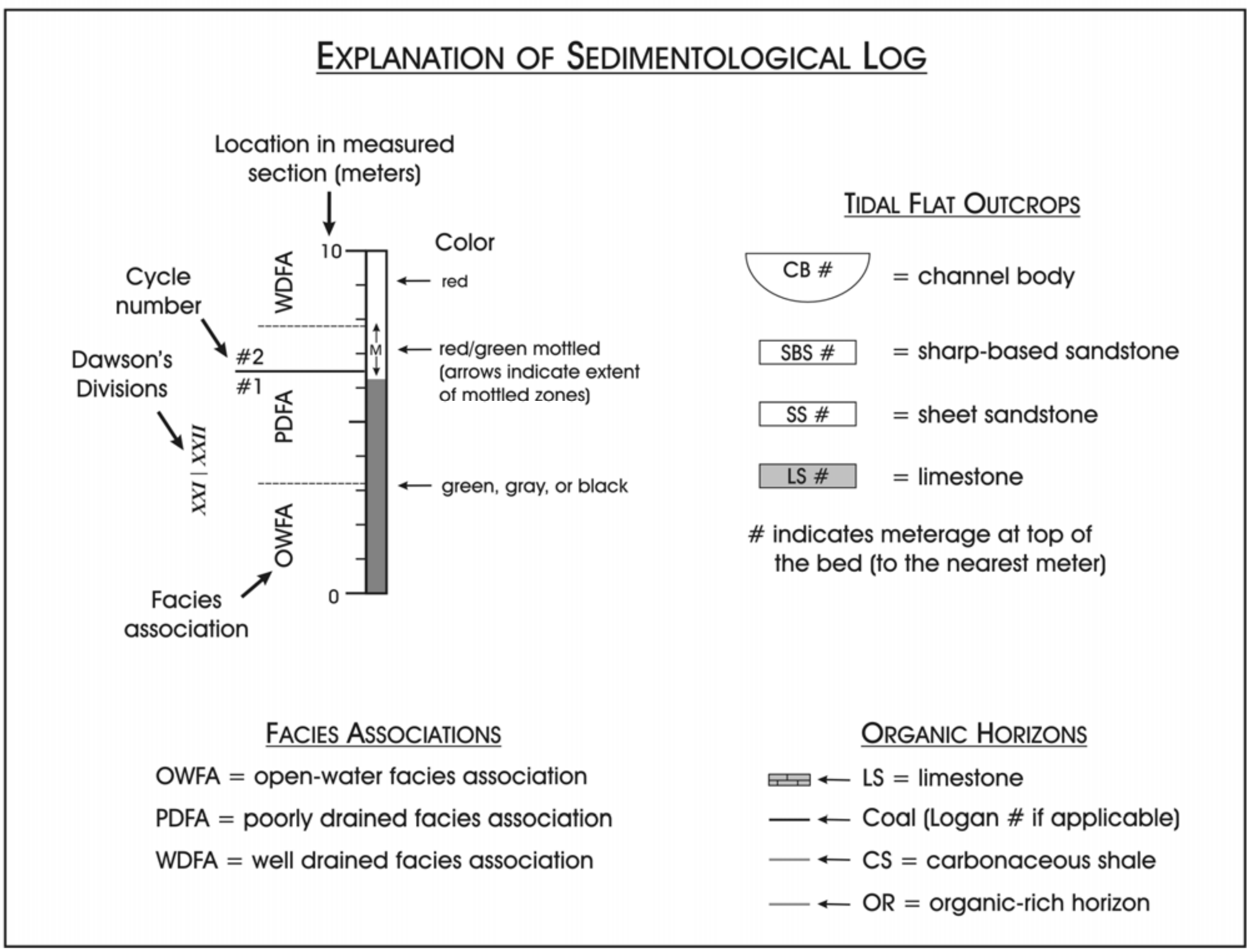


750
WDFA
740
PDFA
XXI | XXII
Coal, 8 cm
CS, 17 cm
Coal, 7 cm
Logan 11
730
WDFA
XX | XXI
720
Logan 10 missing?
Bell's Brook
SS 717
710
PDFA
mudstone-filled channel body
CS, 1 cm
slump blocks
channel body (cont'd)
700
clay
silt
v fn
med
v crs
peb
sand
800
OR, <1 cm
OR, 2 cm
PDFA
790
OR, 1 cm
OR, 1 cm
OR, 2 cm
OR, 1 cm
Coal, 8 cm
Coal, 8 cm
Coal, 2 cm
Coal, 20 cm
Queen Seam (Logan 8)
XXII | XXIII
#11
#10
780
PDFA
channel body
770
channel body
WDFA
760
750



850
840
830
820
810
800
WDFA
PDFA?
OWFA
PDFA
PDFA
XXI | XXII
XXIII | XXIV
#13
#12
#12
#11
CB 849
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 ?
clay
silt
v fn
med
v crs
peb
sand
900
890
880
870
860
850
PDFA
WDFA
PDFA
OWFA
PDFA
WDFA
XXVI | XXVII
XXIV | XXV | XXVI
#14
#13
Coal (Logan 3), 4 cm
CS, 7 cm
CS, 4 cm
Coal, 25 cm
Logan 4
x 3 cliff
sharp-based sandstones
LS, 60 cm
Coal, 1 cm
Logan 5
LS 872
Coal, 2 cm
channel body
LS, 6 cm


OWFA
915.5
XXVII |
#14
LS, 38 cm
Coal, 26 cm
top of Joggins Formation (915.5 m)
SS 912
channel body
910
PDFA
x 1 cliff
OR, <1cm
CS (Logan 2), 1 cm
900
clay
silt
v fn
med
v crs
peb
sand


EXPLANATION OF SEDIMENTOLOGICAL LOG
Location in measured section (meters)
10
0
Color
red
red/green mottled (arrows indicate extent of mottled zones)
green, gray, or black
M
Cycle number
#2
#1
Dawson's Divisions
XXI | XXII
WDFA
PDFA
OWFA
Facies association
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

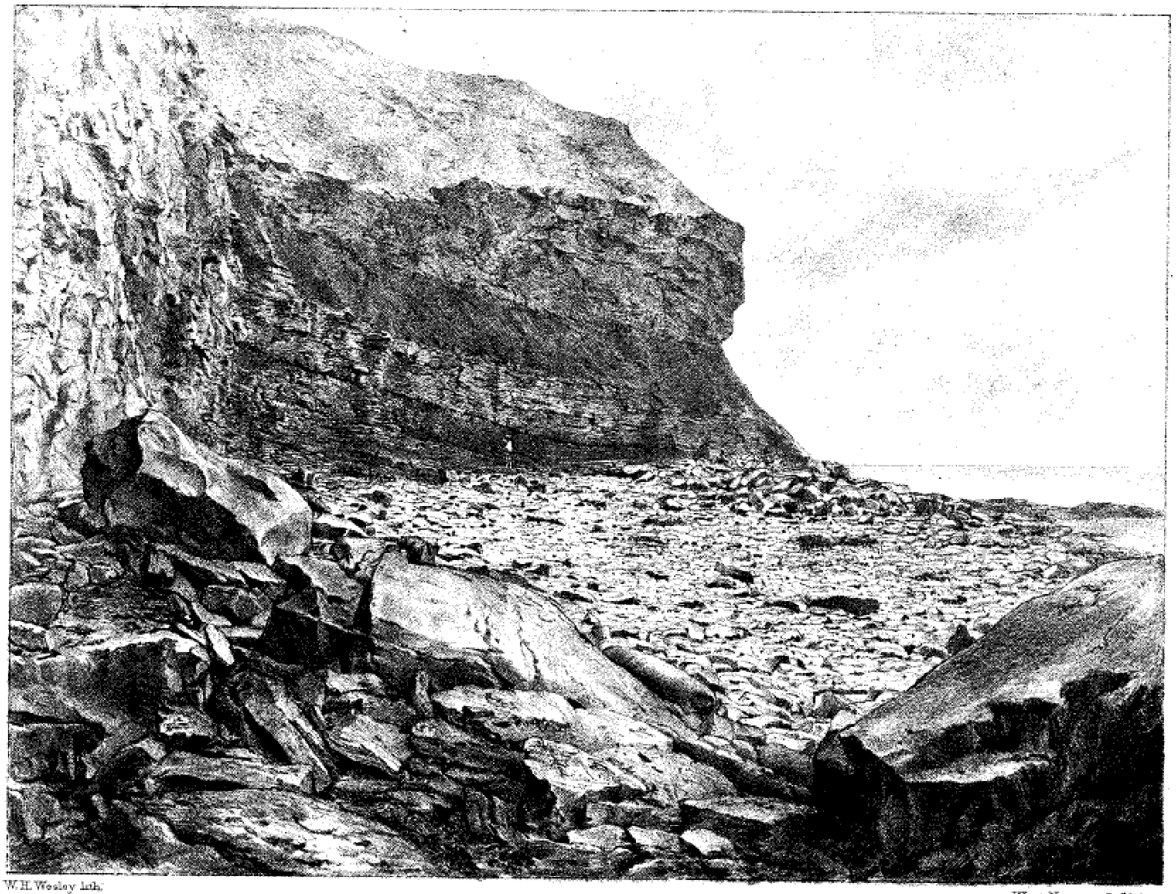
- concretion or nodule (calcareous)
- concretion or nodule (non-calcareous)
- calcareous rip-up clast
- mud-chip rip-up clast
- climbing ripple cross-lamination
- wave ripple
- ripple cross-lamination
- trough cross-bedding
- planar cross-bedding
- horizontal lamination
- groove cast or tool mark
- pedogenic 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



W.H. Wesley lith. West Newman & Co imp.

COAL MINE POINT, S. JOGGINS, 1879.

The head of the human figure is immediately below the Outcrop of the Six-inch Coal, on which the fossiliferous trees stand.

From a Photograph by Weston.

from Dawson (1882).

EPILOGUE

Joggins is a wonderful geological locality, and the many scientists, university and school groups, and enthusiastic members of the public who visit the cliffs each year bear testimony to the enduring fascination of this special site. As Lyell and Dawson 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. We share the opinion of Sir William Dawson, expressed in his letter to his friend and mentor Sir Charles Lyell of 13 August, 1868, that it is far better to study "... plants as they stand in the cliffs at Sydney and the Joggins, instead of on the shelves of the British Museum."

Pre-conference Field Trips

A1 Contamination in the South Mountain Batholith and Port Mouton Pluton, southern Nova Scotia
D. Barrie Clarke and Saskia Erdmann

A2 Salt tectonics and sedimentation in western Cape Breton Island, Nova Scotia
Ian Davison and Chris Jauer

A3 Glaciation and landscapes of the Halifax region, Nova Scotia
Ralph Stea and John Gosse

A4 Structural geology and vein arrays of lode gold deposits, Meguma terrane, Nova Scotia
Rick Horne

A5 Facies heterogeneity in lacustrine basins: the transtensional Moncton Basin (Mississippian) and extensional Fundy Basin (Triassic-Jurassic), New Brunswick and Nova Scotia
David Keighley and David E. Brown

A6 Geological setting of intrusion-related gold mineralization in southwestern New Brunswick
Kathleen Thorne, Malcolm McLeod, Les Fyffe, and David Lentz

A7 The Triassic-Jurassic faunal and floral transition in the Fundy Basin, Nova Scotia
Paul Olsen, Jessica Whiteside, and Tim Fedak

Post-conference Field Trips

B1 Accretion of peri-Gondwanan terranes, northern mainland Nova Scotia and southern New Brunswick
Sandra Barr, Susan Johnson, Brendan Murphy, Georgia Pe-Piper, David Piper, and Chris White

B2 The Joggins Cliffs of Nova Scotia: Lyell & Co's "Coal Age Galapagos"
J.H. Calder, M.R. Gibling, and M.C. Rygel

B3 Geology and volcanology of the Jurassic North Mountain Basalt, southern Nova Scotia
Dan Kontak, Jarda Dostal, and John Greenough

B4 Stratigraphic setting of base-metal deposits in the Bathurst Mining Camp, New Brunswick
Steve McCutcheon, Jim Walker, Pierre Bernard, David Lentz, Warna Downey, and Sean McClenaghan

B5 Geology and environmental geochemistry of lode gold deposits in Nova Scotia
Paul Smith, Michael Parsons, and Terry Goodwin

B6 The macrotidal environment of the Minas Basin, Nova Scotia: sedimentology, morphology, and human impact
Ian Spooner, Andrew MacRae, and Danika van Proosdij

B7 Transpression and transtension along a continental transform fault: Minas Fault Zone, Nova Scotia
John W.F. Waldron, Joseph Clancy White, Elizabeth MacInnes, and Carlos G. Roselli

B8 New Brunswick Appalachian transect: Bedrock and Quaternary geology of the Mount Carleton – Restigouche River area
Reginald A. Wilson, Michael A. Parkhill, and Jeffrey I. Carroll

B9 Gold metallogeny in the Newfoundland Appalachians
Andrew Kerr, Richard J. Wardle, Sean J. O'Brien, David W. Evans, and Gerald C. Squires