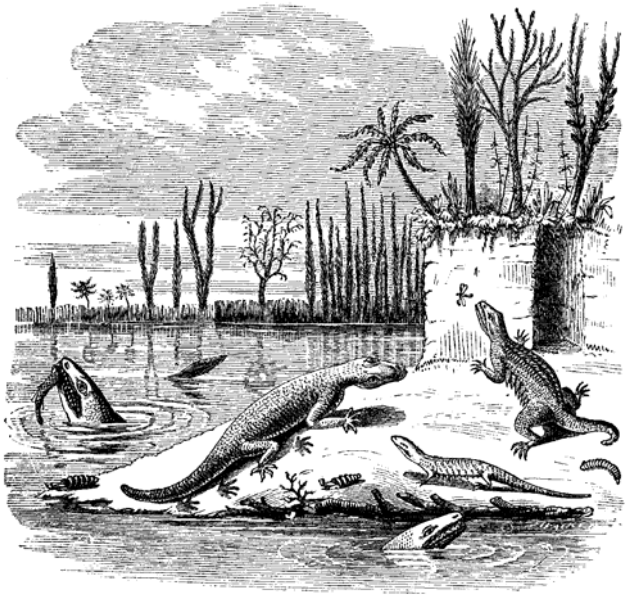
Coals and Organic Deposits of
The Joggins Fossil Cliffs World Heritage Site

Field Trip of the Annual Meeting of The Society for Organic Petrology

Halifax, 3 August, 2011

REPTILES OF THE COAL PERIOD.



RESTORATIONS OF BAPHETES, DENDRERPETON, HYLONOMUS, AND HYLERPETON.

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Safety Precautions

The Joggins Fossil Cliffs are a natural geological showcase, and the tides and cliffs that make them so spectacular also demand respect on behalf of the visitor:

- Stay back from the cliffs, beyond the rock falls apparent at the base. A hard hat is advised, but it will not prevent serious injury or death from a major rock fall.
- Beware of your footing: seaweed, wet rocks, and especially thin muddy veneers and greenish algae are especially slippery. This is particularly important when crossing the reef at Coal Mine Point.
- The tides of the Bay of Fundy are the highest in the world. If you find yourself cut off at a headland, find a spot above the high water mark and stay calm: the tide will go out again in a few hours. Do not risk climbing the cliffs: a fall can be fatal!

Collecting

The Joggins Fossil Cliffs is a UNESCO World Heritage Site, a special place to be shared by all humanity. Collecting of fossils requires a Heritage Research Permit administered by the Nova Scotia Museum. Should you discover an interesting fossil, bring it to the attention of staff at the Joggins Fossil Centre.

Cover images

Top: Panorama of the Joggins Fossil Cliffs from Coal Mine Point: photograph and mosaic by Matt Stimson.

Centre: ‘Reptiles of the Coal Period’ diorama: Sir William Dawson, from *Airbreathers of the Coal Period* (1863), reproduced in *Acadian Geology* (1868 and subsequent editions).

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Location and Access

To reach Joggins by road, leave Highway 104 at Exit 4 (Amherst) and head south on Route 2, turning right on Route 302 at Nappan. At Maccan, turn west (right 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, to the Joggins Fossil Centre.

Introduction

The Joggins coastal section, figured on the cover page, long has been described as the world's best exposed section of Carboniferous coal measures. Coal-bearing strata are exposed from Little River south to MacCarrens Creek, where they form cliffs 25 m high that run for 3 km, bordered by a wave-cut platform about 300 m wide that is completely exposed at low tide. Since the first visit to this coastal section by Sir Charles Lyell in 1842, Joggins has been one of the most celebrated geological sites in the world, found as well in the pages of Darwin's great work, *On the Origin of Species*. The fossil record from whence its claim to fame largely derives, including the oldest known reptiles, we owe largely to the half century labour of love by Nova Scotia-born Sir William Dawson. In recognition of its preeminent place in the history of geology, UNESCO in 2008 inscribed the Joggins Fossil Cliffs on the list of World Heritage as the most outstanding example in the world of the Carboniferous 'Coal Age'. The award-winning Joggins Fossil Centre opened that same year.

Geological setting

The Pennsylvanian Joggins Formation was deposited in the Cumberland Basin of Nova Scotia, a fault-bounded depocentre within the regional Maritimes Basin (Fig. 1).

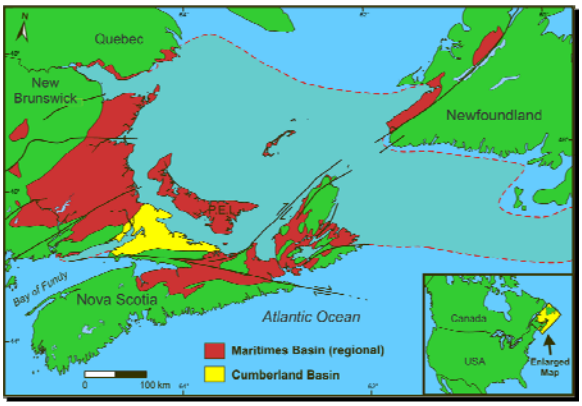

Fig. 1 The position of the Cumberland Basin within the Maritmes Basin of eastern Canada (modified from Gibling *et al*., 1992)

The Maritimes Basin fill is 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 terranes of Avalon and Meguma. This complex terrane history records the closing of the Iapetus Ocean during the mid-Devonian and subsequent amalgamation of Laurasia and Gondwana at the heart of Pangea (Calder, 1998; Calder *et al*., 2005).

Where individual depocentres can be recognized within the Maritmes Basin, they have been termed basins in their own right, and may be bordered by highland massifs, salt-cored anticlines, or major faults. One of these is the Cumberland Basin, containing the Joggins Formation. The Cumberland Basin is a 3600 km^2 depocentre that covers much of northeastern Nova Scotia and

southeastern New Brunswick (Fig. 2). The timing of fault movement in the Cumberland Basin is not clearly known, but the presence of 8 km of Devono-Carboniferous basin fill atop the Avalonian basement attests to significant fault-related subsidence during this time.

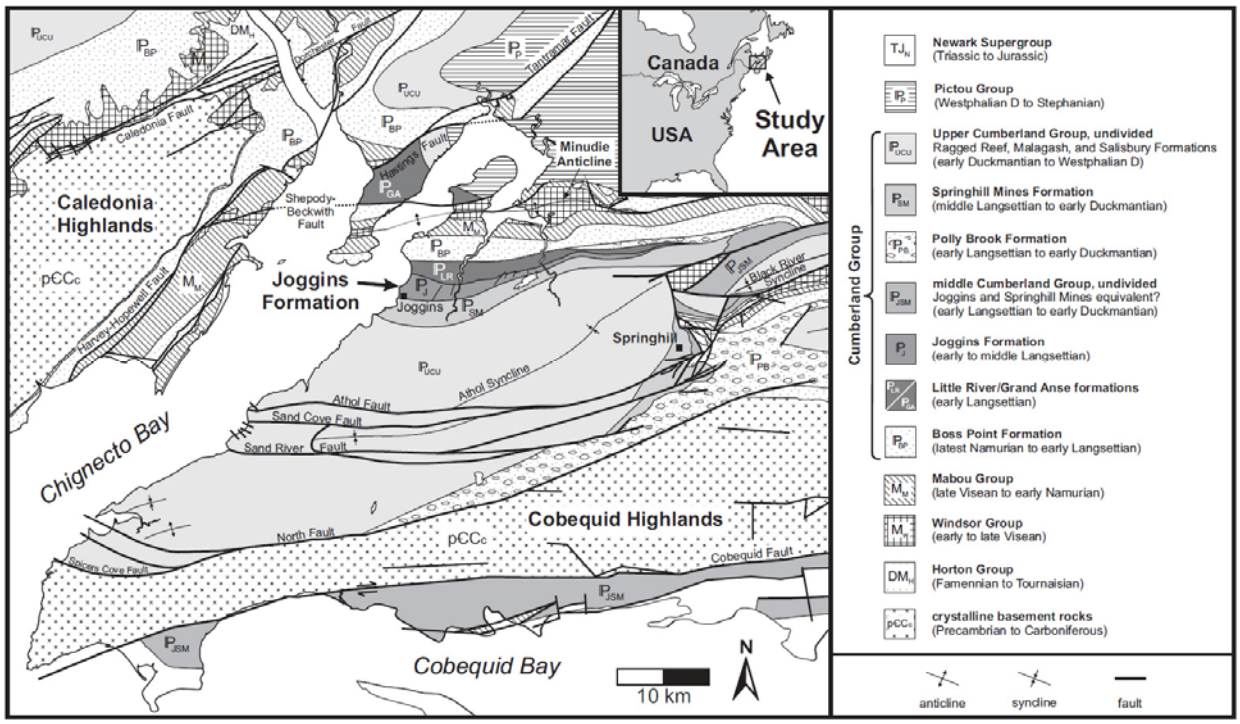

Fig. 2 Geology and stratigraphy of the western Cumberland Basin (after Rygel, 2005).

The role of salt tectonics in the subsidence history of the basin has long been suspected (Hacquebard *et al*., 1967: Calder, 1994), but has only been demonstrated recently with the acquisition of high resolution seismic data. Withdrawal of underlying Mississippian-aged evaporates contributed to subsidence within the Cumberland Basin and accommodation for the deposition of the Joggins Formation in particular (Waldron and Rygel, 2005).

The Joggins Formation crops out along the northern limb of the Athol Syncline, the dominant structural expression of the western Cumberland Basin. This 25 by 75 km syncline lies between the salt-cored Minudie Anticline to the north, the Black River diapir to the east, and the Cobequid Highlands to the south. The syncline is disrupted by the east-west trending Athol-Sand Cove Fault zone on its southern limb. The Athol Syncline is thought to represent a large, salt-withdrawal 'minibasin' similar to those described from the Gulf of Mexico (Waldron and Rygel, 2005).

Stratigraphy of the Joggins Coastal Section, Bay of Chignecto

The Joggins Formation is exposed in its entirety on the eastern shore of the Bay of Chignecto, where it constitutes part of a 4,500 m thick continuous coastal section. The oldest exposed component of the stratal sequence is the Windsor Group

(Mississippian: Viséan), the thickness of which is highly variable due to salt migration into evaporate-cored anticlines. The original thickness of the Windsor Group may have been in the order of 2 to 3 km (Waldron and Rygel, 2005). Seismic stratigraphy suggests that the Windsor sits atop a sequence of older strata, perhaps several kilometres thick, assumed to be Devono-Carboniferous Fountain Lake and / or Horton groups.

The Windsor Group records repeated transgressions and withdrawal of a shallow sea that covered much of the Maritimes Basin during the Viséan.

Above the Windsor Group lie the Shepody and Claremont formations, assigned to the Mississippian Mabou Group (Fig. 3). These formations comprise fluvial deposits that formed in response to basin margin rejuvenation. An arid paleoclimate prevailed across the Maritimes Basin during the Mississippian. A profound lithologic and paleoclimatic change is recorded between the Claremont and overlying Boss Point Formation, which comprises thick, well sorted multi-storey sandstone bodies up to 90 m in thickness. This break records the Mississippian-Pennsylvanian boundary, and here, as across much of the Maritimes Basin and northeastern Appalachians, the boundary is represented by an unconformity.

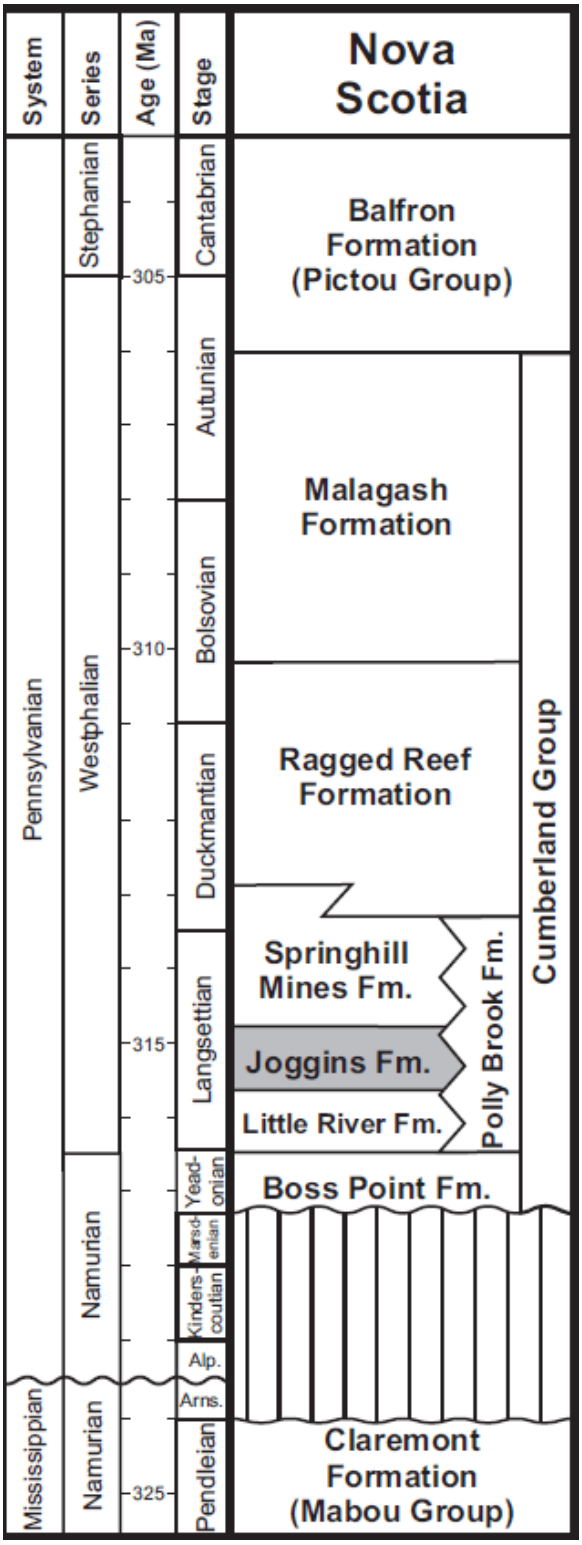

Fig. 3 Stratigraphic position of the Joggins Formation (after Davies *et al*., 2005).

The sandstone-dominated Boss Point Formation is succeeded by red beds of the Little River Formation. Little River strata are mudrock-dominated, and exposed chiefly on the wave-cut platform of Lower Cove. The inherent weakness of these strata may account for the absence here of coastal cliffs, one of the only such places in the coastal section where this occurs. The Little River is considered to be an archetype for ancient seasonal river deposition in the tropics (Fielding *et al*., in press).

The base of the Joggins Formation is marked by the first coal bed (coal 45 of Logan, 1845), and associated grey mudrocks. The occurrence of bivalve-bearing shales and limestones differentiates the Joggins Formation from the overlying coal measures of the Springhill Mines Formation. Inland, coal beds of the Springhill Mines Formation attain thicknesses as great as 4 metres. They represent rheotrophic mires fed in part by groundwater recharge from alluvial fans on the northern flank of the Cobequid highlands, which are coeval with the Joggins and Springhill Mines formations coal measures. Tectonic rejuvenation of the western basin margin and cessation of peat formation is recorded by the braided fluvial deposits of the overlying Ragged Reef Formation.

Joggins Formation

The coastal exposure of the Joggins Formation totals 915.5 m in thickness (Davies et al., 2005). Logan (1845) recorded this interval as 2528’ 7” (771m), an uncharacteristic discrepancy likely resulting from the speed at which he measured the section (Rygel and Shipley, 2006). The age of the Joggins Formation is considered to be Langsettian (Dolby, 1991; R.H. Wagner, personal communication), although the reliance on floral biostratigraphy in the absence of open marine index fossils continues to provide a degree of uncertainty (Calder, 1998; Utting *et al*., 2010).

The formation is divided into 14 cycles (Fig. 4), the bases of which are marked by limestone, fossiliferous shale or coal.

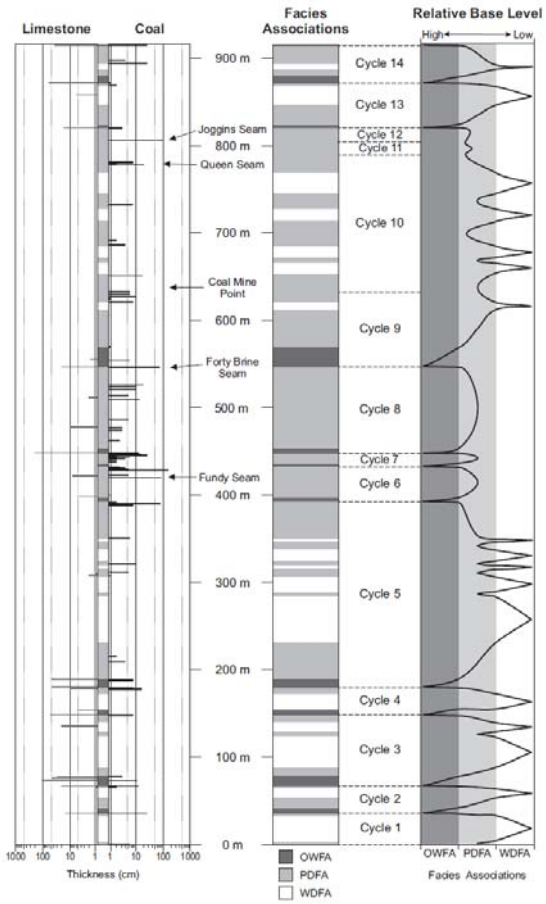

Fig. 4 Distribution of facies associations within the Joggins Formation and interpretation of relative base level (after Davies *et a*l., 2005).

The cycles are divided in turn into stratal intervals that belong to i) open water; ii) poorly drained floodplain; and iii) well drained floodplain facies assemblages (Davies and Gibling 2003). In the cycles, the three assemblages typically succeed each other upwards, although the open water facies assemblage is not represented in some

cycles. 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, fossiliferous shales and by coals.

The formation top was redefined by Davies et al. (2005) 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). This limestone/coal interval is unusually thick, and the limestone is the topmost major calcareous unit in the cliff section. Mapping (Copeland 1959; Ryan *et al.*, 1990) shows that economic coals extend up to 40 km inland, and Falcon-Lang (2003) noted that limestones and overlying platy shales yield abundant remains of upland floral elements, suggesting that major flooding events inundated most of the basin. In contrast, individual channel bodies have yet to be mapped inland, and observations in the coastal section (Davies and Gibling 2003; Rygel and Gibling, 2006) indicate that most channel-sandstone bodies are lensoid and discontinuous. Although thick successions of coarser and finer strata tend to be mappable within the basin, the lensoid nature of and relative similarity between channel bodies in the Joggins and Springhill Mines Formations makes the uppermost limestone a more useful lithostratigraphic horizon.

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. 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 for much of Joggins Formation time, with periods of more sustained open water, wetland or dryland conditions.

Thick limestones and thick coals tend to be mutually exclusive: 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 (cf. 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*. 2006).

Sand accumulated preferentially in the poorly drained floodplain assemblage, where coastal bays formed repositories for coarse detritus (Fig. 5). In these areas, sand deposition was strongly focused into 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 assemblage are relatively thin, and dryland alluvial plains of the well drained assemblage include thick mud intervals, with sands restricted to small channels, levees and splays. The sedimentology of channel sandstone bodies and evolution of fluvial style within the Joggins Formations are described in detail by Rygel and Gibling (2006).

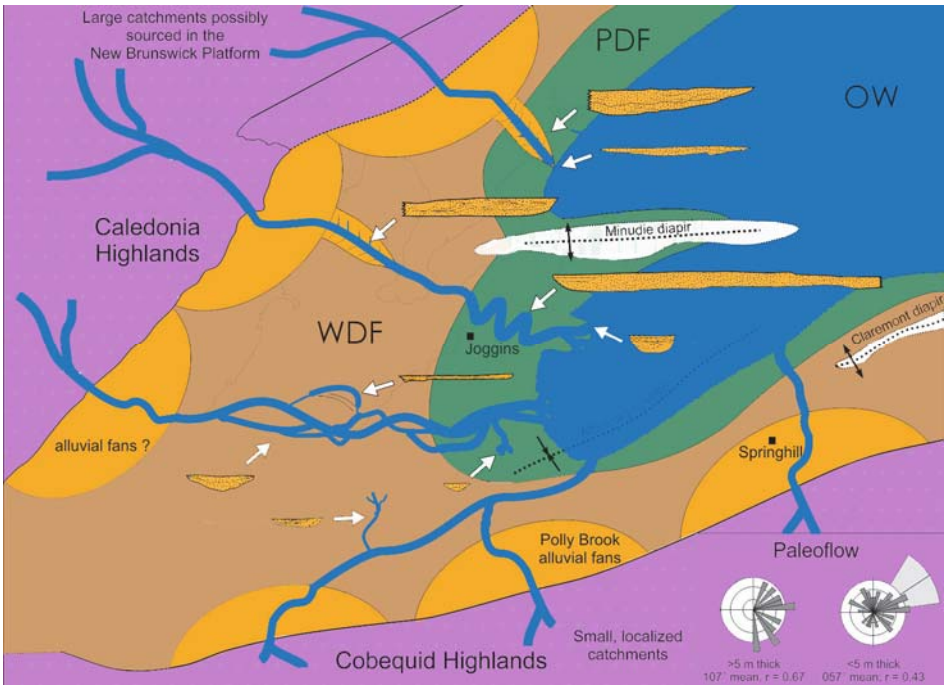

Fig. 5 Interpreted paleogeography of the western Cumberland Basin, showing schematic characterization of sandstone body geometry (after Rygel, 2005).

Coal beds

The Joggins Formation contains a minimum of 45 coal beds (Logan, 1845), ranging in thickness from cm- to metre-scale. The coal beds of the Joggins Formation typically are thin (less than one metre) although they can form seams interstratified with clastic partings that comprise zones exceeding 2 m.

Typically the coals are bright, clarain-rich and pyritic; calcareous permineralization of lycopsid periderm occurs locally within the coal beds. Discrete breaks (plies) in a bed invaribly occur on fusain horizons. Microscopically, the coals are dominated by vitrinite (77-95% in individual ply samples), which is poorly preserved typically (Hower *et al.*, 2000). Coal beds are a defining lithology of the poorly drained facies of Davies and Gibling (2003), although thin coals may occur as well with limestones and bivalve-bearing shales within the open water facies, (see 'Other Hydrocarbon Source Rocks', below).

The Joggins coals are invariably high in sulphur, with yields typically greater than 5% (Copeland, 1959), and as high as 13.7% in individual plies (Hower *et al*., 2000). Pyrite contributes overwhelmingly to the high sulphur yields. Ash yields are also high, typically greater than 30% per ply. Ash geochemistry shows enrichment in the calcophile elements Zn, Pb and As (Hower *et al*., 2000).

Maturation

Within the Joggins Formation, R_o at surface ranges from 0.67 to 0.70 % and may be suppressed to lower values by liquid hydrocarbon expulsion (Mukhopadhyay *et al*., 1991). Within Joggins Formation coals,

liptinite macerals such as sporinite and liptodetrinite are associated with vitrinite (collodetrinite and gelinite), and can be dominant. These coals and coaly shales form kerogen Type II-III condensate-gas prone source rocks having a hydrogen index values of 250 -300 mg HC/g TOC. Maturation varies across the Athol Syncline (Fig. 6), being higher in the vicinity of the Springhill Coalfield to the southeast of Joggins and adjacent the Black River diapir, where salt may have enhanced the geothermal gradient.

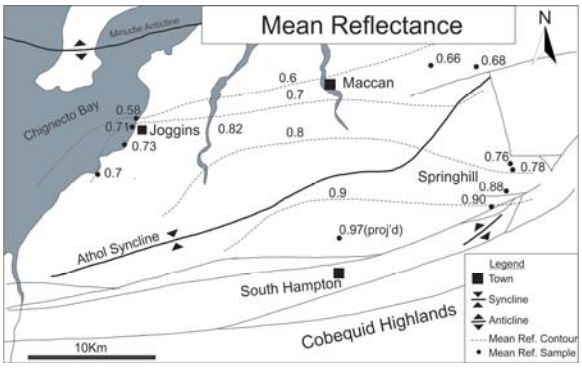

Fig. 6 Mean reflectance of coal beds at surface for the western Cumberland Basin (after Mukhopadhyay, unpublished data).

Floral composition

The coal beds typically are dominated by lycopsid trees including *Lepidodendron*, with the miospore *Lycospora pellucida*, produced by *Lepidophloios*, particularly abundant within the Forty Brine and Queen seams (Dolby, 1998). Conspicuously rare are miospores of *Sigillaria*, which dominates the macrofloral record, and constitutes the most commonly preserved standing fossil tree (Calder *et al*., 2006). Its under-representation in the palynology of coal seams may reflect its weak output of miospores. Alternatively, it may not have been mire-centred, instead showing an ecological preference for ecotonal clastic-rich substrates. Tree ferns comprise a subordinate floral group within the coals (Hower *et al*., 2000).

Origins

The character of the Joggins Formation coals are archtypes of coals derived from rheotrophic (groundwater-influenced, 'planar') mires (Calder 1989; Calder *et al*., 1996), struggling to keep abreast of base level in a rapidly subsiding basin. These characteristics include: a) poorly preserved vitrinite, recording microbial decomposition under elevated pH; b) high mineral content and abundant partings; c) abundant fusain suggesting periodic rainfall deficit, perhaps seasonally, necessitating reliance on ion-rich surface water.

Other Hydrocarbon Source Rocks

The Joggins Formation is differentiated from the overlying coal measures of the Springhill Mines Formation by the co-occurrence with coal beds of limestones and bivalve-bearing organic-rich shales (Ryan *et al*., 1991), colloquially known as 'clam coal'. Limestones are indurated and cemented biomicrite (Gibling and Kalreuth, 1991), whereas 'clam coal' shale beds typically are fissile (in part imparted by abundant bivalves on bedding planes), and clay-rich. These beds are areally extensive, recording basin-wide flooding events, and in large part define the Open Water Facies of Davies and Gibling (2003). They commonly overlie, and in places are interstratified with, coal beds.

Origins

The origin of these bivalve-bearing units remains unresolved. Faunal remains are suggestive of distant marine connections, although the ancient pathway to the sea is equally unclear in the absence of open

marine fauna within the Pennsylvanian strata of the Maritimes Basin (Calder, 1998).

Sedimentologic and paleontologic data from interbedded limestone beds suggest open marine conditions in the oldest part of the Joggins Formation, with a waning marine influence up section (Grey *et al*., 2011). Limestone beds are 15 to 100 cm thick and contain ostracodes, bivalves, and echinoderm fragments. They occur primarily at the base of cycles interbedded with coal and flood plain deposits. The presence of punctate brachiopods, echinoderm fragments, and framboidal pyrite infilling ostracodes in older limestone beds; antithetic abundances between ostracodes and freshwater bivalves; and an overall coarsening upwards provide independent lines of evidence to support a diminishing marine influence in fluvial and coastal deposits with time. These results indicate that Joggins was, at least in the oldest portion of the formation, closer to the open ocean than previously surmised.

Trace fossils

Trace fossil assemblages associated with the open water facies suggest a distal marine connection. Archer *et al*. (1995) described an assemblage of aquatic traces and agglutinated foraminifera preserved in finely laminated sandstone beds that commonly have wave-rippled surfaces. These were interpreted as evidence of a marine connection during the time of deposition of the Joggins Formation.

Abundant trace fossils of limulids including walking and mating traces (*Koupichnium* and *Protichnites*), and resting traces (*Limulocubichnus*) provide evidence of a low energy, coastal environment, likely adjacent to the brackish open waters (Stimson *et al*., 2010). Limulids are typically marine arthropods which have a high tolerance to variations in salinity from haline to fresh water. The evidence of limulids may suggest an endemic fauna stranded after the withdrawl of the Windsor Sea, which evolved to live in brackish to fresh water environments. Alternatively the limulids may have originated from deeper waters beyond the Maritimes Basin, including a possible marine connection far in the northeast (in the direction of fluvial paleoflows) and have migrated to breeding and egg-laying grounds (Fig. 7) along the 'Coal Age' Joggins shoreline.

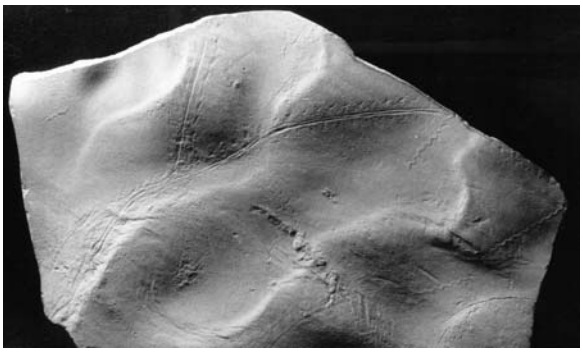

Fig. 7 Superimposed traces of mating limulids ('horseshoe crabs'). Specimen collected by Don Reid, on display at JFC.

Composition and maturation

Analysis of the hydrocarbon-generating potential of these basin-wide organic-rich limestones and shale ('clam coal') beds reveals TOC of 1.41 to 13.10 %. Thermally, these potential source rocks are at an early stage of maturation, with T_{max} values of 414-434° C and R_o from 0.35 % (Gibling and Kalreuth, 1991) to 0.6 %. Hydrogen indices in the range of 316-978 suggest derivation from a mixture of algae, amorphinite 2 and vascular plant sources, with kerogen types I, II and II-III represented. These data are consistent with widespread flooding of lowland plant communities, possibly from a marine source.

Field Stops at Joggins

Stops for this field trip are shown on Figures 8 and 9, and introduced below.

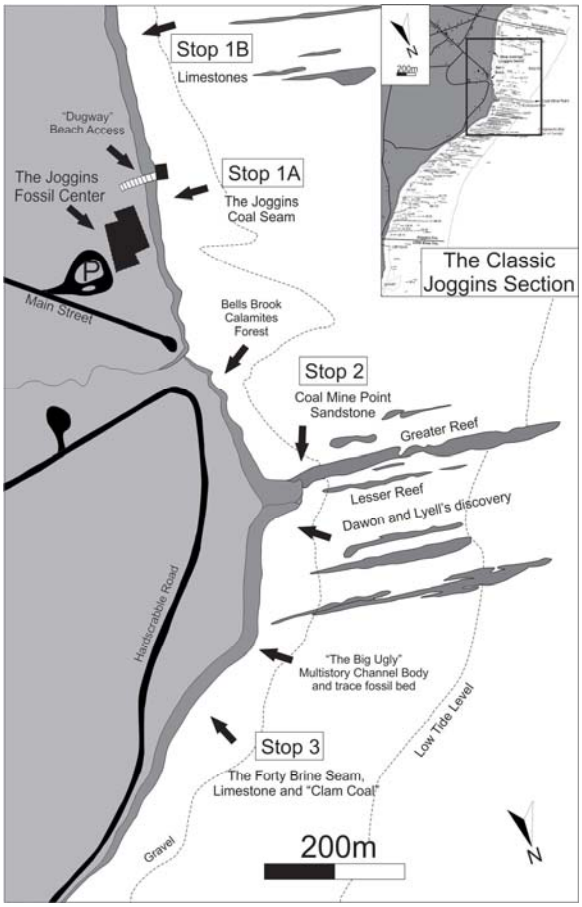

Fig. 8 Map of field stops.

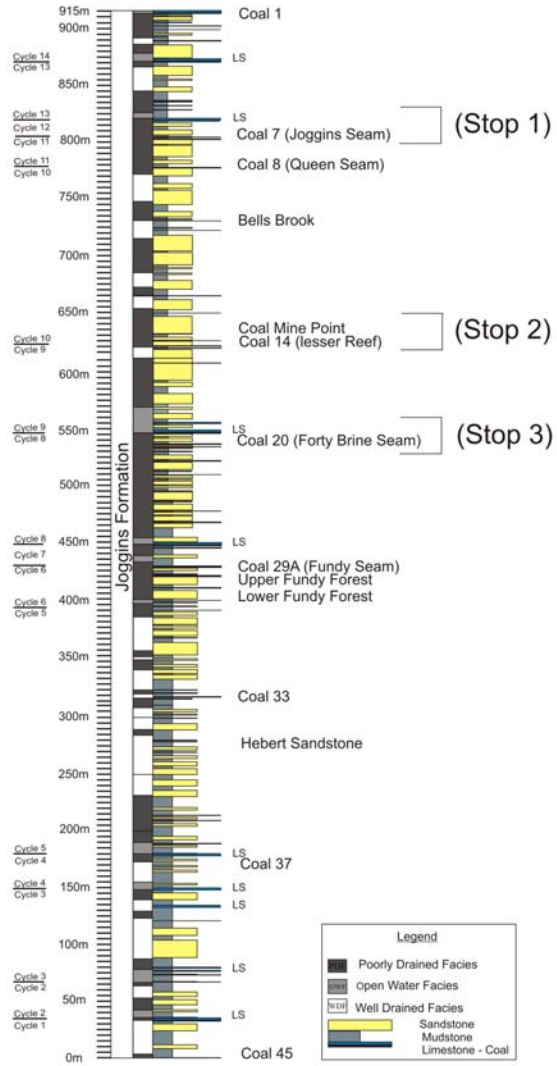

Fig. 9 Stratigraphic log of the Joggins Formation, showing cycles of Davies and Gibling (2003), coals of Logan (1845), and field stops. Modified from Davies *et al*. (2005).

Stop 1A Joggins Seam

At our first stop (north side of stairs from the Joggins Fossil Centre), we will see exposed the Joggins Seam (Figs. 8 and 9: coal 7 of Logan, 1845). The 2 m-thick Joggins Seam was the most important economically in the coalfield. Workings in the Joggins No. 7, which was located at the site of the Joggins Fossil Centre, extended westward beneath the Bay of Fundy. The path that we descend to the stairs was a 'dugway' along which coal cars descended on rails to waiting sailing ships tied up at the coal loading wharf, the pilings of which can be seen on the foreshore beyond the stairs.

Fig. 10 The Joggins seam, with exposed level of the old Joggins No. 7 colliery.

Two levels of the old No. 7 colliery are exposed presently at beach level. At the northernmost level (Fig. 10), the lower portion of the coal bed (bench) is 56 cm thick and clarain-rich. Pit props indicate the height of worked coal to have been 1.10 m. A 36 cm-thick coal roof of alternating coaly shale and impure (shaly) coal was left intact above the mined section.

Stop 1B Limestones

Immediately to the left (south) of the stairs from the Joggins Fossil Centre, blocks of indurated, cemented limestone derived from the cliff lie on the beach for ready examination. Whitish, conical coprolites of aquatic vertebrates are scattered on bedding surfaces.

Stop 2 Coal Mine Point sandstone body

Overlying the fossil forest is the prominent headland and intertidal "reef" of Coal Mine Point (Fig. 11).

Fig. 11 The cliffs as seen from the sandstone 'reef' of Coal Mine Point, the headland at centre-right.

This 10.5 m thick channel body represents a rare example at Joggins of a classic meandering channel. The sandstone body is organized into lateral accretion deposits representing point bar accretion. These deposits are crosscut by 4th 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 seen on the airphotograph in Figure 12.

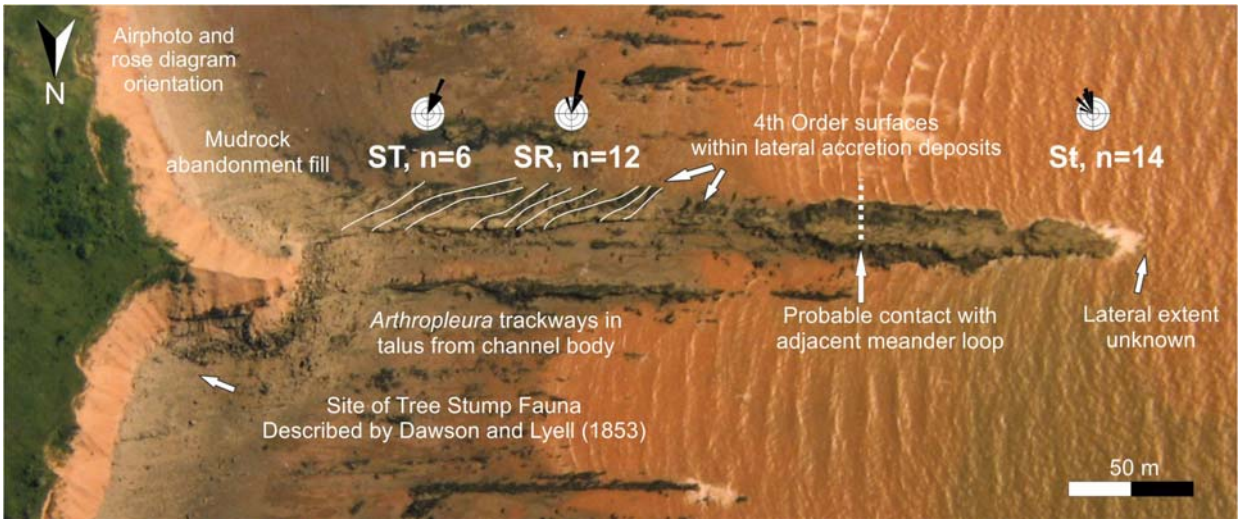

Fig. 12 Interpreted features of the meandering sandstone channel body exposed at low tide in the 'reef' of Coal Mine Point (after Calder *et al*., 2005).

A thinner sandstone body to the north, underlying Coal Mine Point and called the 'Lesser Reef of Coal Mine Point' by Dawson (Fig. 13), is the site of Dawson's explorations – and detonations – in the second half of the Nineteenth Century (Dawson, 1882).

His efforts produced the richest record of terrestrial tetrapod life from the Pennsylvanian Coal Age, including the oldest known reptile and amniote from the fossil record (Carroll, 1963). The fossil forest in which the tetrapods were entombed is rooted in a ply of the split Kimberley Seam (coal 15), which is exposed in the intertidal zone.

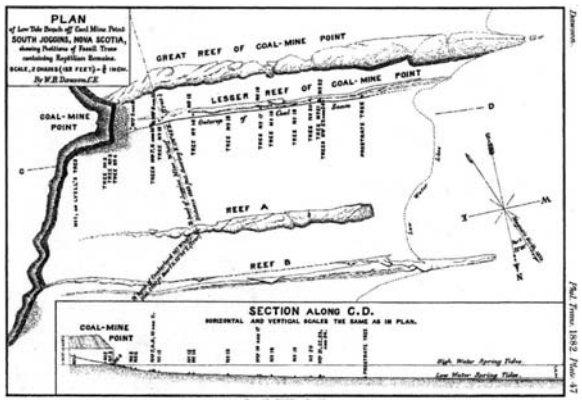

Fig. 13 Sir William Dawson's 1882 map of his explorations for tetrapod-bearing tree fossils at Coal Mine Point.

Stop 3 Forty Brine Seam, limestone & 'clam coal'

At this stop, we will have the chance to observe the three organic-rich lithofacies of coal, limestone and fossiliferous 'clam coal' shale. "Coal 19" of Logan (1845) lies 12.5 m above the Forty Brine, and is better described as an organic-rich fossiliferous shale ('clam coal').

Fig. 14 Organic-rich bivalve-bearing shale and limestone ('clam coal') overlying coal 19.

Packed, disarticulated shells of bivalves including the mussel-like *Naiadites* form wavy, calcareous laminae. Whitish cylindrical bodies - coprolites of fishes and sharks – can be observed scattered across bedding surfaces, where they co-occur with fish scales, bones and teeth, including those of metres-long rhipidistians, the top predators of the primeval Joggins waters.

Although less than a metre thick (0.89 m at this locality), the Forty Brine Seam (Fig. 15: coal 20 of Logan, 1845) was extensively mined, and was preferred by miners in part because of the competent roof provided by the overlying limestone, which persists across the basin.

Maturation levels of the Forty Brine and overlying limestone differ markedly, mean vitrinite reflectance values being 0.57% in the coal and only 0.35-0.47% in the limestone (Gibling and Kalreuth, 1991).

Recent investigations by Calder, Stimson, Brian Hebert and Andrew Scott have resulted in the discovery in strata below the Forty Brine of a succession of tetrapod-bearing fossil trees (Fig. 15), the first to be discovered since the pioneering work of Dawson in the nineteenth century. Here. As in Dawson's trove at Coal Mine Point, there is an ubiquitous presence of fusain (charcoal) associated with the tetrapod skeletons, implicating the role of wildfire.

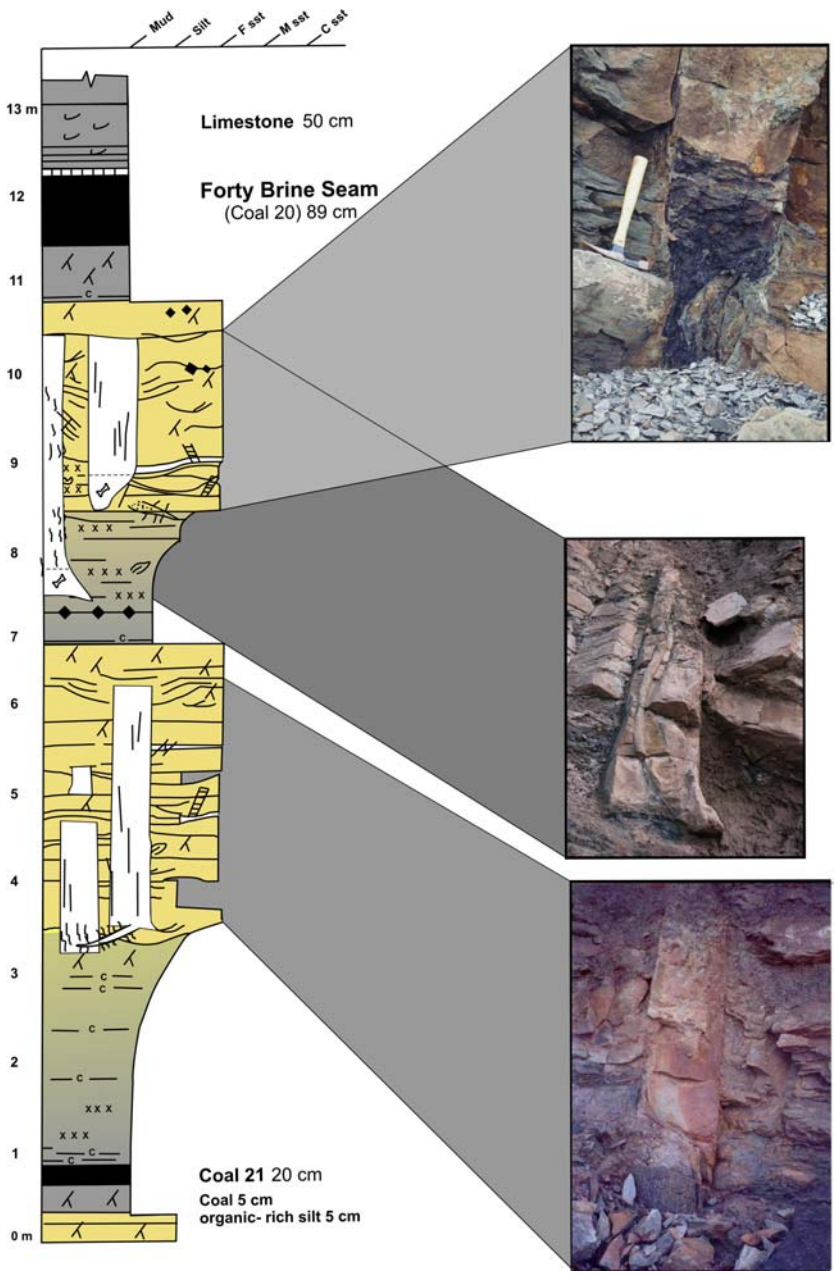

Fig. 15 Sedimentological log of the Forty Brine seam (Coal 20) and recently discovered tetrapod-bearing tree horizons. The charred, fusain-rich base of the uppermost tree (top right inset) is interpreted as a preserved fire scar.

References

Archer, A.W., Calder, J.H., Gibling, M.R. Naylor, R.D., Reid, D.R., 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*, 32, 2027-2039

Calder, J.H. 1993. Evolution of a groundwater-influenced peat-forming ecosystem in a piedmont setting: the No. 3 seam, Springhill coalfield, Cumberland Basin, Nova Scotia; Geological Society of America Special Paper 286, p. 153-180.

Calder, J.H. 1994. The impact of climate change, tectonism and basin hydrology on the formation of Carboniferous tropical intermontane mires: the Springhill Coalfield, Cumberland Basin, Nova Scotia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 106, 323-351.

Calder, J.H. 1998. The Carboniferous evolution of Nova Scotia. *In* D.J. Blundell and A.C. Scott (editors) *Lyell: the Past is the Key to the Present*. Geological Society (London) Special Publication 143, 261-302

Calder, J.H. 2006. 'Coal Age Galapagos': Joggins and the Lions of Nineteenth Century Geology. *Atlantic Geology*, 42, 37-51.

Calder, J.H., Boehner, R.C., Brown, D.E., Gibling, M.R., Mukhopadhyay, P.K., Ryan, R.J. and Skilliter, D.M. 1998. Classic Carboniferous sections of the Minas and Cumberland Basins in Nova Scotia, with special reference to organic deposits. The Society for Organic Petrology Annual Meeting Field Trip, 29-30 July, 1998. Nova Scotia Department of Natural Resources Open File Report ME 1998-5, 86 pp.

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: Sedimentology, paleoecology and floral response to changing edaphic conditions; *International Journal of Coal Geology*, 31, 277-313.

Calder, J.H., Gibling, M.R. and Rygel, M.C. 2005. The Joggins Cliffs of Nova Scotia: Lyell & Co's "Coal Age Galapagos". Field Trip B2, Joint Meeting of the Geological Association of Canada, Mineralogical Association of Canada, Canadian Society of Petroleum Geologists, and Canadian Society of Soil Sciences, Halifax, May 2005. Atlantic Geoscience Society, 44 p.

Calder, J.H., Gibling, M.R., Scott, A.C. and Hebert, B.L. 2006. A fossil lycopsid forest succession in the classic Joggins section of Nova Scotia: paleoecology of a disturbance-prone Pennsylvanian wetland. *In* S.F. Greb and W.A. DiMichele (editors), *Wetlands Through Time*. Geological Society of America Special Paper 399, 169-195.

Carroll, R. 1963. The earliest reptiles. *Journal of the Linnaen Society*, 45, 61-85.

Copeland, M.J. 1959. Coalfields, West Half Cumberland County, Nova Scotia. Geological Survey of Canada, Memoir 298, 89 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*, 50, 415-439.

Davies, S.J., Gibling, M.R., Rygel, M.C., Calder, J.H. and Skilliter, D.M. 2005 The Pennsylvanian Joggins Formation of Nova Scotia: sedimentological log and stratigraphic framework of the historic fossil cliffs. *Atlantic Geology*, 41, 115-142.

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. Dawson Brothers, Montreal, 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. Second edition. MacMillan & Co., London, 694 p

Dawson, J.W. 1882. On the results of recent explorations of erect trees containing animal remains in the coal formation of Nova Scotia. *Philosophical Transactions of the Royal Society of London*, 173, 621-659.

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 91-006, 39 p.

Falcon-Lang, H.J. 2003. Response of Late Carboniferous tropical vegetation to transgressive-regressive rhythms at Joggins, Nova Scotia. *Journal of Geological Society of London*, 160, 643-647.

Fielding, C.R., Allen, J.P., Alexander, J., Gibling, M.R., Rygel, M.C. and Calder, J.H. in press. Fluvial systems and their deposits in the seasonal tropics and subtropics: modern and ancient examples. In S. Davidson, S. Leleu and C. North (editors), *Rivers to Rock Record*.

Gibling, M.R. and Kalreuth, W.D. 1991. Petrology of selected carbonaceous limestones and shales in Late Carboniferous coal basins of Atlantic Canada. International *Journal of Coal Geology*, 17, 239-271.

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*, 29, 338-352.

Grey, M., Pufahl, P.K. and Aziz, A.A. 2011. Using Multiple Environmental Proxies to Determine Degree of Marine Influence and Paleogeographical Position of the Joggins Fossil Cliffs UNESCO World Heritage Site. *Palaios*, 26, 256-263.

Hacquebard, P.A., Birmingham, T.F. and Donaldson, J.R. 1967. Petrography of Canadian coals in relation to environment of deposition. Energy, Mines and Resources, Symposium on Science and Technology of Coal, Ottawa, 84-97.

Hower, J.C., Calder, J.H., Eble, C.F., Scott, A.C., Richardson, J.D. and Blanchard, L.J. 2000. Metalliferous coals of the Westphalian A Joggins Formation, Cumberland Basin, Nova Scotia. *International Journal of Coal Geology*, 42, 185-206.

Kosters, E.C. and Suter, J.R. 1993. Facies relationships and systems tracts in the Late Holocene Mississippi delta plain. *Journal of Sedimentary Petrology*, 63, 727-733.

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, v. 4, Appendix W, 28-45.

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*, 9, 58-63.

Mukhopadhyay, P.K., Hatcher, P.G. and Calder, J.H. 1991. Hydrocarbon generation of coal and coaly shale from fluvio-deltaic and deltaic environments of Nova Scotia and Texas; *Organic Geochemistry*, 17, 765-783.

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, Map 90-12, scale 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*, 39, pp. 289-314.

Rygel, M.C. 2005. Alluvial sedimentlogy and basin analysis of Carboniferous strata near Joggins, Nova Scotia, Atlantic Canada. PhD thesis, Dalhousie University, Halifax.

Rygel. M.C. and Gibling, M.R. 2006. Natural geomorphic variability recorded in a high accommodation setting: fluvial architecture of the Pennsylvanian Joggins Formation of Atlantic Canada. *Journal of Sedimentary Research*, 76, 1230-1251.

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*, 51, 531-552.

Rygel, M.C. and Shipley, B.C. 2005. “Such a section as never was put together before”: Logan, Dawson, Lyell, and Mid-Nineteenth Century measurements of the Pennsylvanian Joggins section of Nova Scotia. *Atlantic Geology*, 41, 87-102.

Stimson, M.R., MacRae, R.A., Calder, J.H., 2010 *Abstract*:Evidence of fossil horseshoe crabs from Joggins, Nova Scotia: Paleoichnology and Paleoenvironmental implications. Abstracts Volume, Atlantic Geocience Society 36th Annual Colloquium and General Meeting Greenwich, Nova Scotia, 46, p. 69.

Utting, J., Giles, P.S. and Dolby, G. 2010. Palynostratigraphy of Mississippian and Pennsylvanian rocks, Joggins area, Nova Scotia and New Brunswick, Canada. *Palynology*, 34, 43-89.

Waldron, J. and Rygel, M.C. 2005. Role of evaporate withdrawal in the preservation of a unique coal-bearing succession: Pennsylvanian Joggins Formation, Nova Scotia. *Geology*, 33, 337-340.