



JOGGINS RESEARCH SYMPOSIUM

September 22, 2018



INTRODUCTION AND ACKNOWLEDGEMENTS

The Joggins Fossil Cliffs is celebrating its tenth year as a UNESCO World Heritage Site! To acknowledge this special anniversary, the Joggins Fossil Institute (JFI), and its Science Advisory Committee, organized this symposium to highlight recent and current research conducted at Joggins and work relevant to the site and the Pennsylvanian in general.

We organized a day with plenty of opportunity for discussion and discovery so we invite you to share, learn and enjoy your time at the Joggins Fossils Cliffs!

The organizing committee appreciates the support of the Atlantic Geoscience Society for this event and in general.

Sincerely,

JFI Science Advisory Committee, Symposium Subcommittee:

*Elisabeth Kisters (Chair), Nikole Bingham-Koslowski,
Suzie Currie, Lynn Daffoe, Melissa Grey, and Jason
Loxton*



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SYMPOSIUM SCHEDULE

8:30 – 9:00 am	Registration
9:00 – 9:10 am	Welcome by Dr. Elisabeth Kusters, JFI Science Advisory Committee Chair
9:10 – 10:30 am	Talks
10:25 – 10:40 am	Coffee Break and Discussion
10:45 – 12:00 pm	Talks and Discussion
12:00 – 1:30 pm	Lunch
1:30 – 4:30 pm	Joggins Formation Field Trip
4:30 – 6:00 pm	Refreshments and Wrap-up



TECHNICAL SESSION SCHEDULE

Chair: Melissa Grey

9:10 – 9:20 am	Peir Pufahl
9:20 – 9:30 am	Nikole Bingham-Koslowski
9:30 – 9:40 am	Michael Ryan
9:40 – 9:50 am	Lynn Dafoe
9:50 – 10:00 am	Matt Stimson
10:00 – 10:15 am	Olivia King
10:15 – 10:25 am	Hillary Maddin

COFFEE BREAK

Chair: Elisabeth Kusters

10:40 – 10:50 am	Martin Gibling
10:50 – 11:00 am	Todd Ventura
11:10 – 11:20 am	Jason Loxton
11:20 – 11:30 am	Nathan Rowbottom
11:30 – 11:40 am	John Calder
11:40 – 12:30	Discussion led by Elisabeth Kusters

LUNCH



ABSTRACTS

Breaking down Late Carboniferous fish coprolites from the Joggins Formation

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The Joggins Fossil Cliffs UNESCO World Heritage Site preserves exemplary Late Carboniferous terrestrial and aquatic environments. The terrestrial environment has been studied in detail; however, little is known about the salinity and trophic structure of the aquatic realm. Late Carboniferous fish coprolites of the Joggins Formation contain undigested material that provide information on the diets of these fish and the species interactions that existed within the aquatic ecosystem. There are six coprolite morphotypes, representing four trophic levels, identified at Joggins. It is here hypothesized that coprolites from different trophic levels will have discrete, identifiable compositional signatures due to dissimilar dietary requirements. This study aims to investigate the elemental and physical composition of each morphotype through scanning electron microscopy-energy dispersive x-ray spectroscopy (SEM-EDS), x-ray diffraction (XRD), and ultrasonic disintegration. Preliminary SEM-EDS analyses indicates variations in elemental composition between cylindrical and equant morphotypes: the equant coprolite is enriched in barium and the cylindrical morphotype is enriched in zinc. These elemental discrepancies may be due to dissimilarities in diets, supporting the classification of these morphotypes into different trophic levels. Additional analyses will investigate the elemental signatures of all morphotypes to see if SEM-EDS is a viable method for trophic classification of coprolites. XRD analyses on the coprolites will complement SEM-EDS, refining elemental composition. Furthermore, representative coprolites will be physically dismantled via ultrasonic agitation in order to isolate components such as teeth, bones, and scales with the intention of better defining diet and potentially relating these components to the elemental differences observed in SEM-EDS.



Joggins 300 million years plus 10: thoughts and reflections

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On the 10th anniversary of the inscription of the classic geological section at Joggins on the list of UNESCO World Heritage Sites, the author would like to share some thoughts for the future in the areas of science, engagement, conservation and legislation. Science: i) taphonomy of tetrapods; ii) ongoing recording of spatial distribution of lycopsid forests as revealed by erosion; iii) reassessment of vertebrate and invertebrate traces; iv) paleoenvironment of beds above Coal 1 of Logan in the Joggins Formation (north of Dennis Point); and v) careful assessment of the marine vs terrestrial realms. Engagement: 'engagement over science': scientific investigation will proceed, but only the Joggins Fossil Institute and Centre are in a position to advance engagement. Conservation: i) reclaim the integrity of rocks on the shore, particularly the introduction of exotic rock types brought in to the World Heritage Site as decorative stone or for armour stone; and ii) pursue funding for construction of a storage facility for curation and study of tetrapod- bearing trees, the single most important aspect of the fossil legacy of Joggins. Legislation: revision of the Special Places Protection Act to empower the staff of the World Heritage Site to engage visitors and school children.



Fish coprolites and new insights into the brackish Carboniferous ecosystem of the Joggins Formation

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The Joggins Fossil Cliffs UNESCO World Heritage Site (Nova Scotia) holds a wealth of fossils, terrestrial and aquatic, from the Late Carboniferous Period. Fossils from the aquatic realm have historically been understudied and the ecosystem they represent is poorly understood. This research broadens our understanding of the aquatic ecosystem, specifically the food web, by examining fish coprolites that are abundant in the limestones of the Joggins Formation. Coprolites preserve undigested material that give us a window into the diets of these fish and interactions between species. The coprolites have been studied in thin section and hand sample, as well as cathodoluminescence and computed tomography to determine the contents. We found that specimens could be divided into six categories based on size and shape: cigar/cylindrical shaped; cone shaped; small/equant; spiral; irregular; and massive (samples greater than 5 cm in length). The small coprolites are the most abundant and the massive coprolites are the rarest. They range in size from <1 cm to >10 cm and are 2-3 centimetres on average. The mineralogy of the coprolites is high calcium phosphate, similar to the composition of bone. This suggests that the fish producing the coprolites were carnivorous and that there is a lack of herbivores present. Bone fragments have been found in almost all samples, however specific species identification has not been possible thus far. This research provides both a foundation for further studies on coprolites and a deeper understanding of aquatic ecosystems as fish diversified further into fresh water in the Palaeozoic.



Terrestrial to marine transitions recorded in invertebrate trace fossils of the Joggins Formation

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The Joggins Fossil Cliffs, a renowned Carboniferous UNESCO World Heritage Site, is found along the shores of Chignecto Bay, Nova Scotia. This spectacular outcrop has a well-established stratigraphy with 14 cycles comprising alternations between open-water, poorly drained floodplain and well-drained floodplain facies assemblages. The ichnology of the formation has been previously studied; however, the majority of the trace fossils identified primarily include surface trails and vertebrate trackways, resulting in a limited record of infaunal activity. Analyses of primarily invertebrate trace fossils from both the Joggins Fossil Cliffs and approximately 700 m of Joggins Formation onshore core (REI B2-1) provide further documentation of the trace fossil record for these Carboniferous rocks. The diverse suite of traces includes: *Acanthichnus*, *Arenicolites*, *Beaconites*, *Chondrites*, *Cochlichnus*, *Diplichnites*, *Diplocraterion*, *Diplopodichnus*, *fugichnia*, *Gordia*, *Haplotichnus*, *Kouphichnium*, *Limulichubichnus*, *Lingulichnus*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Protichnites*, *Rhizocorallium*, *Skolithos*, *Stiaria*, *Teichichnus*, *Thalassinoides*, *Treptichnus*, *Undichnia*, tunnel and chamber structures, plausible wood borings, and rhizoliths. A number of these trace fossils have not been previously recognized from the formation and reflect the work of annelids, arthropods, fish and molluscs. Combining the trace fossil record with the sedimentological framework provides a robust approach in interpreting depositional settings. Within alluvial plain to fluvial channel margin settings, the trace fossil suites include both the *Skolithos* and *Scoyenia* Ichnofacies. In marine-influenced strata including bayhead delta and brackish bay settings, trace fossil suites reflect proximal to archetypal *Cruziana* Ichnofacies and include some strictly marine trace fossils such as *Chondrites* and *Phycosiphon*.



When did plants influence river landscapes much as they do today? Evidence from Early Pennsylvanian strata of the Joggins Fossil Cliffs

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Vegetation profoundly influences modern river systems, but direct evidence for these dynamic relationships is usually difficult to find in ancient deposits. The Joggins cliffs (~310 million years old) display interactions between a range of river systems and upright and transported vegetation in wetland and dryland settings. Observations in the Joggins Formation show that upright vegetation with deep roots stabilized rivers banks and bars. Groves of lycopsids and calamitaleans colonized the channels during periods of reduced flow and trapped sediment after the flow resumed, forming river bars. Upright trees along the banks of meandering channels are locally tilted towards the channel, implying that they stabilized the banks. Narrow, fixed channels of anastomosing rivers are prominent in the formation but rare in older strata. In braided-river deposits of the Boss Point Formation, cordaitalean logs are present in nearly 20% of channel deposits, lining channel bases, filling deep channels, and serving as nuclei for shallow sandbars. Within some channels, thick log accumulations are interpreted as log jams that caused blockage and the formation of new channels. Rooted sandstones with upright trees are interpreted as vegetated islands in the braided rivers – the oldest yet described. Better than anywhere else on Earth, the Joggins cliffs show that fluvial landscapes crossed a threshold into a fully ecological mode in the Early Pennsylvanian, with feedback loops between vegetation and fluvial processes. Thereafter, patterns of interaction between rivers and vegetation broadly resembled those of today, with profound consequences for aquatic, soil and other terrestrial ecosystems.



***Kouphichnium aspodon*, a new occurrence of invertebrate traces from the Joggins Fossil Cliffs
UNESCO World Heritage Site, Nova Scotia, Canada**

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The vertebrate ichnofossil record at Joggins is a template for Paleozoic vertebrate ichnotaxonomy dating back to the early 1900s. However, despite some of the earliest descriptions of invertebrate ichnofossils (*Diplichnites*) being noted by Dawson at Joggins (1863, 1872), invertebrate ichnofossils have yet to be systematically studied at Joggins. Although the ichnogenus *Kouphichnium* is known from the Joggins Fossil Cliffs, the ichnospecies *Kouphichnium aspodon* has only been recorded previous to this study from the Mississippian-aged Mauch Chunk Formation (Pennsylvania), and from the ichnospecies type section in the Pottsville Formation (Alabama). A third occurrence of this species has now been discovered at the Joggins Fossil Cliffs from the Springhill Mines Formation at Denis Point. The specimen described here was discovered by the late citizen scientist Donald Reid. The invertebrate trackway is associated with other invertebrate ichnofossils including different ichnospecies of *Kouphichnium*. *Kouphichnium* has been ascribed to xiphosuran locomotion. A single specimen of *Kouphichnium aspodon* is here interpreted to be produced by either a eurypterid or synxiposurian from the lower most Springhill Mines Formation. Like limulids, eurypterids are known to travel inland from the oceans to quiescent brackish conditions to moult and mate. Although body fossils of eurypterids are rare at Joggins, they have been described from cuticle fragments that were found inside lycopsid trees by J.W. Dawson in the 19th century, associated with tetrapod bones, millipedes and land snails. This discovery may have paleoenvironmental implications as the strata exposed at Dennis Point may have been at least distally connected to marine waters.



The Joggins Fossil Cliffs
inscribed on the World
Heritage List in 2008

Leveraging Nova Scotia's Carboniferous to communicate earth science concepts: following Ireland's lead

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Ireland and Nova Scotia share similar Paleozoic geological histories, with Carboniferous bedrock exposures especially widespread. Carboniferous sites in both regions are recognized with UNESCO status (the Burren and Joggins Fossil Cliffs) and Carboniferous strata are intimately connected with each region's industrial and cultural histories (coal, kiln lime, building materials, gypsum desalination). In Ireland, however, educational, conservation, and tourism infrastructure is more fully developed than in Nova Scotia, including two Geoparks and county-level geoheritage surveys. In addition, materials describing and celebrating Irish geology and its connection to human history are readily available in print and online, including overviews aimed specifically at teachers and tourists (e.g., *Understanding Earth Processes, Rocks and the Geological History of Ireland*—also known as “the School’s Book”). These materials describe the specifics of Carboniferous geology/paleontology, but perhaps more importantly leverage the period to communicate more general earth science concepts, e.g., the relationship between climate change and sea level, ground water pollution in karstic environments, the carbon cycle, and the geography of deltaic and carbonate platform environments. As a geological and cultural “sister”, Ireland provides an example of how Nova Scotia can develop its geotourism and earth science communication potential, especially the potential of its Carboniferous geology.



Recent tetrapod discoveries and the changing view of the Carboniferous

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Over five years ago, a long-term field program focused on the fossil tetrapods of the Carboniferous of Nova Scotia was launched. It is widely known that Nova Scotia's fossil tetrapods are of global significance due to the earliest records of several key taxa represented by *Hylonomus*, *Archaeothyris* and *Paleothyris*. Our efforts have contributed new aspects of significance to Nova Scotia's Carboniferous tetrapods, including possible new growth series and CT data for *Dendrysekos* (= *Dendrerpeton*) with taxonomic reevaluation, new embolomere diversity data for Point Edward, and new earliest occurrence data for several otherwise currently-known Permian taxa. The recent discovery of a fossiliferous stump from the Sydney Mines Formation, Cape Breton Island, remarkably contains the remains of at least six taxa. Most notable among these is a virtually complete skull of a large pantylid recumbirostran. CT scanning reveals a highly specialized dental apparatus composed of opposing dental fields on the palate and coronoids, well advanced to that of any known tetrapod of equivalent age. As well, three partial, articulated skeletons of a varanopid synapsid, including an associated very small fourth, alludes to the possibility of a social aggregation – a behavior otherwise known from this clade in the Late Permian. A fragment of a large proximal femur is also attributable to a varanopid, and approaches the size and morphology of later occurring varanodontines, such as the Permian-aged *Varanops*. Together these new data revise many of our current understandings of the composition and evolution of some of the earliest terrestrial tetrapod communities and their constituents.



Fossil Finder: a case study of the use and development of machine learning models to identify fossils *in situ*

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Machine learning has developed rapidly over the last few years, both in complexity, versatility and ease of use. A myriad of different cloud platforms and application programming interfaces exist in the common marketplace that could be of use to both scientists and citizen scientists alike. However, the machine learning development has been so rapid, that it is somewhat intimidating for anyone that is not a data scientist or at least an experienced programmer. I am conducting an initial inquiry for the development of machine learning models for scientists in the context of making a smart device app to identify fossils that can be found *in situ* at the Joggins Fossil Cliffs, a noteworthy representation of Pennsylvanian Carboniferous flora and fauna. The *raison d'être* of the app will be for citizen scientists (tourists) to use the app to identify fossils and, over the long term, develop a heat map for locating various types of fossils. Various trade-offs between several machine learning platforms is compared and contrasted in the context of the app. A specific platform was chosen for a proof of concept prototype of using machine learning for fossil identification and its effectiveness was analyzed over several iterations.



An Upper Mississippian rhizodontid (Sarcopterygii, Tetrapodomorpha) from the Bluefield Formation of West Virginia, USA

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Sarcopterygian rhizodontids are poorly understood due to the incomplete nature of most available specimens. Although postcranial remains are known from *Strepsodus*, *Gooloogongia*, and *Sauripteris*, many specimens only consist of incomplete mandibles making taxonomic assignment difficult. A rhizodontid left dentary (CMNH 10940) from the Upper Mississippian Bluefield Formation of West Virginia preserves a single symphyseal tusk, 12 marginal teeth, and a row of dentary teeth in pairs with each marginal tooth. There is no evidence of marginal teeth anterior to the tusk and the ventral margin has been broken away. The dentary appears to lack any evidence of a lateral or vertical pit line on the labial surface. A restricted rhizodontid phylogenetic analyses was conducted using either *Glyptolepis* or *Kenichthys* as the outgroup on a data set empathizing mandibular characters. Each analysis resulted in two best trees, the strict consensus of which both recovered the rhizodontid taxa as a polytomous monophyletic clade with the same ingroup topology. Although the placement of CMNH 10940 could not be resolved, the clade of UK rhizodontids (*(Strepsodus+(Rhizodus+Screbinodus))*), was resolved and is congruent with previous analyses. Both analyses supported the validity of the CMNH 10940 as representing a distinct taxon based on one unambiguous character, the presence of long, smoothly curving longitudinal striations on the marginal teeth that are separated by broad bands of enamel, and teeth that are polished labially.



The *Diplichnites aenigma* enigma: ichnotaxonomic implications of a restudy of Dawson's type locality at Coal Mine Point, Joggins, Nova Scotia.

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In 1862, Sir William Dawson, while exploring the Coal Mine Point strata at Joggins, discovered the site's first example of arthropod footprints that would later be attributed to the largest terrestrial invertebrate in the fossil record, *Arthropleura*. Dawson later named the trace fossil *Diplichnites aenigma*, the first species of the new and now widely-used genus *Diplichnites*. Unfortunately, no type specimen was selected, presumably due the huge size of the sandstone blocks that erode from Coal Mine Point. The lack of a collected type specimen for Dawson's trackway, the simplicity of its published woodcut illustration, and a limited description has caused confusion for ichnotaxonomists over the past 150 years. For example, a new ichnospecies (*D. cuithensis*) from Arran, Scotland was erected in 1979, abandoning Dawson's species because of the uncertainties. More recent explorations by multiple researchers have added new specimens of *Diplichnites aenigma* for study. Key specimens recovered by the late Dr. Laing Ferguson, the late Don Reid, Bob Grantham, and by the authors have allowed for an ichnotaxonomic reevaluation of the ichnogenus and its type species from the type locality. New observations shed light on the morphological variability of *Diplichnites* and has refined the type concept, accounting for underprint fallout, gait variability, substrate variability and microbial mat sediment stabilization. This work lays the foundation for a long-overdue reevaluation of the genus concept and all species of *Diplichnites*.



Marine Influence and other controls on organic matter preservation in Langsettian, Carboniferous lacustrine source rocks of the Joggins Formation, Nova Scotia, Canada

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The Joggins Fossil Cliffs of Nova Scotia, represents one of the most continuous exposures of a Carboniferous coal basin in the world. Much of this section is marked by the Joggins Formation, which extends for 2.8 km along the coastal section of the Cumberland Subbasin. Subsidence from salt-withdrawal deeper in the basin resulted in rapid accommodation to produce 14 well-characterized parasequences. Many of these repeated transgression events, which are composed of fluvial/deltaic mudrocks overlain with bioturbated paleosols and bituminous coal measures, began with the deposition of carbonaceous-rich, freshwater limestone units marking the maximum flooding surface of the shallowing upward interval. Although the Joggins Formation was deposited ~2,500 km inland from the Tethys paleo-shoreline, the basal section contains evidence of marine incursions. This study investigates whether geochemical data can 1) help resolve the temporal extent of these events and 2) determine what effects marine conditions had on the type and preservation of the organic matter in these prospective source rocks. Specific emphasis is focused on resolving whether sulfurization of organic matter was involved in kerogen formation. Forty samples spanning seven well-characterized parasequences extending from the base to the top of the formation are analyzed for transition metal and elemental sulfur concentrations using portable X-Ray Fluorescence. These data are compared with bulk pyrolysis measurements to evaluate factors controlling the richness, quality, and maturity of the host rock's organic matter. Additional geochemical constraints are provided via biomarker-based paleoecological reconstruction using comprehensive two-dimensional gas chromatography. This presentation highlights our recent progress and tentative conclusions.



FIELD TRIP: JOGGINS FORMATION

Many of you know the cliffs like the back of your hand but for those that are newer to the site, this guide is for you! Please also refer to Davies et al (2005), sent as a separate file, for detailed information on the stratigraphic column.

This will be an unusual field trip in that all presenters will take part in leading the group through the Formation and there are no pre-determined field stops. The cliffs are constantly changing and we will take time to discover any newly exposed spots, as well as visiting classic sites along the way. Who knows, we may find another *Hylonomus* (fingers crossed)!

SAFETY

The Joggins section is a safe place to visit but there are some hazards at this location. As part of the Bay of Fundy, Joggins experiences the world's highest tides; parts of the section can be completely covered at high tide and exit routes from the beach can be flooded up to 3 hours before/after high tide. Trips to the beach are therefore planned around low tide. The beach at Joggins is rocky and becomes very muddy in the lower intertidal zone. Rocks can be very slippery (especially those covered with algae) and the mud is soft and deep. Sturdy footwear is required. Fall can be cold and damp; warm clothes and rain gear are recommended. We suggest staying a reasonable distance away from the cliffs and hard hats are recommended because the cliffs are unstable and rock falls happen frequently. Linger underneath overhangs is not recommended.

FOSSIL COLLECTING

All fossils in Nova Scotia belong to the Province of Nova Scotia. The Joggins beach and cliffs are protected by three pieces of provincial legislation (Special Places Protection Act, Beaches Act, and Mineral Resources Act) which preclude the collection of *any* natural material. Fossil collecting is legal only with a Heritage Research Permit that can be applied for through the Nova Scotia Department of Communities, Culture and Heritage.

INTRODUCTION

The Joggins Fossil Cliffs (Nova Scotia, Canada; Figure 1) was granted UNESCO World Heritage status in 2008 as a result of its unparalleled fossil record of terrestrial life, preserved *in situ*, from the Pennsylvanian (Late Carboniferous). This record extends also to the aquatic realm, with many species of amphibians, fish, bivalves, crustaceans, agglutinated foraminifera, and ostracods preserved there. The year 2009 marked the 150th anniversary of arguably the most famous discovery from the cliffs, namely the oldest known reptile in the world, *Hylonomus lyelli* (Figure 2A and B). A Nova Scotian geologist, Sir William Dawson, made the discovery in 1859 and named it after his mentor, Sir Charles Lyell, who also studied the cliffs. Research and discovery at the site has been very active since that time and, with World



Heritage inscription, Joggins now has an even greater presence on the global stage (see Calder 2006; Grey et al 2011; Falcon-Lang 2006; Rygel and Shipley 2005 for reviews).



Figure 1. Location (in light green) of the 14.7 km Joggins Fossil Cliffs World Heritage Site along the Cumberland Basin, Nova Scotia, Canada (altered from Boon and Calder 2007).



Figure 2A. *Hylonomus lyelli* (Dawson) type specimen housed at the Natural History Museum, London. Figure 2B. Artist's reconstruction of *Hylonomus lyelli* (images: JFI).

THE JOGGINS FOSSIL INSTITUTE AND CENTRE

The Joggins Fossil Institute is a non-profit, charitable organization that is responsible for co-managing the Joggins Fossil Cliffs World Heritage Site with the Province of Nova Scotia. The Institute is also a research and education centre, hosting international researchers, visitors, and educational groups. The Centre (Figure 3) is built on what was Joggins' largest coal mine. As a brownfield site, the Institute has taken an active role in remediation of the grounds, including: phytoremediation (planting of trees to mitigate contaminants) and introducing natural landscaping policies (e.g., re-introducing native plant species and not mowing the entire



property). The Institute has won national and international awards for its environmental initiatives (including use of alternative energy, natural landscaping, a green roof for insulation and non-potable water collection, low flush toilets, green purchasing policies, and more) and has obtained LEED (Leadership in Energy & Environmental Design) Gold certification.



Figure 3. The Joggins Fossil Centre from above (image: JFI).

GEOLOGICAL SETTING AND AGE

The World Heritage Site

The Joggins Fossil Cliffs World Heritage Site comprises a 14.7 km coastal section which includes formations within the Mississippian (Early Carboniferous) Mabou Group: Shepody and Claremont Formations, and the Pennsylvanian (Late Carboniferous) Cumberland Group: Boss Point; Little River; Joggins; Springhill Mines; and Ragged Reef Formations (Figure 4). Only sedimentary rocks are found within the section making radiometric dating impossible, but this time period most likely comprises nearly fifteen million years (Gradstein *et al.* 2004). The site represents the thickest sedimentary succession of a Carboniferous coal basin in the world, measuring over 4,400 m (Boon and Calder 2007).



The Joggins Fossil Cliffs
inscribed on the World
Heritage List in 2008

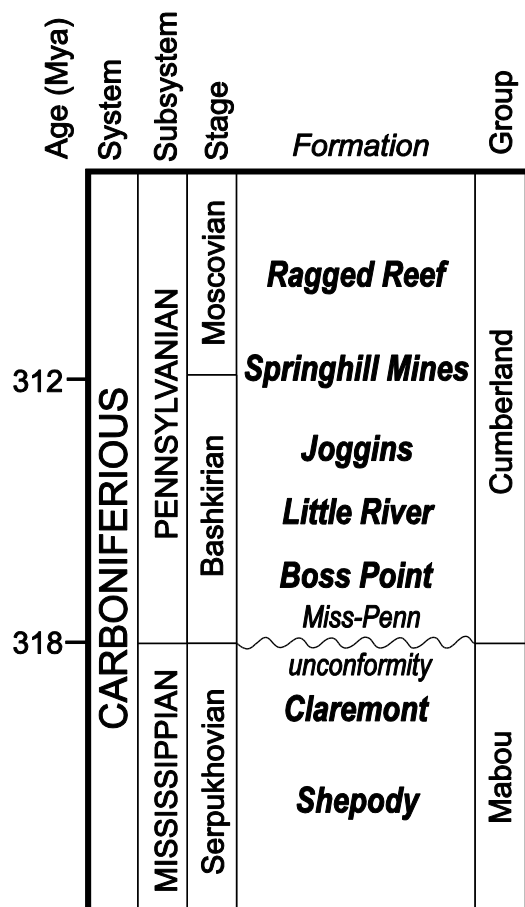


Figure 4 (left). The stratigraphic column and corresponding ages (according to the IUGS timescale) represented at the World Heritage Site (image: JFI).

During the Mississippian (about 340 mya), the Windsor Sea spread over the majority of the Maritimes Basin; Windsor Group rocks are comprised of alternating deposits of carbonates, evaporates, and red beds. As the Windsor Sea withdrew (probably to the northeast) with the coming of the Late Carboniferous, the rapid subsidence observed in the Cumberland Basin was caused by withdrawal of basal Mississippian evaporates (Waldron and Rygel 2005). This rapid subsidence allowed for excellent preservation of fauna and flora, including the upright lycopsid trees, at the site and explains the tilted nature of the cliffs. The cliffs at Joggins are part of the Athol syncline and the dip slowly decreases to the South; to the North, the dip steepens toward the Minudie anticline.

Palynological analyses place the Cumberland in the middle to late Bashkirian stage of the Pennsylvanian but this is tentative because Cumberland assemblages lack diversity and many diagnostic taxa (Utting *et al.* 2010). The probable duration of this unit is nearly 1 my (c. 313.4-314.5 Ma), therefore the Joggins Formation almost certainly comprises <1Ma (Falcon-Lang *et al.* 2006).

Davies and Gibling (2003) detailed the sedimentology and sequence stratigraphy of the Joggins Formation, outlining observed cyclicity and identifying three primary facies associations, an open-water unit (OW) and two terrestrial units: a poorly drained coastal-plain unit (PD) and a well-drained alluvial plain unit (WD) (Davies and Gibling 2003; Figure 5). These facies associations are representative of three distinct paleoenvironments represented at Joggins: coastal plains and seas; terrestrial wetlands; and terrestrial drylands (Falcon-Lang *et al.* 2006). Each cycle, of which 14 were recognized, tends to begin with a retrogradational poorly drained coastal plain association and is typically overlain by an open-water association (Davies *et al.* 2005). This marks basin-wide flooding, which is then followed by progradational poorly drained coastal plain and well-drained alluvial plain associations (Davies *et al.* 2005; Figure 5). Limestone beds defining the cyclothems boundaries are considered part of the OW facies assemblage (Davies *et al.* 2005).

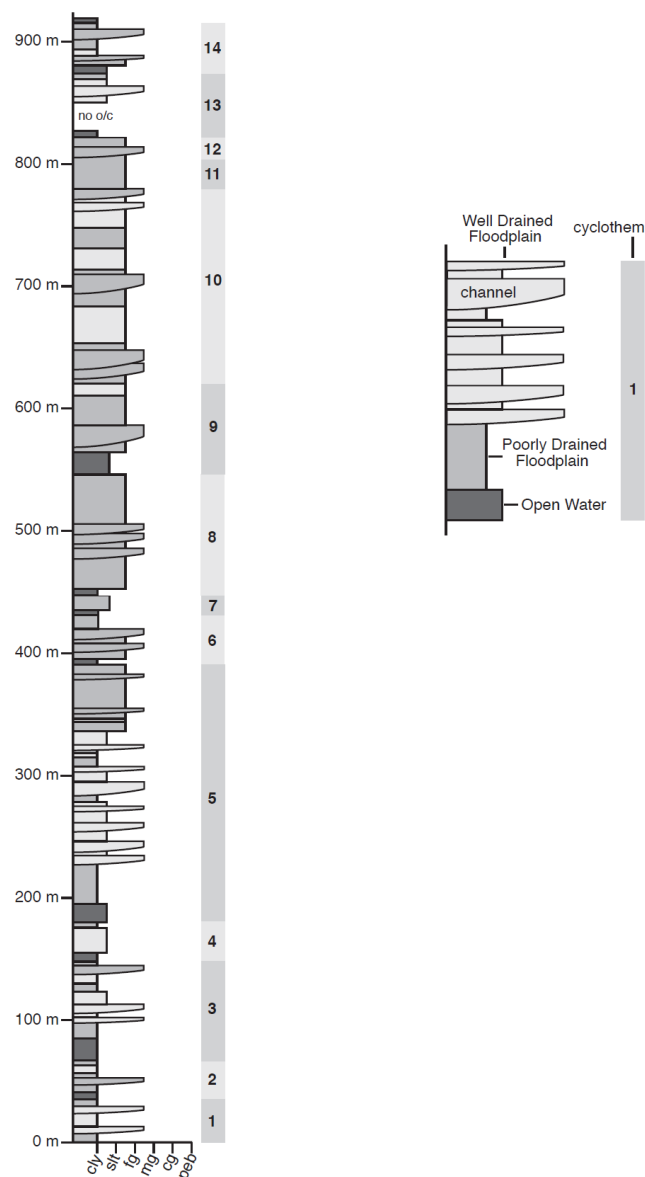


Figure 5 (left). Simplified stratigraphic column for the Joggins Formation, outlining the cyclothems by number (Davies *et al.* 2005).

ENVIRONMENTAL CONDITIONS

Sedimentological studies illustrate changing climatic conditions within the 14.7 km World Heritage Site. Evaporite rocks mark the arid conditions that were widespread during the Mississippian in the Cumberland Basin (Waldron and Rygel 2005), but the Pennsylvanian marked a significant climatic change. Humid conditions that were common in the Pennsylvanian can be witnessed in the Boss Point Formation (the basal-most formation of the Pennsylvanian) in part by the thick sandstone deposits from large river systems that demonstrated alternating cycles of braidplain and shallow lacustrine environments (Browne and Plint 1994). Seasonal drylands were prevalent during the time of the Little River Formation and the rocks within the formation lack the

coal and limestone beds that are extensive within the wetlands of the younger Joggins Formation (Calder *et al.* 2005). As basin floors subsided, environmental conditions within the Joggins Formation became progressively wetter, allowing widespread growth of lycopsid (relatives of club mosses) trees and seed ferns that, over time, became the raw material for coal formation (see Figure 6 for environmental interpretation of the Joggins Formation).

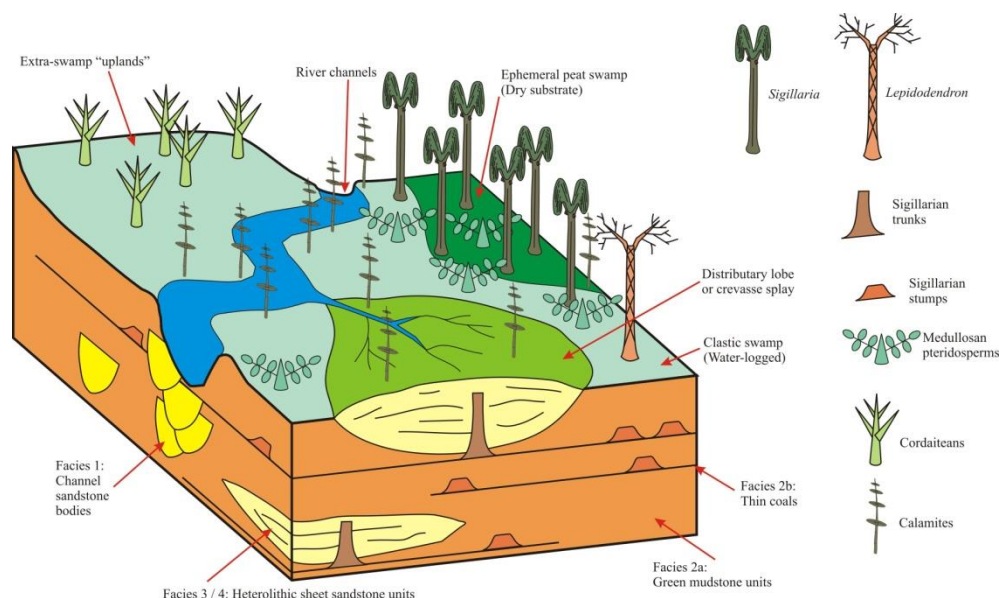


Figure 6. Environmental reconstruction for part of the Joggins Formation (modified after Falcon-Lang 1999).

THE FOSSIL RECORD

The fossil record at Joggins contains over 200 species (Joggins Fossil Institute, unpublished data) of trace and body fossils of vertebrates and invertebrates from both the aquatic and terrestrial realms (Boon and Calder 2007; Figure 7). These fossils represent elements of the entire food web, from primary producers to the hypothesized top predator on land, an amphibian known fondly as “Rex” (probably within the genus *Pseudobradypus*; Figure 7). Some of the most interesting findings include: the world’s oldest reptile (*Hylonomus lyelli*; Figure 2); the world’s oldest land snail (*Dendropupa vetusta*; Figure 7); and the tracks of the largest-known land invertebrate (*Arthropleura*). The famous “fossil forests”, including upright lycopsids, can be also found throughout much of the Joggins Formation. These trees are of particular interest because they are preserved *in situ* and sometimes contain the remains of other organisms, including millipedes and land snails, known as the tree-hollow fauna.

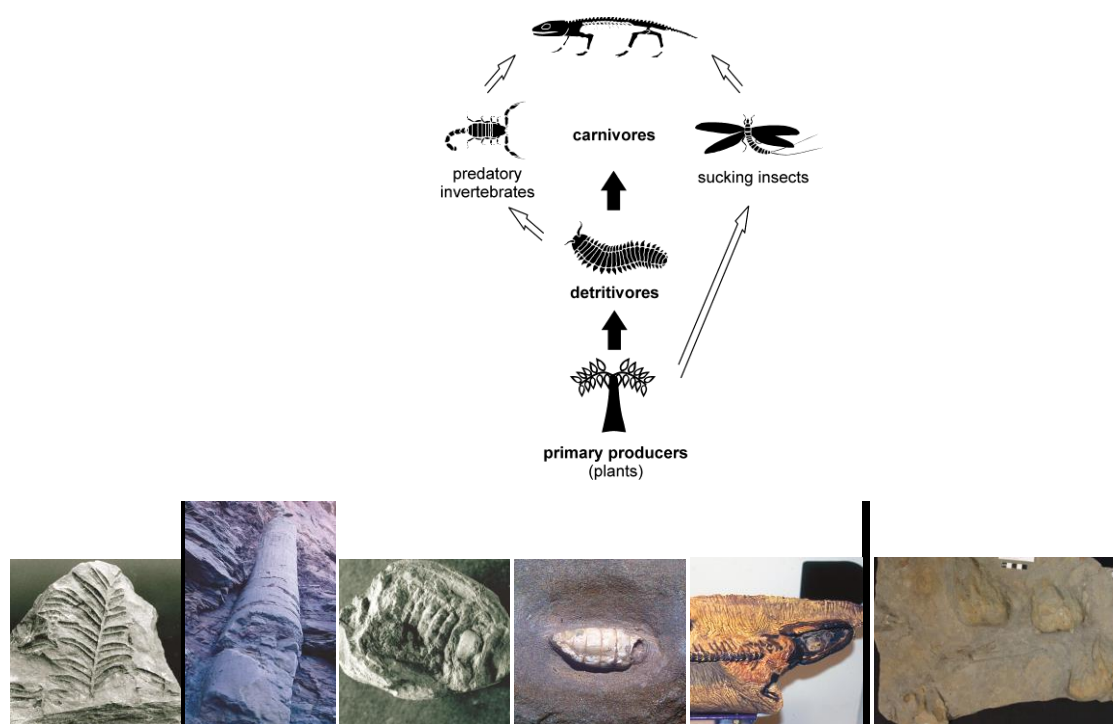


Figure 7. The food web and representative fossils from different trophic levels at the Joggins Fossil Cliffs. Left to right: *Alethopteris* (seed fern); *Sigillaria* (tree-sized club moss); *Graeophonus* (whip spider, abdomen); *Dendropupa* (land snail); *Dendrerpeton* (amphibian); *Pseudobradypus* (taxonomy unconfirmed; amphibian) trace (images: JFI).

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Joggins Fossil Institute: www.jogginsfossilcliffs.net; on-line fossil collection: <https://mims.ednet.ns.ca/Joggins/search.aspx>

The Paleontology Portal:

http://www.paleoportal.org/index.php?globalnav=flora_fauna§ionnav=assemblage&submission_id=2082&x=7&y=10

