Ichnology of the Pennsylvanian-aged Boss Point Formation at Cape Enrage, New Brunswick: Implication for the paleoenvironmental context for the Lower Boss Point Formation in the Cumberland Subbasin of the Maritimes Basin

By

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ABSTRACT

The Langsettian aged Boss Point Formation (i.e. ~320 million years old) outcrops at Cape Enrage in southeastern New Brunswick along the shores of the Chignecto Bay, Bay of Fundy. Although traces have been noted from the type section at Joggins Nova Scotia, newly discovered invertebrate repichnia tracks at Cape Enrage represent the first ichnofossil assemblage to be systematically described from the Boss Point Formation in Atlantic Canada. The tracks described in this thesis include: *Diplichnites, Diplopodichnus, Kouphichnium, Protichnites, Selenichnites* and *Stiaria.* Given the presence of some diagnostic ichnotaxa, some of the lithofacies can be interpreted as shallow coastal and channel bar lithofacies conformable to the poorly-drained to open-water lithofacies assemblage transition described from the Joggins Formation. The implications of this ichnoassemblage, specifically the presence of horseshoe crab traces, indicate that the Boss Point Formation, at least in part, was more closely connected to open-water depositional settings than previously thought.

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Introduction

Trace fossils, otherwise known as ichnofossils, are sedimentary structures created by the movement of living organisms (i.e. footprints, trackways, worm burrows, etc). Trace fossils show an action or movement of a living organism, without having a preserved body fossil of the organism itself. Trace fossils are governed using the same taxonomic naming system (International Code of Zoological Nomenclature) as biological genera and species. However, they do not represent the biotaxon, and therefore trace fossils are considered to be form-taxa (or morpho-taxa) called "ichnotaxa" and are assigned to "ichnogenera and "ichnospecies" to separate them from biological taxa. Since these "ichnospecies" refer to sedimentary structures and do not always correlate immediately to a biological species, they were once considered not to be useful for biodiversity and evolutionary studies. However, more recently the study of ichnology has been able to use trace fossils to fill in evolutionary gaps in the fossil record, albeit at a lower resolution to body fossils (Lucas et al. 2022).

Trace fossils have been noted in literature from the Maritimes Basin (Fig. 1, 2) since the early seminal works of Dawson (1862, 1863, 1864, 1873, 1882, 1890) and Matthew (1903a, b, 1905, 1910). Since these early works, trace fossils have helped to provide additional lines of evidence for paleobiodiversity and palaeoecological studies through much of the geologic history represented in the Maritimes, from the Late Devonian through Early Permian (~375-290 million years ago; Fig. 3 Archer et al. 1995, Calder 1998, Calder et al. 2006, Defoe et al. 2011, King et al. 2019, Lucas et al. 2022, Prescott et al. 2014, van Allen et al. 2005, Gradstein et al. 2020).

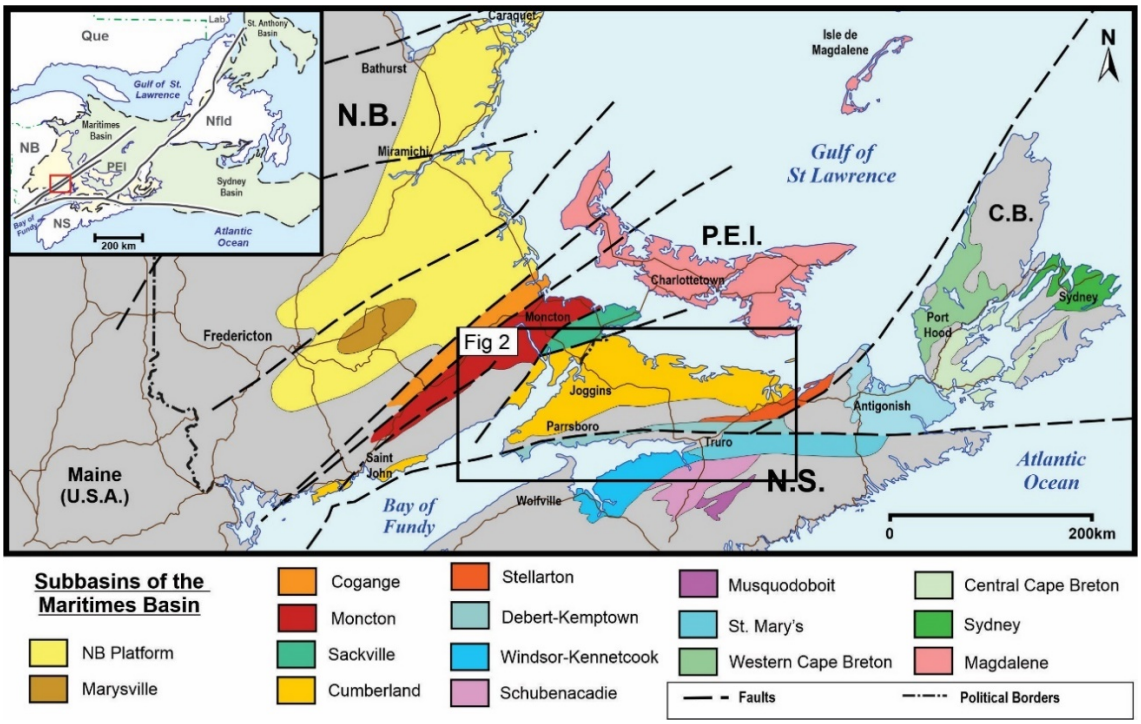


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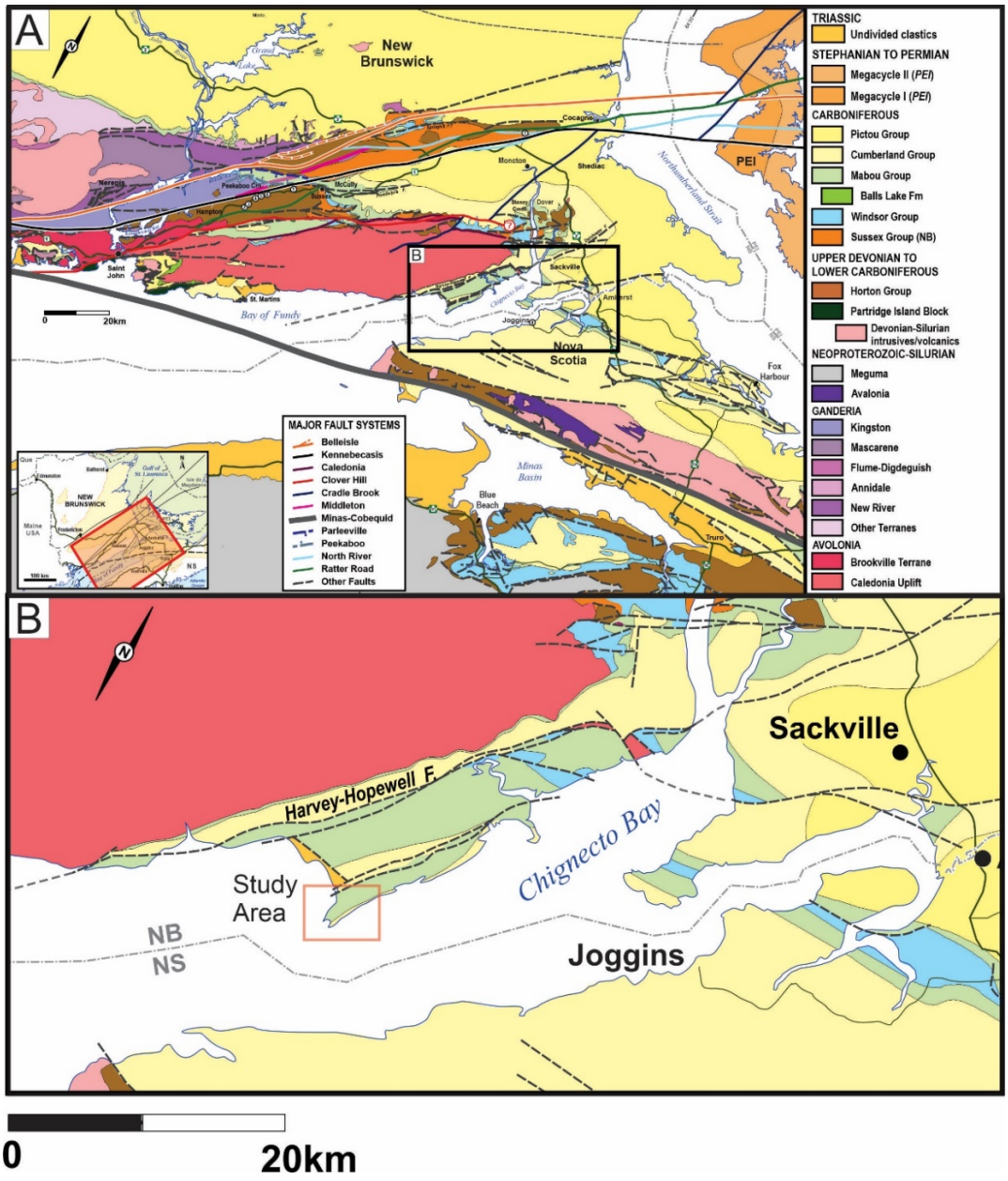


Figure 2. A) Map of Cumberland Subbasin. B) Zoomed-in section of map to Chignecto Bay showing geological groups in various colours after St Peter (2008).

In New Brunswick, tetrapod trackways and limited invertebrate traces were first described at Fern Ledges by Matthew (1910) and later redescribed by Stimson et al. (2016a). The Tynemouth Creek Formation has been studied for both its tetrapod tracks

(Falcon-Lang et al. 2010, 2015) and its invertebrate ichnofaunal assemblages that fall into the *Mermia, Scoyenia* and *Skolithos* ichnofacies (Falcon-Lang et al. 2015). Atlantic Canada has been home to significant tetrapod ichnofossil discoveries such as the oldest reptile footprints (Falcon-Lang et al. 2007, 2010; Marchetti et al. 2021), and the smallest known tetrapod footprints (Stimson et al. 2012), and has been considered one the best places to study vertebrate ichnotaxa (Lucas et al. 2022). However, despite their early recognition at Joggins and McKay Head Nova Scotia (Dawson 1890), invertebrate traces have been far less studied, and are even more limited in New Brunswick in the literature.

The Boss Point Formation is a distinct unit of rock that outcrops in southern New Brunswick, and in Nova Scotia, Canada as part of the Cumberland Subbasin within the broader composite Maritimes Basin (Gibling et al. 2019; Figs. 1, 2 and 3). The formation has been dated to the early Pennsylvanian (Yeadonian-Langsettian), by Utting et al. (2010) at its type section at Boss Point Nova Scotia (Fig. 3). More recent palynology data that was collected as part of this and concurrent studies has identified the Boss Point Formation at Cape Enrage as early Langsettian (McLean, pers. comm., 2024). The formation has been previously interpreted to be comprised of fluvially transported sediments and lacustrine deposits (Browne and Plint 1994) or floodplain deposits (Rygel et al. 2015). The cliffs of Cape Enrage, NB are made up of near vertical beds of the Boss Point Formation (Wards Point Member), save a small unit at the base of the stratigraphic package of the basal Boss Point redbed, Chignecto Bay Member (St. Peter and Johnson, 2009), that outcrops to the west of the Cape Enrage lighthouse on Barn Marsh Beach (Fig. 4). The Boss Point Formation has been locally known for its abundance of plant fossils, yet the ichnofossils have only recently been recognized.

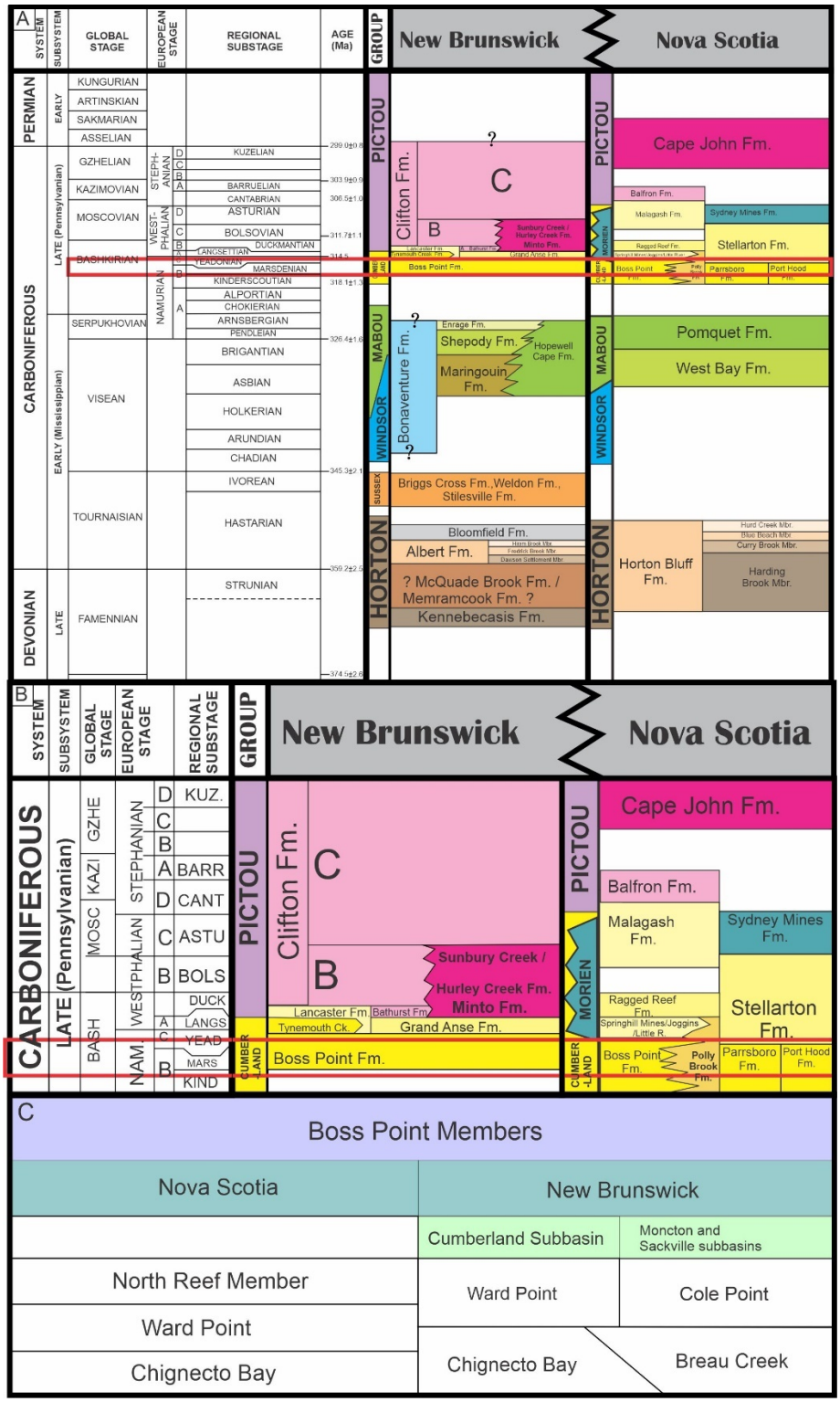


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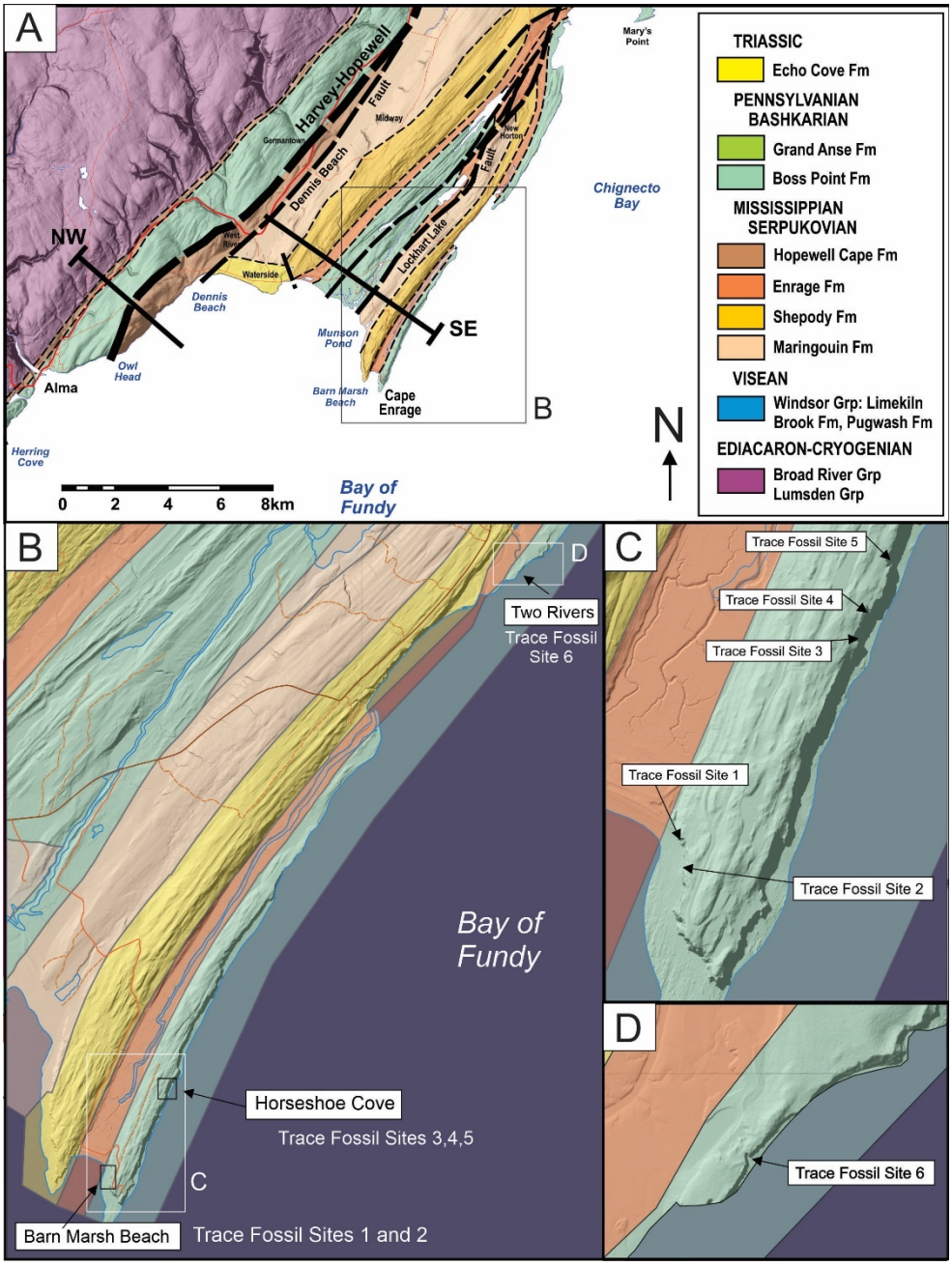


Figure 4. A) Map showing geological formations in Cape Enrage area. A black line from NW to SE shows the distance of the cross section in Figure 5A. B) Zoomed-in map, showing Barn Marsh Beach, 'Horseshoe Cove' and Two Rivers, as well as geological formations in similar colours as A. C) shows an even further zoomed-in map to show the locations of Trace Fossil Sites 1,2,3,4 and 5. D) shows location of Trace Fossil Site 6.

This is the first systematic invertebrate ichnological study of the Boss Point Formation that is described in literature. In recent years, many ichnofossils have been found and identified from 8 stratigraphic horizons at 6 sites from the cliff outcrops along the shoreline at Barn Marsh Beach, and a single locality east of Two Rivers along the eastern shoreline between Cape Enrage and Mary's Point (Fig. 4). These sites include several ichnogenera and ichnospecies, which have been interpreted to have been produced by a variety of invertebrates including arthropods and annelids. A manuscript by Allen et al. (In Preparation) has identified tetrapod footprints from 3 stratigraphic horizons and outlines these ichnotaxa and their interpretation. This new research area is coeval with traces described from the Port Hood Formation in Cape Breton (Keighley and Pickerill 1998, 2003) and unpublished ichnofossils from the Boss Point Formation at Lower Cove, Nova Scotia at the type section (Brian Hebert pers. Comm.; Fig. 3).

The Boss Point Formation was previously thought to have been solely made up of fluvial and lacustrine sediments, with sandy cross-bedding features throughout 60% of the formation (Browne and Plint 1994). Many abandoned and backfilled river channels can be observed as tapering semi-circular sandstone bodies along the cliff outcrops at Cape Enrage. These strata also preserve abundant allochthonous terrestrial paleofloral elements which include *Calamites* stems, lycopsid, pteridosperm and cordaitalean axes and disarticulated bark, cones and other paleofloral elements. These plants, especially the *Calamites* and lycopsids, have been interpreted to have once grown in swampy, low-lying interdistributary areas of large river channels that flowed to the northeast (Rygel et al. 2015, Craggs et al. 2017, Calder et al. 2006, Ielpi et al. 2014). Commonly, *Cordaites* logs are preserved within the backfilled river channels as log jams (Ielpi et al. 2014). These

trees were interpreted to have been transported and preserved from upland hinterland areas of the Caledonian Mountains to the fluvial plains now represented by the Boss Point Formation. Terrestrial plants *in situ*, especially lycopsid roots, have been used to describe the environment of sedimentary deposition, (eg. lycopsid trees growing in waterlogged areas, Rygel et al. 2015). While the thick sandstone channel units preserve fossil log jams representing the transported palaeoflora that existed in the upland regions, Trace Fossil Site 5 (45°36'24.32"N; 64°46'18.04"W) preserves *Calamites* and *Stigmaria* roots within the fine-grey shales and mudrocks representing the floodplains between trunk river systems (Fig. 4). These fine-grained units also commonly preserve autochthonous ichnofossils that provide details of the Boss Point inter-channel ecologies, which make an extremely useful tool in describing the environment of a rock formation. Tetrapod trackways have been mentioned by Rygel et al. (2015) as additional evidence for subaerial exposure and presence of a firm substrate, however an in-depth, thorough analysis of the ichnofossil assemblage of the Boss Point Formation has yet to be conducted.

Among the new discoveries of ichnofossils in these strata at Cape Enrage are ichnofossils that are commonly interpreted to be produced by xiphosuran horseshoe crabs. Horseshoe crab body fossils (*Belinurus* and *Euproops*; Copeland 1957) and their ichnofossils (*Kouphichnium, Protichnites, Selenichnites*), are commonly found in Carboniferous sedimentary rocks of Atlantic Canada (Archer et al. 1995, Buhler and Grey 2017, Copeland 1957, Calder 1998, Falcon-Lang et al. 2010, Stimson et al. 2010).

The study presented here exhibits the first reported evidence for xiphosuran activity in the Boss Point Formation from NB or NS. *Kouphichnium* (Nopsca 1923) is an ichnogenus interpreted to be trackways made by xiphosurans (horseshoe crabs). This ichnogenus has been renamed from the previous ichnospecies *Ichnites lithographicum* originally named by Oppel (1862) and now, as an ichnogenus, includes 15 identified ichnospecies (King et al. 2019) with varying morphologies caused by differences in preservation or differences in movement by what is interpreted to be the same type of animal. King et al. (2019) suggested that many of these ichnotaxa might be synonyms but this was beyond the scope of their research, with the ichnotaxa still being in need of revision. Recently, *Kouphichnium minkinensis* was interpreted to be made by a form of "bouncing" motion under subaqueous conditions by a semi-buoyant synxiphosuran, whereas *K. aspodon* is interpreted to be a "walking trace" of the same animal (King et al. 2019). A single ichnospecies of *Kouphichnium* (*K. atkinsoni*) was interpreted to be made by eurypterids while all other ichnospecies of the genus *Kouphichnium* have been interpreted to be made by xiphosurans or synxiphosurans (King et al. 2019).

Trace fossils of both vertebrates and invertebrates are well known from younger Pennsylvanian-aged strata in both NB and NS (Archer et al. 1995; Stimson et al. 2012; Falcon-Lang et al. 2015; Stimson et al. 2016a, b; Buhler and Grey 2017; Marchetti et al. 2021, Allen et al. 2022; Lucas et al. 2022). This thesis gives the first systematic description of invertebrate trace fossils from the Boss Point Formation and outlines the paleoenvironmental implications for the depositional settings of the Boss Point Formation at Cape Enrage. The trace fossil assemblage of the Boss Point Formation contains

implications about the paleoenvironment that may not have been considered by previous workers and may change our understanding of the formation history as a whole.

Geological Background

Maritimes Basin

The Maritimes Basin covers an area of approximately 250,000 km^2 from southern Quebec to northern Nova Scotia and beneath the Gulf of St. Lawrence to southern Newfoundland (Ryan and Boehner 1994, Deitrich et al. 2011, Gibling et al. 2019; Fig. 1). The basin can be defined as a successor basin, formed as the result of tectonic activity during the Acadian Orogeny Mountain building event, and it is comprised of several subbasins with independent depositional histories separated by uplifted crystalline massifs (Williams 1974, St. Peter and Johnson 2009, Gibling et al. 2019). This study will focus on the Boss Point Formation, an early Pennsylvanian formation belonging to the Cumberland Subbasin (Fig. 2).

Cumberland Basin

The strata exposed along the shores of Cape Enrage are preserved within one of the compartmentalized subbasins of the Maritimes Basin known as the Cumberland Subbasin (Fig. 2). The Cumberland Subbasin stretches from the Cobequid Mountains in Nova Scotia to Caledonia Mountain in southern New Brunswick where the northern and northwest boundaries of the subbasin are defined by the Shepody–Beckwith Fault and the Harvey-Hopewell fault respectively (St. Peter and Johnson 2009). Sediments deposited within this basin are thought to be locally derived from these adjacent uplifts. It contains

approximately 7km of sedimentary strata interpreted as being mostly terrestrial, ranging from late Devonian to early Permian beds, with upper Carboniferous and lower Permian beds making up the majority of exposed surface rock (Ryan and Boehner 1994). These strata encompass five geological groups, in ascending order: Horton Group (subsurface; Tournaisian); Windsor Group (Visean); Mabou Group (Serpukhovian); the Cumberland Group (Bashkirian); and the Pictou Group (Moscovian to early Permian; Fig. 3). The entire depositional history of the strata of the latest Visean through the end of the Serkupovian has sediments sourced from the Caledonia highlands to the northwest (Jutras et al. 2015). Jutras et al. (2015) interpreted paleoflow to be from South to North (330°-10°). Craggs et al. (2015) re-examined the Boss Point Formation of Cape Maringouin and found the paleocurrent direction and provenance of the Boss Point Formation to be in agreement with Browne and Plint (1994), and Rygel et al. (2015) who describe the paleocurrent as going towards the East and South. Rygel et al. (2015), in their detailed description of the Boss Point Formation in Nova Scotia, measured the paleocurrent of the three members (sections). They measured the paleocurrent of the Chignecto Bay Member from major channel bodies as North (353°) and Northeast (49°), the Ward Point Member as 119° (ranging from 44-161°), and for the North Reef Member measured a flow to the East (84-118°). The strata exposed at Cape Enrage are mapped as the Boss Point Formation and are believed to represent the earliest Pennsylvanian strata of the Cumberland Group within the Cumberland Subbasin (Fig. 2, 3).

Cape Enrage Geological Context

There are four geological formations in the Cape Enrage area: Maringouin, Shepody, Enrage and Boss Point formations, which overlie each other respectively, with the Boss Point Formation being the highest (youngest) in stratigraphic order (Fig. 3,4). The beds of these formations are tilted to near vertical due to halokinetic processes (Fig. 5; i.e. the movement of thick salt layers underground may form salt diapirs, or domes, which then disrupt overlying strata; see Appendix 1 for more detail). The Cape Enrage site sits on a strip of land against the Bay of Fundy, made up of the Boss Point Formation save for a small outcrop of the underlying Enrage Formation on the Northwest side of this strip of land. The Boss Point Formation is of Langsettian age (i.e ~320 million years old; Gradstein et al. 2020) and is described herein from along the shorelines of Chignecto Bay, where it outcrops as an ~ 45m tall cliff face and as a wave-cut platform along the beachfront. The base of the formation is exposed in an outcrop along the eastern shore of Barn Marsh Beach (45°35'50.78"N, 64°46'53.09"W) where the strata have an orientation of 15° / 76° (strike and dip; Fig. 4, 6, 7). A total of 307 m of strata is exposed along the shoreline below the Cape Enrage lighthouse with the youngest strata being exposed in the wave cut platform outcrop (45°35'35.89"N, 64°46'43.73"W) (Fig 6, Appendix 4, 5). The upper 80m of strata can be followed along strike which is roughly parallel to the shoreline between Cape Enrage and Mary's Point to the northeast (Fig. 6), although most of the sequence is buried in cobbles and covered by seaweed on the wavecut platform that forms a beach at low tide. About 20-30 m of these strata can be confidently measured and traced at the cliff face along strike to the northeast between fossil sites. The Boss Point Formation overlies the Early to Mid-Serpukhovian-aged strata of the Enrage

Formation below, the unconformable contact of which has been interpreted to be exposed below the base of the Boss Point Formation at Barn Marsh Beach (Fig. 4). The upper contact of the Boss Point is not known at Cape Enrage as the upper portion of the formation outcrop extends under water within the Bay of Fundy and is not accessible at Cape Enrage. The Boss Point Formation can be traced eastward from Mary's Point to Slacks Cove on Cape Maringouin, where it is folded into an anticline and is unconformably overlain by the Grande Anse Formation (Craggs et al. 2015) which is time equivalent to the Ragged Reef Formation in Nova Scotia (Fig. 2, 3). The Boss Point and Grande Anse formation unconformable contact is also exposed at Dorchester Cape, north of the Cape Maringouin localities (Fig. 2). Across the bay at its type section at Boss Point Nova Scotia, the middle and upper Boss Point Formation stratigraphy is exposed in the coastal outcrop (Rygel et al. 2015, Ielpi et al. 2014), where it is conformably overlain by the Little River Formation (Fig. 2,3). In New Brunswick at Giffin Pond, the Boss Point Formation is overlain conformably by the Tynemouth Creek Formation, that is roughly equivalent to the Little River and Joggins Formation in Nova Scotia (Fig. 3).

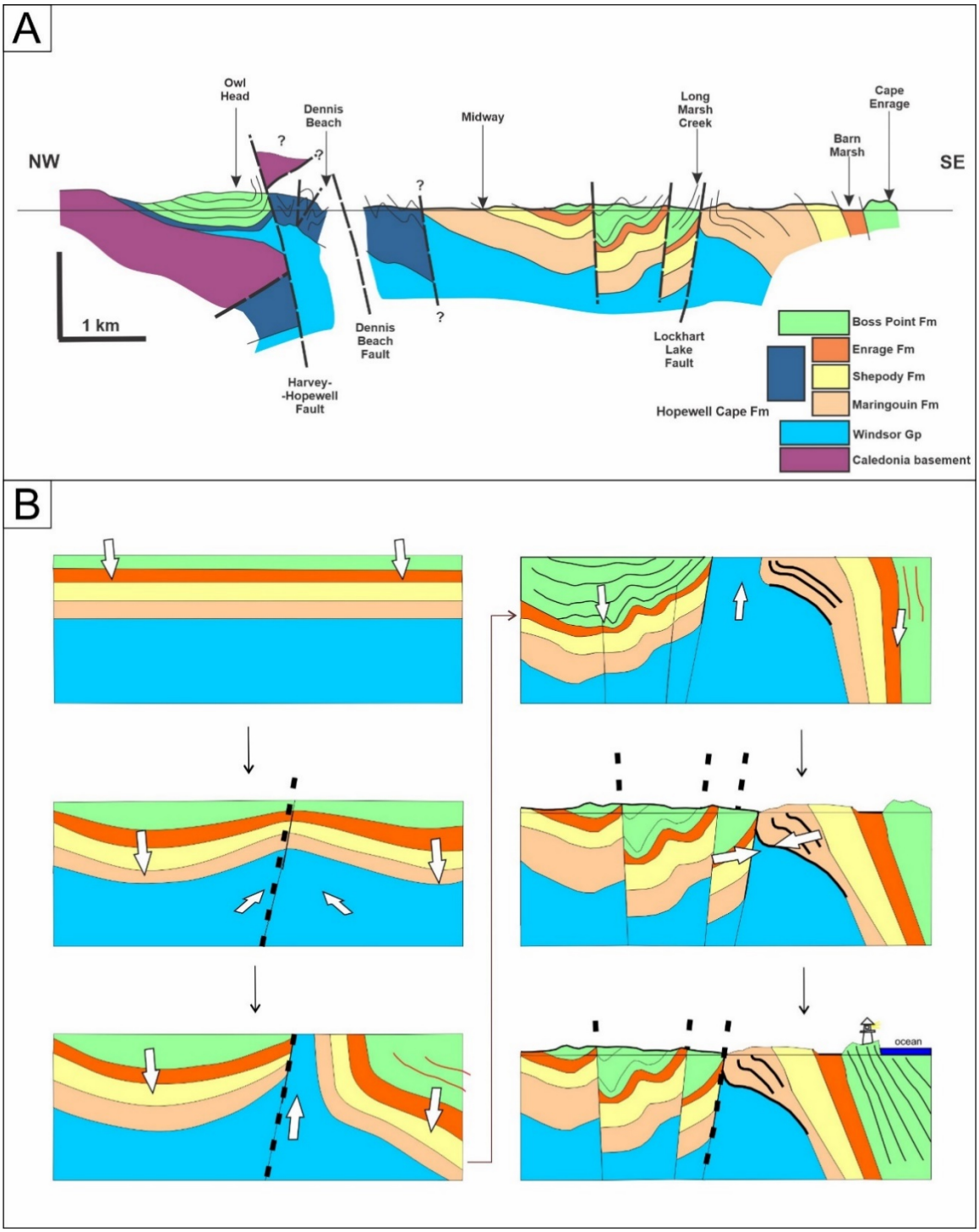


Figure 5. A) Cross section of geological formations in the Cape Enrage area following the line drawn in Figure 4A. B) Sketches showing interpreted process of halokinesis. (Fig 5A courtesy of Dr. Adrian Park, NB Geological Survey Branch)

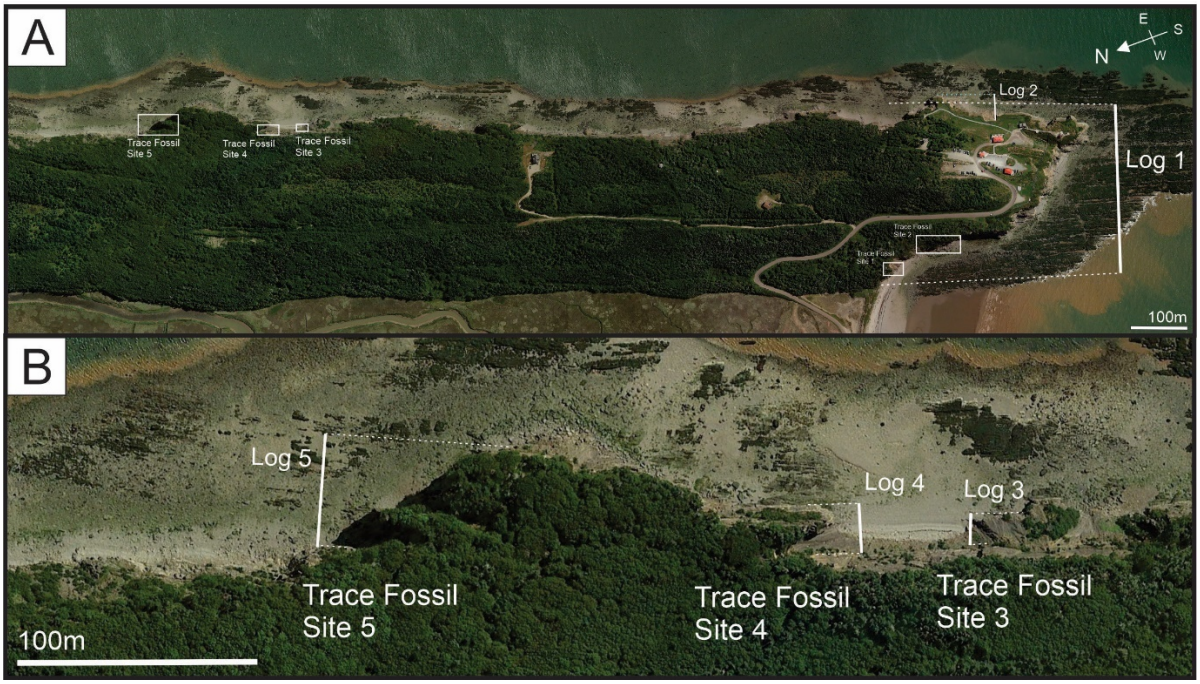


Figure 6. Satellite images taken from Google Earth showing stratigraphic sections of the Boss Point Formation at Cape Enrage. A) Large-scale satellite image showing stratigraphic section logged in Log 1 (appendix 4), and Log 2 (appendix 4), as well as trace fossil sites shown in boxes. B) Zoomed satellite image showing stratigraphic sections logged in Log 3 (appendix 6), Log 4 (appendix 7) and log 5 (appendix 8).

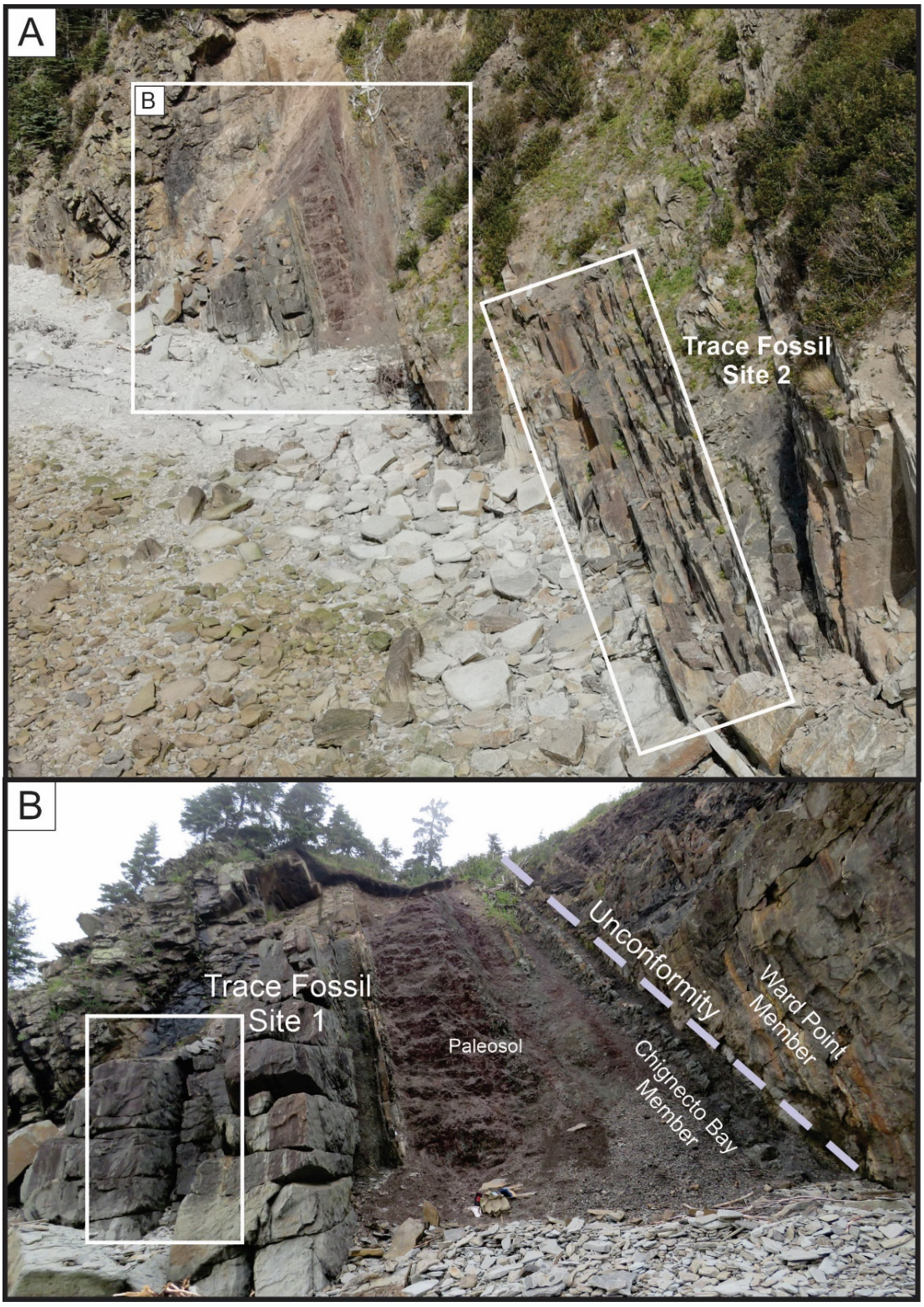


Figure 7. A) Image showing Trace Fossil Sites 1 and 2 B) Closer image of Trace Fossil Site 1 to the left as well as the interpreted unconformity between Chignecto Bay Member (left side of dashed line) and the Ward Point Member (right side of dashed line)

Boss Point Formation Type Section

The Boss Point Formation is originally defined by its 982m (Ryan and Boehner 1994) to 1125m (Rygel et al. 2015) thick type section in Nova Scotia that stretches along the Bay of Fundy coast from Lower Cove to Downing Head. This formation forms the base of the Pennsylvanian Cumberland group, overlying the latest Mississippian (Serpukhovian) Claremont Formation and is overlain by the Little River, Joggins, Springhill Mines and Ragged Reef formations (Fig. 3). In Nova Scotia it consists of grey quartzose sandstone and well-rounded quartz pebble conglomerate in beds often containing river channels or cross-bedding, which have been interpreted to contain mostly fluvial, transported sediments from the early Pennsylvanian Period within the Cumberland Basin (Rygel et al. 2015). An in-depth description of the main lithologies of the Boss Point Formation is provided in Appendix 2.

Boss Point Formation (New Brunswick)

There are four members of the Boss Point Formation in New Brunswick, two of which, similar to Nova Scotia, are the Chignecto Bay and Ward Point members, as well as the added Breau Creek and Cole Point members (St. Peter and Johnson, 2009; Fig. 3C). As with Nova Scotia, the Chignecto Bay Member is the lowest in succession in the Boss Point Formation and sits stratigraphically below the Ward Point Member in the Cumberland Subbasin (St. Peter and Johnson, 2009). This member in New Brunswick represents the earliest Pennsylvanian rocks of the Boss Point Formation and is described as containing mostly redbeds consisting of siltstone and mudstone as well as fine-grained

sandstone. The Ward Point Member is defined by the presence of greyish rocks and multistory trough cross-bedded sandstone with the occasional fine-grained sandstone, to siltstone or mudstone layers. The sediment is interpreted to alternate between braid-plain and lacustrine sediments (Rygel et al. 2015). The Breau Creek and Cole Point informal members in the Moncton and Sackville subbasins (Fig. 1) can be considered mostly equivalent to the Chignecto Bay and Ward Point members of the Cumberland Basin respectively (St. Peter and Johnson, 2009; Fig. 2,3). These two members make up the majority of the exposed Boss Point Formation in New Brunswick, although this project will only focus on the Chignecto Bay and Ward Point members of the Cumberland Subbasin at Cape Enrage (Fig. 4).

Browne and Plint (1994) studied depositional stratigraphy of the Boss Point Formation at twenty-five sites, most of which are in New Brunswick, and they concluded that there are two main facies associations in the Boss Point Formation: sandy braidplain with rivers flowing to the southeast to the Cumberland Basin, and muddy lacustrine. They defined the alternations of these as two main facies “megacycles”. The sandstone-dominated (mostly braidplain facies) packages are up to 90m thick and make up 70% of the Boss Point Formation in New Brunswick. Trough-cross-bedded sandstone makes up to 60% of the total formation. Other sandstone facies identified include pebbly sandstone, planar-laminated sandstone, ripple-cross-laminated sandstone, planar-tabular cross-bedded sandstone, sigmoidal cross-sets and hummocky cross-stratification, although the last three are rather rare. These packages may contain 40cm to 7.5m thick conglomerate units, usually containing poorly sorted, sub-rounded to well-rounded pebbles with medium to coarse sandstone matrix.

The lacustrine facies association refers to mudstone packages, which are usually thinner and often contain thin coal seams, limestone, claystone and the occasional sandstone unit, albeit lesser than in the braidplain facies. Browne and Plint (1994) interpret these mudstone packages to represent calm, shallow lakes and deltas. These packages abruptly overlie the braidplain packages whereas the braidplain packages erosively overlie the lacustrine packages. Sometimes the erosion cuts far enough into the lacustrine package to leave behind only a lag of mudstone boulders from the mudstone unit.

Boss Point Formation stratigraphy and sedimentology at Cape Enrage

Five stratigraphic logs were measured in the Boss Point Formation at Cape Enrage (Fig. 6, Appendix 4-8); Log 1 was measured between Barn Marsh Beach along the shoreline to East of the Cape Enrage Lighthouse and contains trace fossil sites 1 and 2 (Fig. 6,7,8, 9). Log 2 (Appendix 4) was measured between the Cape Enrage Lighthouse and the Cape Enrage Beach access that can be easily tied to the main stratigraphic log (Fig. 6, 10). Logs 3 and 4 (appendix 6, 7) were measured at the informally named Horseshoe Cove area, and describe trace fossil sites 3 and 4 respectively (45°36'17.05"N, 64°46'22.93"W and 45°36'18.35"N, 64°46'22.10"W; Fig. 6B, 11); while Log 5 was measured from the East side of the eastern sandstone headland of Horseshoe Cove (45°36'24.38"N, 64°46'17.85"W; Fig. 6B). The 5 stratigraphic logs can be easily correlated along strike with minor structural interruptions to the stratigraphy near the Cape Enrage Beach access (Fig. 6, 10, 12). A sixth trace fossil site was noted at Two Rivers (45°39'12.19"N; 64°43'24.53"W) and specimens were collected (Fig 4, 13).

The beds containing trace fossils at Cape Enrage can be organized into different horizons. These horizons do not perfectly correspond with the stratigraphic logs listed above, or the "trace fossils sites" listed below. Figure 14 shows a simplified stratigraphic log indicating the relative location of these stratigraphic horizons. Although trace fossils sites 1 and 2 correspond to horizons 1 and 2 respectively, sites 3,4 and 5 contain the same layers of strata (figure 15). The beds containing trace fossils in unit 2 of these three sites as seen in Figure 15 will be assigned to Horizon 3, while the fossils in unit 4 will be assigned to Horizon 4.



Figure 8 Trace fossil site 2. A) Full site photo. B) Close up of crescent and interference ripple marks on trackway surface.

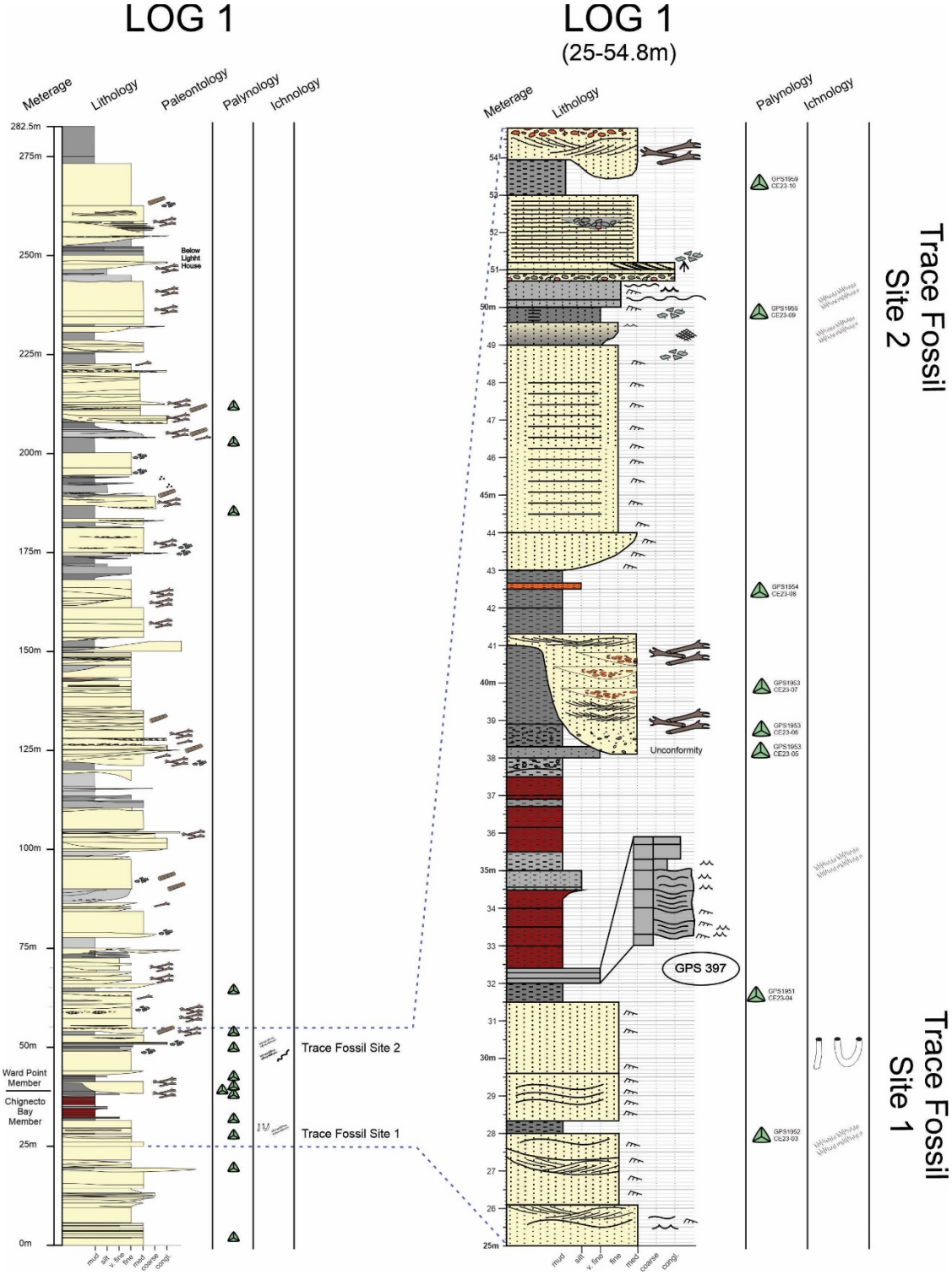


Figure 9. A condensed version of Log 1 with an expanded section, showing details of the stratigraphy of Trace Fossil Sites 1 and 2.

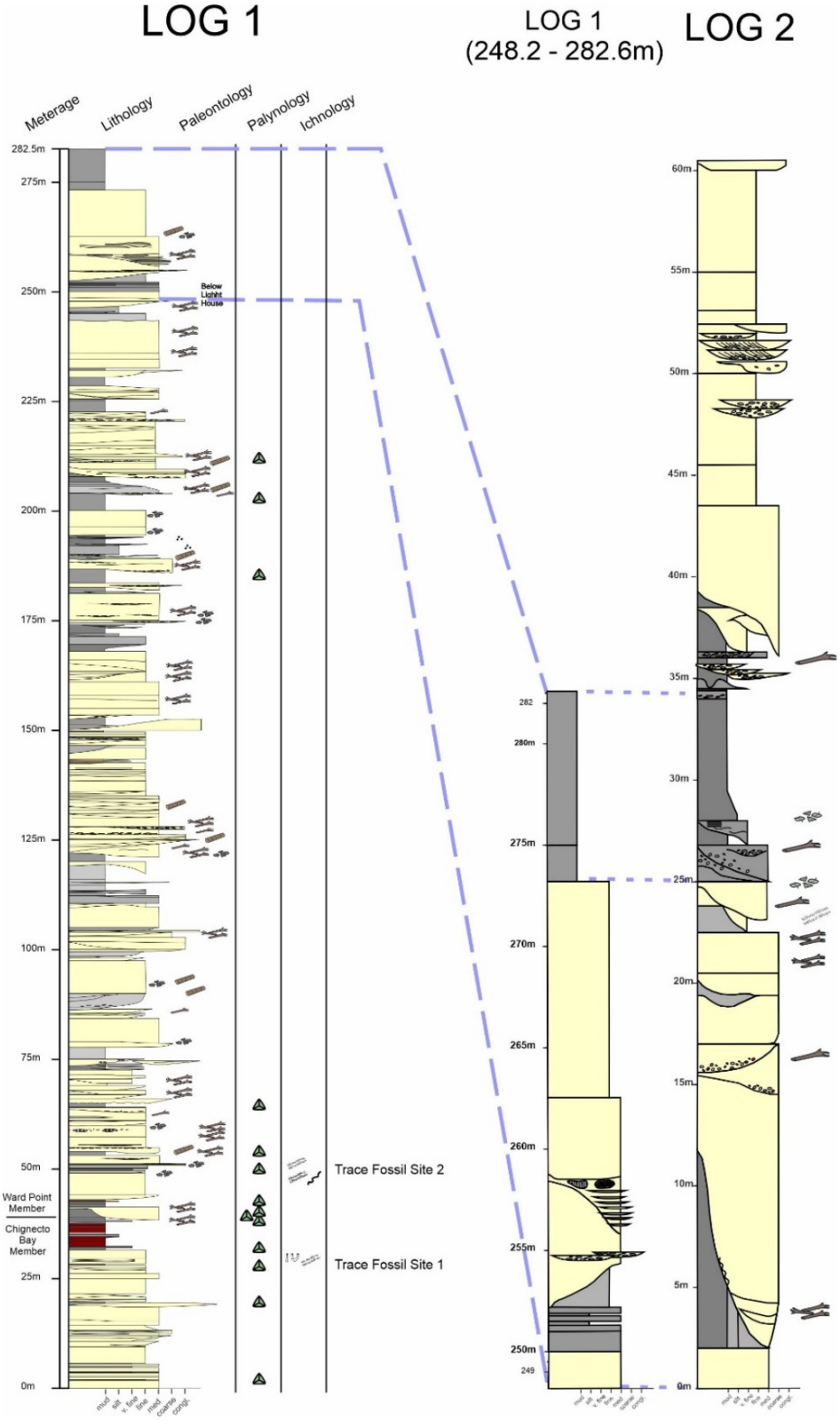


Figure 10. Uppermost portion of a condensed version of Log 1 is expanded and compared to Log 2, to show how the uppermost mudstone unit is traceable between both logs.

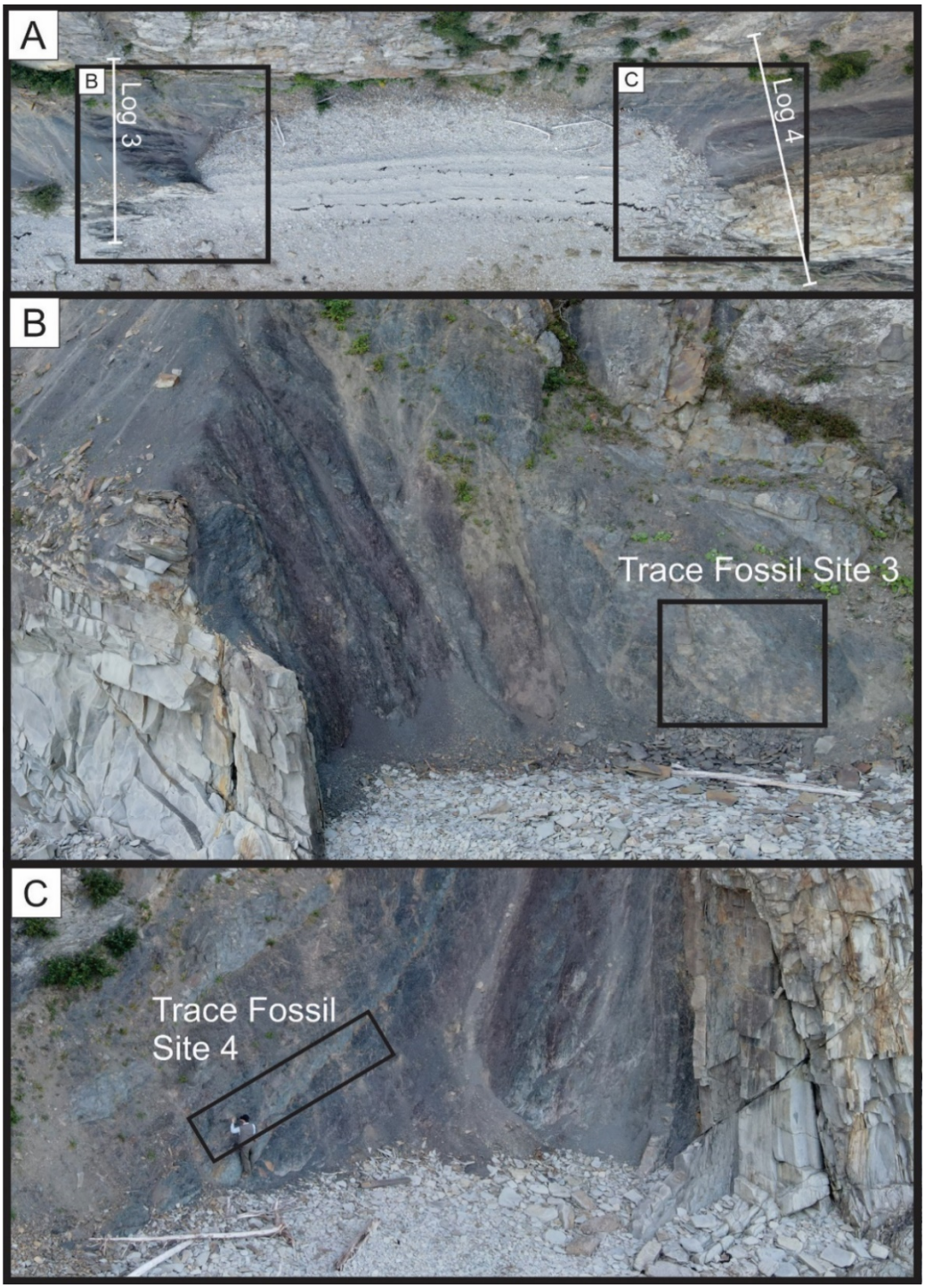


Figure 11. Drone images of 'Horseshoe Cove' containing Trace Fossil Sites 3 and 4. A) Birds eye photo of Horseshoe Cove showing locations of Fossil Sites 3 and 4, as well as the stratigraphic sections where Logs 3 and 4 were made (Appendix 6,7). B) Image of Trace Fossil Site 3 showing main trackway surface. C) Image of Trace Fossil Site 4 showing main trackway surface.

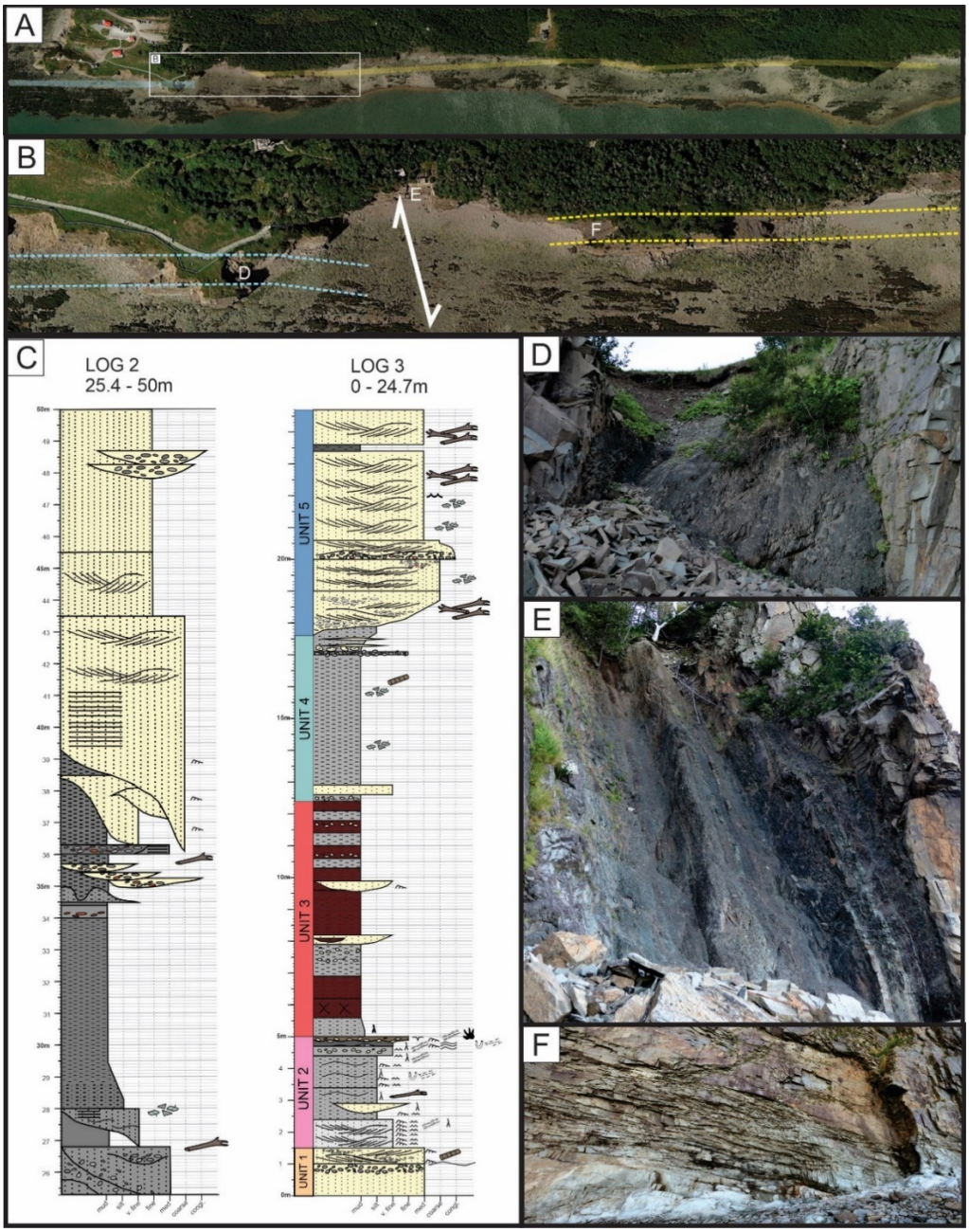


Figure 12. A) Satellite image of Eastern coast at Cape Enrage, showing the location of two large traceable mudstone units. The blue line represents the mudstone unit at the top of Log 1 (Appendix 4), while the yellow line represents a second mudstone unit that can be traced along the coast to Horseshoe Cove. B) shows a zoomed-in image of where these two mudstone units, outlined as blue and yellow similar to A, appear to "meet", yet are offset by a fault zone shown with a white line between them. C) shows a comparison between Logs 2 and 3, to compare the lithological differences between the two mudstone units. Some of these include the second mudstone being much thicker and containing redbeds and abundant ichnofossils, unlike the first mudstone unit. D,E,F) show close up images of the areas labelled in B. D) shows the first mudstone unit, highlighted and outlined in blue in A and B. E) shows the second mudstone unit, highlighted and outlined in yellow in A and B. F) shows evidence of fault zone activity on the cliff walls between the two areas, specifically its cracked and broken appearance.

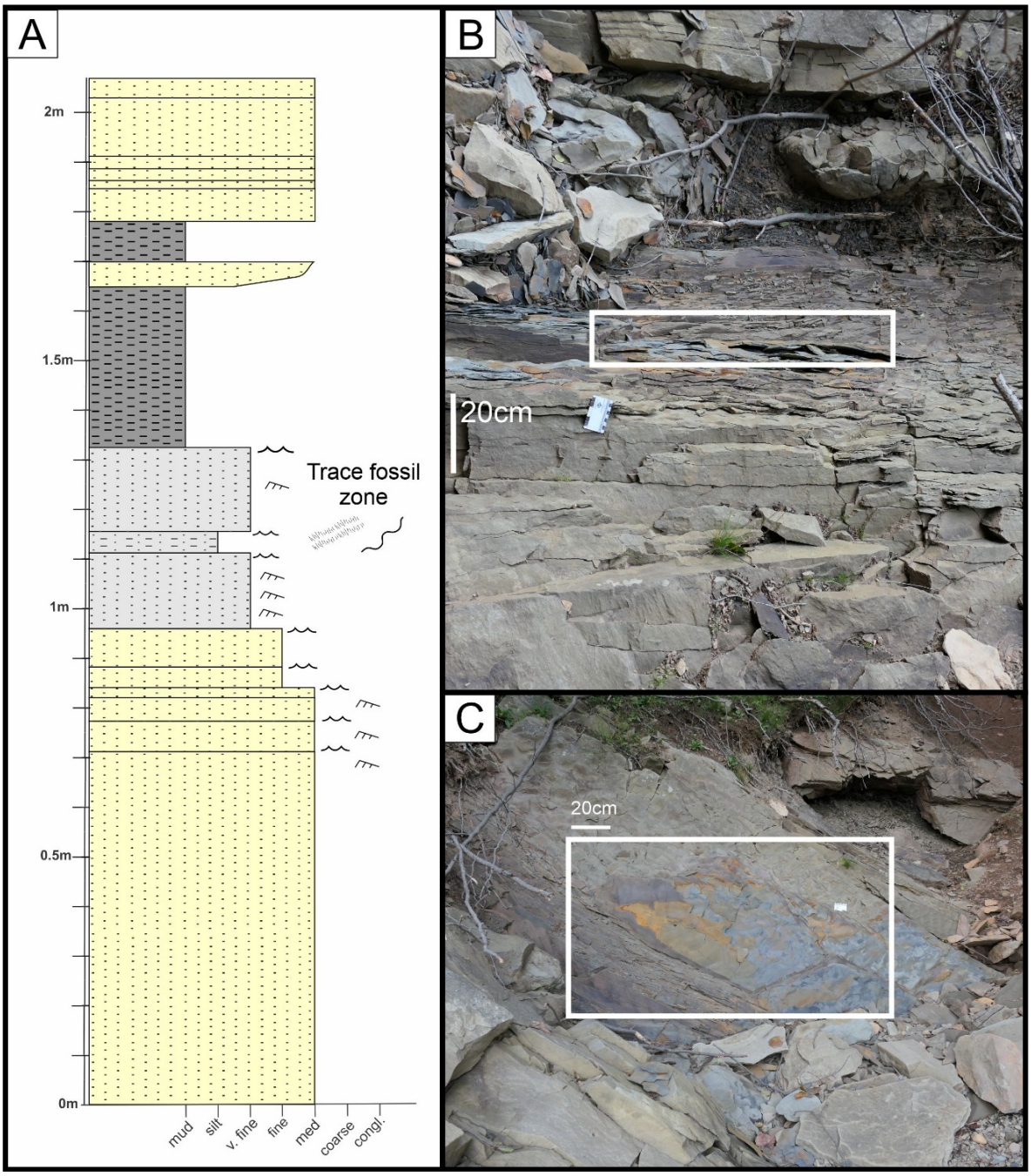


Figure 13. Trace Fossil Site 6. A) Stratigraphic log. B) Image showing stratigraphic layers of rock parallel to strata. C) Image of trace fossil surface perpendicular to strata. White boxes in B and C show the location of the trace fossil zone.

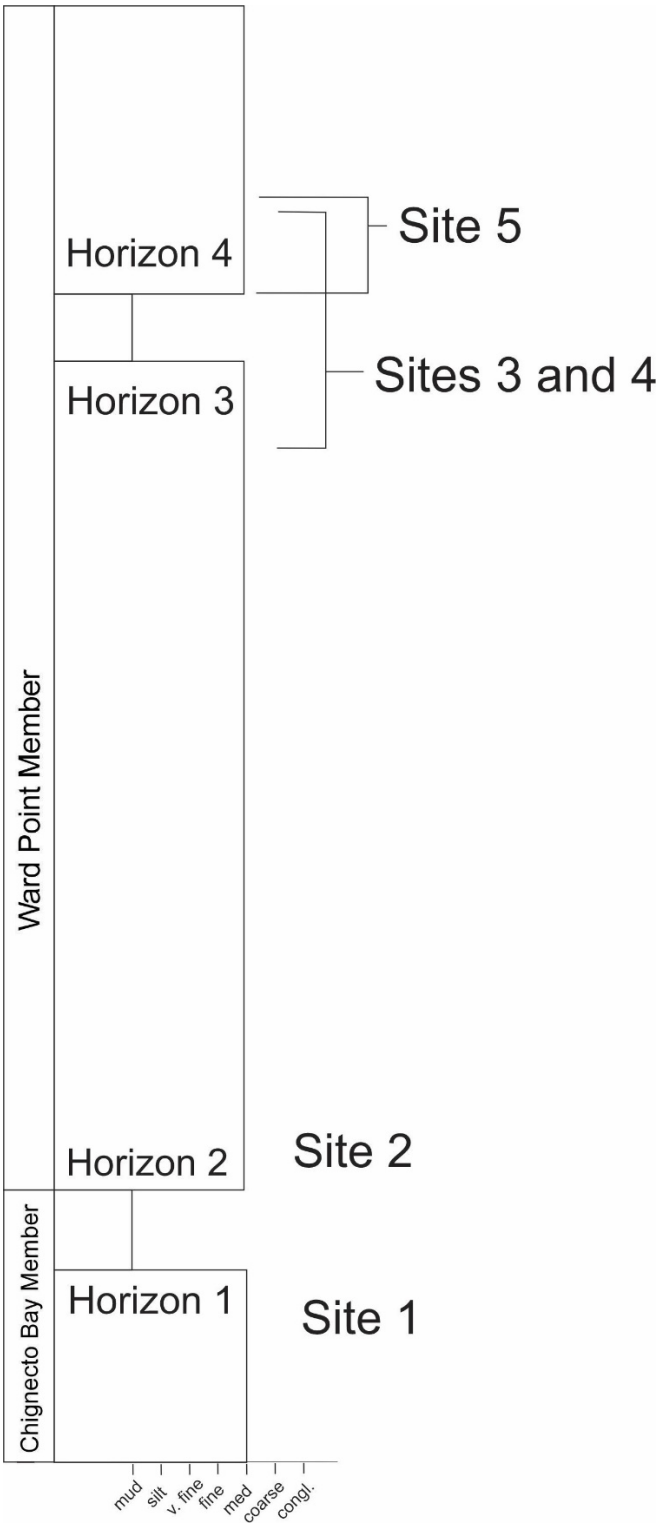


Figure 14. Simplified stratigraphyic column (not to scale), showing relative locations of fossil sites and horizons in the logged Boss Point Formation stratigraphy.

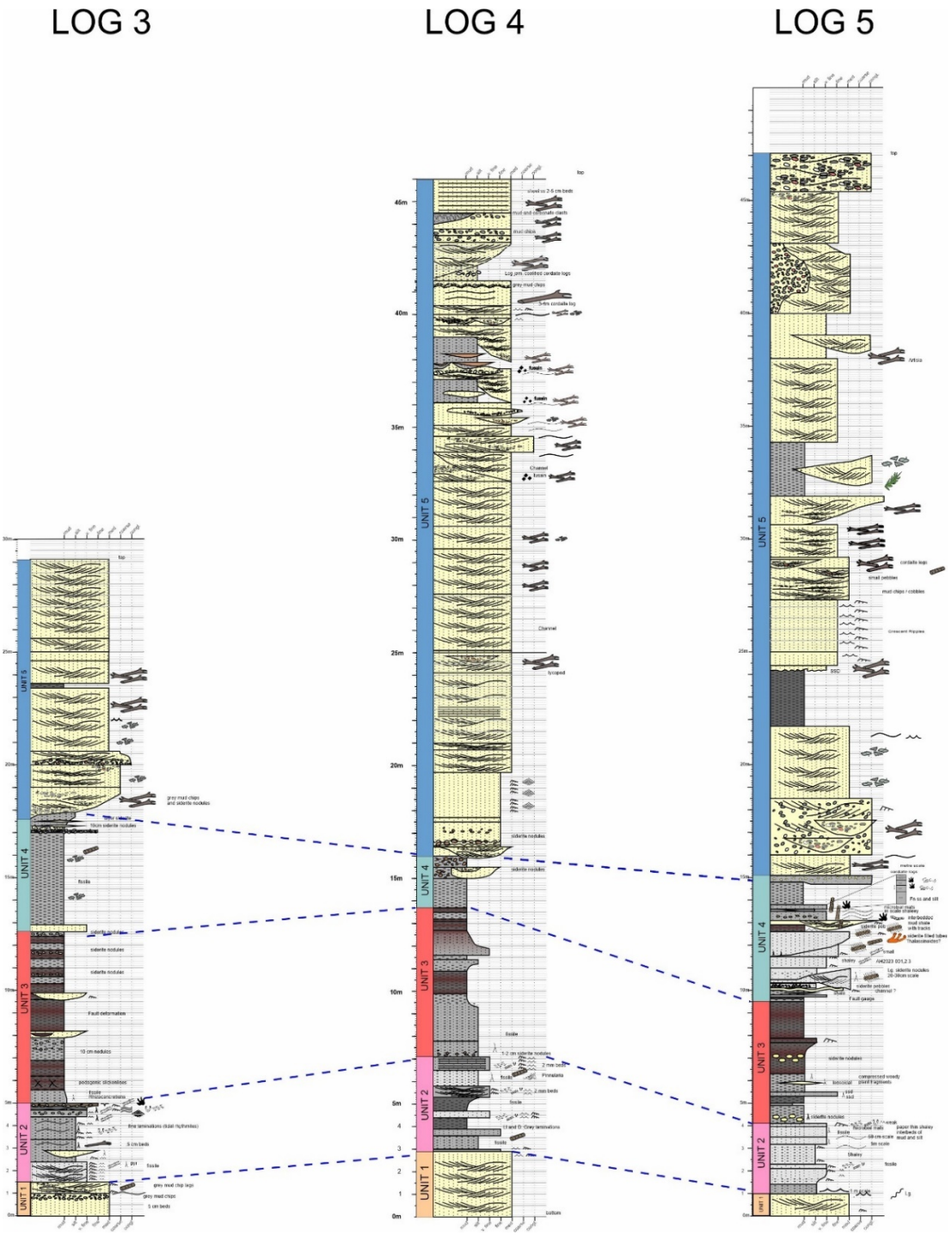


Figure 15. Logs 3, 4 and 5, from trace fossil sites 3, 4 and 5 respectively. Five units traceable between the three sites are outlined and compared.

Trace Fossil Sites

Five main fossil sites have been recorded at Cape Enrage (Figs. 4, 6, 7, 11, 13) and a sixth at Two Rivers down-shore (45°39'12.19"N; 64°43'24.53"W; Fig. 13). Two of these occur on the western side of Cape Enrage (eastern side of Barn Marsh Beach) near the base of the Boss Point Formation and represent the oldest trace fossils observed in the formation in New Brunswick, with the remaining three sites on the eastern side of Cape Enrage along the shore between Cape Enrage and Mary's Point. These strata are among the youngest accessible sedimentary beds.

Trace Fossil Site 1: Barn Marsh Beach – Boss Point Formation, Chignecto Member (45°35'49.41"N, 64°46'52.21"W; Log 1 (Appendix 4); Fig. 7, 9)

Trace Fossil Site 1 is located 28 m above the base of the measured section. Here, fine-medium grained sandstone channel bodies with associated conglomerate basal channel fills commonly preserve plant stems that have been transported by fluvial river channels and have been interpreted to have been incorporated into an ancient log jam (Ielpi et al. 2014). Two sandstone bodies of very fine-grained, medium to light grey sandstone preserve ripple bedforms and cross-bedding. Invertebrate traces are preserved on bedding planes along the ripple bedforms in both convex hyporelief and concave epirelief. This locality preserved invertebrate repichnia dominated by small (1-2 cm outer width) *Diplichnites*. No other trace fossils have been observed from this site.

Trace Fossil Site 2: Barn Marsh Beach – Boss Point Formation, Ward Point Member) (45°35'47.69"N, 64°46'51.93"W; Log 1 (Appendix 5); Fig. 7, 8, 9)

Trace fossil site 2 is located 49 meters above the beginning of Log 1 and consists of fine to very fine-grained sandstone with multidirectional ripple bedforms. Here, ripple bedforms are well developed on several bedding planes. These interference ripple bedforms exhibit both symmetrical and asymmetrical bedforms and commonly climbing ripples. Organic debris tends to fill the troughs of many ripples and commonly preserves trace fossils of *Cochlichnus, Diplichnites, Acripes, Undichna, Kouphichnium, Helminthoidichnites* and *Helminthopsis*, interpreted to be made by arthropods, vermiform worms, and the ventral fins of fish and horseshoe crabs. These traces, like Site 1, are preserved on bedding planes along the ripple bedforms in both convex hyporelief and concave epirelief.

Trace Fossil Site 3: 'Horseshoe Cove' - Boss Point Formation, Ward Point Member (45°36'17.05"N, 64°46'22.93"W; Log 3; Appendix 6, Figure 11,15)

Trace fossil Site 3 (Log 3) is located along the eastern shoreline of Cape Enrage between Cape Enrage and Mary's Point (Fig 4). The stratigraphic package at this locality can be subdivided into 5 sedimentary units (Fig. 15): a lower buff coloured medium-grained sandstone unit (Unit 1); a fine-grained, grey coloured, siltstone and fine grained sandstone unit that preserves abundant trace fossils such as *Diplichnites, Kouphichnium*, U-Shaped burrows and even a large *Arthropleura*-scale (19-25cm wide) *Diplichnites cuithiensis* trackway (Unit 2); a grey to red/maroon mudstone and siltstone unit (Unit 3);

a grey mudstone (Unit 4); and an upper medium to coarse grained sandstone with conglomerate beds unit (Unit 5) that caps the section and incises Unit 4.

Trace Fossil Site 4: 'Horseshoe Cove' - Boss Point Formation, Ward Point Member (45°36'18.35"N, 64°46'22.10"W; Log 4; Appendix 7, Fig. 11, 15)

Trace Fossil Site 4 (Log 4, Appendix 7) is 46 m thick, is located on the eastern side of Horseshoe Cove, and is stratigraphically equivalent to Trace Fossil Sites 3 and 5 (Fig. 15) with minor variations. Similar to Site 3 (Log 3), the section of Site 4 (Log 4) consists of 5 main lithological units. Unit 1 is a basal buff, medium sandstone (>3m). Unit 2 is a grey fine-grained sandstone, siltstone and mudstone unit that is rich with *Diplichnites, Kouphichnium* and U-shaped burrows (4.2 m). Unit 3 is a mostly grey siltstone/mudstone unit with localized red and mottled zones (6.6 m thick). Unit 4 is a 2.3 m thick mudstone with siderite nodules in the upper 1 m with small localized channel bodies. Unit 4 is incised by Unit 5 which is dominantly medium-grained, buff coloured sandstone that is about 30m thick.

Trace Fossil Site 5: 'Horseshoe Cove' - Boss Point Formation, Ward Point Member (45°36'24.38"N, 64°46'17.85"W; Log 5; Fig. 15, 16, Appendix 8)

Trace fossil Site 5 is located north of Horseshoe Cove, and can be divided into 5 main units, 4 of which are comparable to trace fossil sites 3 and 4 (Logs 3 and 4). Site 5 (log 5) is the longest measured section of the three Horseshoe Cove sites with ~47m of measured strata and mostly consists of buff colored sandstone. Although similar (with minor variations) to logs 3 and 4, the main difference can be found in unit 4 of this section. Unit 4 of Log 5 consists of grey mudstone with minor red beds, that alternate

between very fine grey sandstone and siltstone, with channel bodies that are comprised of medium to coarse sandstones. This unit preserves a unique terrestrial ichnofossil assemblage with plants preserved in life position.

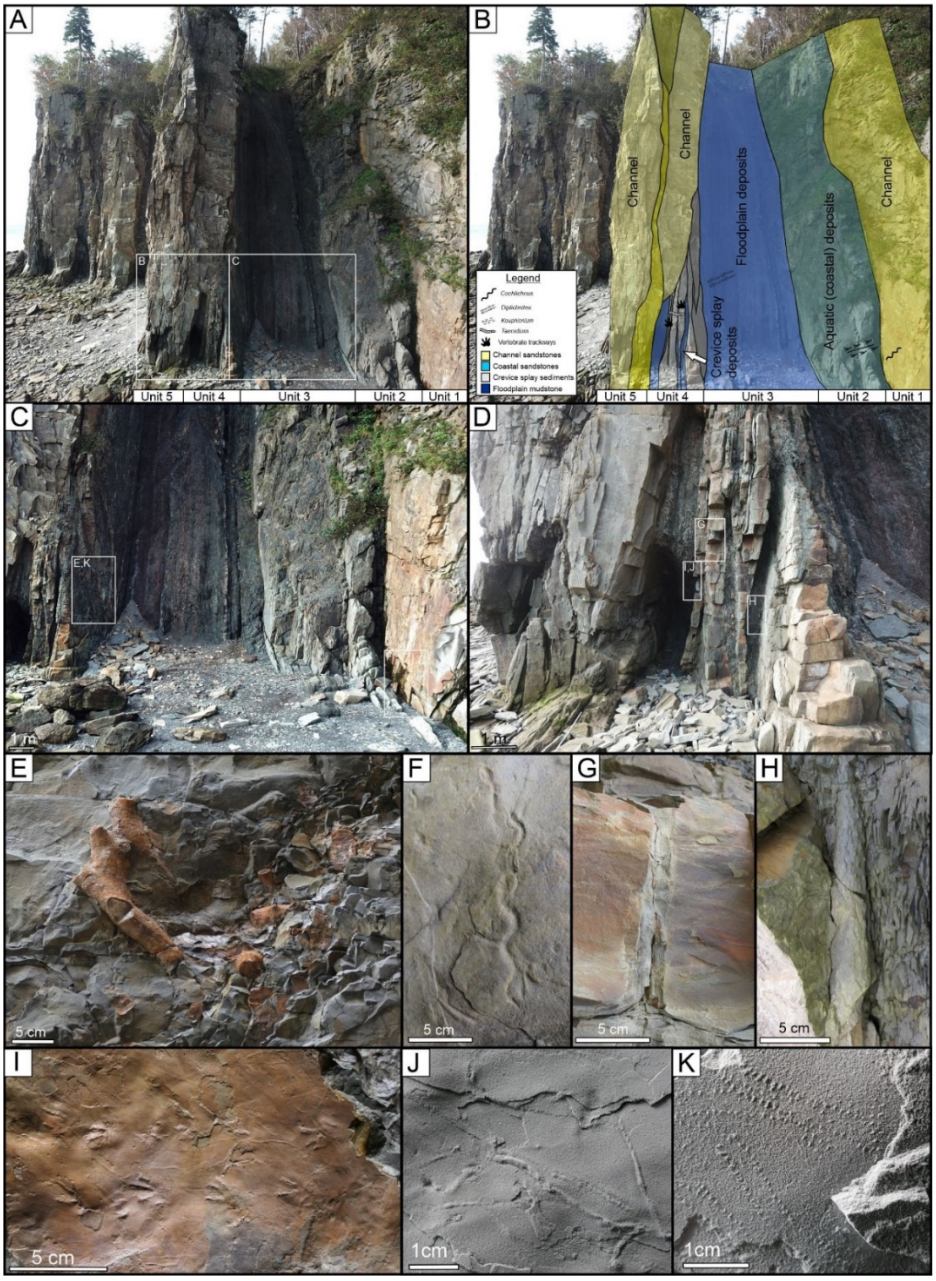


Figure 16. A) Photo of Trace Fossil Site 5 parallel to bedding. B) Annotated photo "A", showing sedimentary units and trace fossils. C and D) are close up photos of the site, showing the locations of images E to K. E) Siderite filled tubes, potentially *Thalassanoides* F) *Cochlichnus* burrows G) *Calamites* H) *Stigmaria* cast I) Tetrapod trackway (*Hylopus*) J) *Taenidium* K) *Diplichnites*.

Methods

Site Documentation

Stratigraphic logs were measured using standard meter sticks and the stratigraphy was described in the field using standard sedimentological descriptions. Extra detail was given to describe the beds in the vicinity of fossils being collected. The stratigraphic logs were hand drafted on millimetric scaled templates and then later converted to digital figures using CorelDraw.

A Mavic Pro drone was used to capture aerial photos of fossil sites for digital site documentation. Drone images were obtained perpendicular to sedimentary beds to show the differences in layers, as well as from a bird's eye view of the site. There were also photos taken at different angles of the site as well as different distances from the rocks.

Specimens were excavated and collected using hand tools such as chisels and hammers. The specimens were high graded in the field based on clarity, morphological variability, and completeness.

Lab Component

When brought back to the lab, the specimens were cleaned using a toothbrush and water to remove excess mud. Previously collected ichnofossils held at the NBM were selected in addition to new specimens, based on clarity and morphological variability so that the best examples of each morphology observed were selected for study. The selection criteria depended on size, clarity, and completeness of the ichnofossil in order to permit collection of data from the trace.

Specimens were coated in ammonium chloride to accentuate the vertical relief of the ichnofossils for specimen photography. Ammonium chloride is a fine white powder that is heated in a fume hood by a propane torch to above 338°. The heated ammonium chloride is sprayed on the sample using a specialized apparatus utilizing a quartzite drying tube and small air pump to plume the now gaseous ammonium chloride. When the sublimated ammonium chloride (gas) comes into contact with a colder medium (i.e. the fossil) the gas reverts back to a very fine powder which forms a temporary frost on the surface. This method has been used to mask colour variation in invertebrate body fossils (i.e. ammonites) in order to better examine the morphology of the fossil (Grabau and Shimer 1910, Ulriche and Bassler 1923, Teichert 1948). This technique was utilized on vertebrate tracks by Stimson et al. (2012, 2016a, b). For this project, the ammonium chloride helps to differentiate between shadows and highlights of otherwise very faint and hard to see trace fossil morphologies.

While coated in ammonium chloride, the specimens were photographed in low angled light (<45°). The low angled, raking light cast shadows against the whitened fossil surface highlighting the vertical relief. Neewer LED photography lights were used from the upper left and right corners of the rock. Digital photos were taken using a Panasonic - Lumix bridge camera and a Canon Rebel Ti8 camera. Images were taken as panoramic, overlapping sets in several rows which were themselves overlapped. These sequences of photos were then used to generate 3D models using digital software including Agisoft metashape to render the 3D model, Mesh Lab and Cloud Compare to scale and generate scalar fields of the vertical relief, and Paraview to contour and generate false colour relief maps of the trackway surface. This method is used to accentuate cryptic details that might

be missed with a camera and can be coloured with a colour gradient to show vertical relief on the specimen surface as well as omit camera distortion as the resulting image is a rectified orthographic 3D model. Photogrammetry and false colour relief techniques have been commonly used in the field of vertebrate ichnotaxonomy (Meade et al. 2016, Petti et al. 2008, Falkingham et al. 2018) and have been applied widely in Paleozoic rocks by Marchetti et al. (2019, 2020, 2021) and recently in New Brunswick by Allen et al. (2022). Figure plates of fossil sites and high-quality specimens were made using CorelDraw with the photographs mentioned previously.

Invertebrate repichnia ichnofossils are described utilizing the standard terminology of Trewin (1994) and Keighley and Pickerill (2003) and following the concept of major and minor morphological variability as explained by Minter and Braddy (2009). Measurements of traces were taken using the free digital software ImageJ. These measurements include inner and outer width of trackways, length of trackway and angle of track row series. Outer widths of common trackways (*Kouphichnium, D. incertipes, Protichnites* and *Stairia*) were graphed to visualize size ranges. The location where each specimen was found in the stratigraphic column was also recorded. Presence of ichnofossil types was then marked on the stratigraphic logs themselves (appendix 4-8). This helps tie the ichnospecies to a specific environment.

Systematic Ichnology

Systematic ichnology uses the same naming formula as biotaxonomy with trace fossils (ichnotaxa) being grouped into “ichnospecies” and “ichnogenera”, much like biological species and genera, with some key differences. Ichnology describes sedimentary structures created by organisms long ago; as such, it is difficult to correlate one ichnospecies to a specific biological species if the body fossil of the organism was not preserved alongside the trace. One animal may make a variety of different traces depending on behavior (such as walking, resting or burrowing), sediment type, water saturation of said sediment, and trackway degradation (paleo and modern erosion), and likewise, one type of trace can often be made by many different animals with similar walking appendages. Therefore, we give these traces their own names based on the morphology of the trace. These are known as “morphotaxa”, but are still governed by the international code of zoological nomenclature. After they are named, we can then give interpretations of their source.

This systematic ichnology section aims to describe the main ichnogenera and ichnospecies that this thesis focuses on, specifically the different walking trackway (repichnia) morphologies at Cape Enrage. It should be noted that other ichnospecies of infaunal burrows are commonly found at these fossil sites including the ichnotaxa *Helminthoidichnites*, *Arenicolites, Taenidium* and *Cochlichnus.* These ichnotaxa will not be considered for systematic description due to time constraints but will be utilized in the discussion below.

Ichnogenera and ichnospecies are listed alphabetically below, with the ichnogenus/ichnospecies diagnoses from literature, a description of the specimens found

at Cape Enrage, and a remarks section, which aims to explain the history of the ichnogenus/ichnospecies and why we have decided to use this name, as well as interpretations.

Table 1. Trackways identified at different stratigraphical horizons

Horizon	Trackways Identified	Extra, undescribed fossils noted:
1	*Diplichnites incertipes*	none
2	*Diplichnites incertipes, Diplopodichnus, Kouphichnium, Protichnites septanensis*	*Helminthoidichnites, Arenicolites, Cochlichnus, Undichna, Chondrites, Gordia*
3	*Diplichnites incertipes, Diplopodichnus, Kouphichnium, Protichnites septanensis, Stiaria*	*Helminthoidichnites, Arenicolites, Cochlichnus, Undichna, Augerinoichnus, Chondrites, Gordia, Treptichnites*
4	*Diplichnites incertipes, Diplichnites cuithiensis*	*Taenidium, stigmaria, Calamites* roots in situ.
5 (two rivers)	*Diplichnites incertipes*	none

Diplichnites Dawson 1873

D. cuithiensis Briggs et al. 1979

Fig. 17

Ichnogenus Diagnosis:

"Morphologically simple trail, up to 37 cm wide, consisting of two parallel rows of tracks, (each up to 11cm wide); width of opposed rows increasing on curves corresponding to greater lateral separation of individual tracks; each row may divide into two on acute curves due to lateral separation of the track rows; individual tracks elongate roughly normal to trail axis, spaced closely and regularly at as few as one per cm in large examples" (Briggs et al. 1984, p. 853).

Ichnospecies emended diagnosis:

Very large *Diplichnites*, with crescent impressions perpendicular to midline, arranged in track row series of up to >20 impressions. Track row series and therefore individual impressions of this ichnospecies often overlap, creating bifid or trifid shaped tracks shallowing towards axis of trail (emended from Briggs et al. 1979).

Description:

Only one sample from Cape Enrage was assigned to the ichnospecies *D. cuithensis*. The trackway is preserved in concave epirelief and shows two turning points on the 68.5cm long, 50cm wide and 7.5cm thick slab of rock (Fig. 17). The 80.5cm long trackway has an outer width that ranges from 19cm to 31cm with as little as 0cm spacing between tracks due to overstepping impressions and track row. The trackways have an inner width of up to 12cm. Impressions are mostly crescent and comma morphologies, that are elongated perpendicular to the midline, with some overlapping impressions creating the false impression of bifid or trifid track morphologies.

Track row width varies between 2cm (width of one impression) to 16cm along the trackway, with track rows being thicker at the trackway's turning points. Track row series

are not easily distinguished on this specimen due to overlapping of individual impressions as well as track row series and incompleteness of the trackway locally.

Remarks:

The ichnogenus *Diplichnites* was first named by Dawson (1873), who described the informal type specimen as *Diplichnites aenigma*. However, the type specimen has not been found, nor have replicas been submitted to museum collections, leaving only the original woodcut sketch from Dawson (1873), thus making this ichnospecies difficult to define. Briggs et al. (1979) erected a new ichnospecies (*Diplichnites cuithensis*), to replace Dawson's type ichnospecies due to its ambiguity. Briggs et al. (1979) describe Mississippian trackways from Scotland which have been more widely used in literature (Ferguson 1966; Briggs et al. 1984, 1986; Lucas et al. 2005; Schnieder et al. 2010; Prescott et al. 2014; Buckman et al. 2023).

Briggs et al. (1979) included the appearance of trifid impressions in the diagnosis of this ichnospecies, but this morphology was questioned by Prescott et al. (2014) who suggested that this imprint morphology was most likely due to the overlap of several appendage impressions. This ichnospecies has been known to have track row series that are not clearly visible unless the trackway is curved, in which the track row width widens, and the track row series begin to separate out (Briggs et al. 1984, 1986). When the trackway is straight, these track row series overlap, and the overlapping of individual impressions may often give a bifid or trifid shape, as opposed to the shape correlating to an individual impression.

This ichnospecies is interpreted to have been made from the giant myriapod *Arthropleura* (Briggs et al. 1979, Schnieder et al. 2010, Prescott et al. 2014, Davies et al.

2022), which has been noted in the fossil record to have existed between the Serpukhovian (Pendleian) (Davies et al. 2022) and the Early Permian (Schnieder et al. 2010), similar to this trackway, which has been found in in the fossil record between the Visean (Holkerian-Asbian) (Buckman et al. 2023) and the Early Permian (Schnieder et al. 2010). No other terrestrial arthropod is known from the Carboniferous Period with so many appendages, suggesting that the Cape Enrage specimen was likely made by a large *Arthropleura*.

There are multiple *Diplichnites* ichnospecies that describe similar trackways, and therefore the ichnogenus needs revision, however this is beyond the scope of this paper.

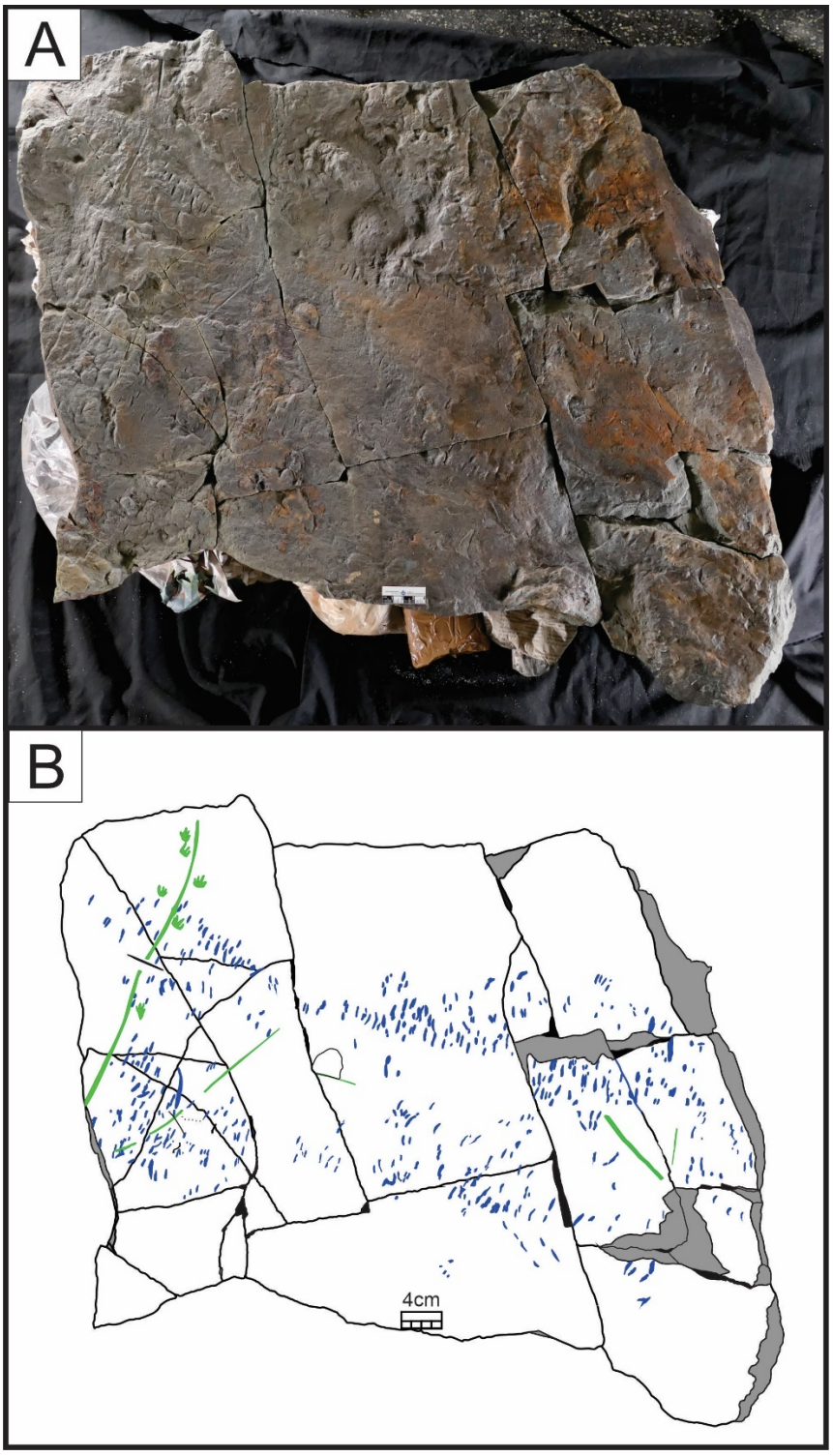


Figure 17. A) Image of *Diplichnites cuithensis* B) Sketch of image A showing individual *D. cuithensis* impressions (in blue) as well as other overlying traces such as a tetrapod trackway (green).

Diplichnites incertipies Matthew 1910

Fig. 18

Emended Ichnospecies diagnosis:

Two parallel rows of tracks containing V-shaped track row series angled towards the midline that include ~8 impressions in well preserved examples. They can be symmetrical or asymmetrical. Individual impressions are well separated, and morphologies vary between crescent, ellipsoidal, elongate, comma/tapered internal or S-shaped and are usually oriented perpendicular to the midline but can sometimes be oblique. Impressions are often punctate for smaller trackways. The ichnospecies does not possess a medial telson drag impression (emended from Matthew, 1910 and Pickerill, 1992).

Description:

Trackways contain two parallel rows of impressions of varying morphology including crescent, ellipsoidal, elongate, and comma/tapered internal, and are usually oriented perpendicular to the midline but can sometimes be oblique. Impressions are often punctate for smaller trackways, although overlapping track row series can cause imprints to appear “V” shaped (Fig. 18C). Outer widths range between 3 mm and 45mm, with most ranging between 4 mm and 6mm, while inner widths range between 0mm (with overlapping track row series on turns) and 17mm. The presence of track row series was a key factor in identifying these trackways. Track row series often contain 7-10 (most commonly 8) visible consecutive imprints and have an angle of 9.3-39° to the trackway midline with an average of 17.5 °. Imprints range from overlapping to 7mm distance between imprints.

Trackways are often asymmetrical with one side of the trackway showing separated track row series angled towards the midline and the other half of the trackway having overlapping track row series parallel to the midline (Fig 18 A). Trackway stride (distance between a repeated impression) ranges from 4 mm and 51 mm. *D. incertipies* do not include a medial drag impression (telson impression), as part of the ichnospecies diagnosis.

Remarks:

Diplichnites incertipies was first coined as the ichnogenus *Acripes* with several ichnospecies by Matthew (1910) and reassigned to the ichnogenus *Diplichnites* by Pickerill in 1992, who suggested all ichnospecies of *Acripes* be synonymized as junior synonyms into the senior synonym *D. incertipies*. *Diplichnites incertipies* is distinguished from other *Diplichnites* ichnospecies such as *Diplichnites cuithensis* by its V-shaped track row series containing ~8 impressions that are relatively separated, even within straight trackways, as well as evenly spaced impressions, compared to *Diplichnites cuithensis*, which have up to 27 impressions within a track row series, that often overlap, and are not usually separated unless the trackway is curved.

Diplichnites gouldi is an ichnospecies that has been noted in literature to resemble *D. incertipies* (Getty et al. 2017), with the only notable difference described by Matthew (1910) as *D. gouldi* being symmetric, while *D. incertipies* is asymmetric. Many of the observed specimens of *D. incertipies* from Cape Enrage show varying levels of asymmetry, usually shown as track row series being separated on one side of the trackway but overlapping on the opposite side. This is most likely due to the tracemaker

walking on an inclined plane and should therefore be considered a minor morphological variation, much like gait, and should not be used to separate ichnospecies (Getty et al. 2017, Minter et al. 2007). Getty et al. (2017) also noted that *Diplichnites gouldi* strongly resemble other *Diplichnites* ichnospecies as well, such as *Diplichnites cuithensis* (Briggs et al. 1979) and *Diplichnites triassicus*, and the ichnospecies is therefore in need of revision.

D. incertipies are similar to the ichnogenus *Protichnites* but do not show a telson drag. These may be made by the same animal as *Protichnites,* described below, as the two trackway types share all other features besides presence of telson drag. Telson drags have been shown to appear and reappear within singular trackways (Fig 19), opening the possibility of a telson being present, however not preserving a tail drag due to poorer preservation conditions, or the animal lifting its telson.

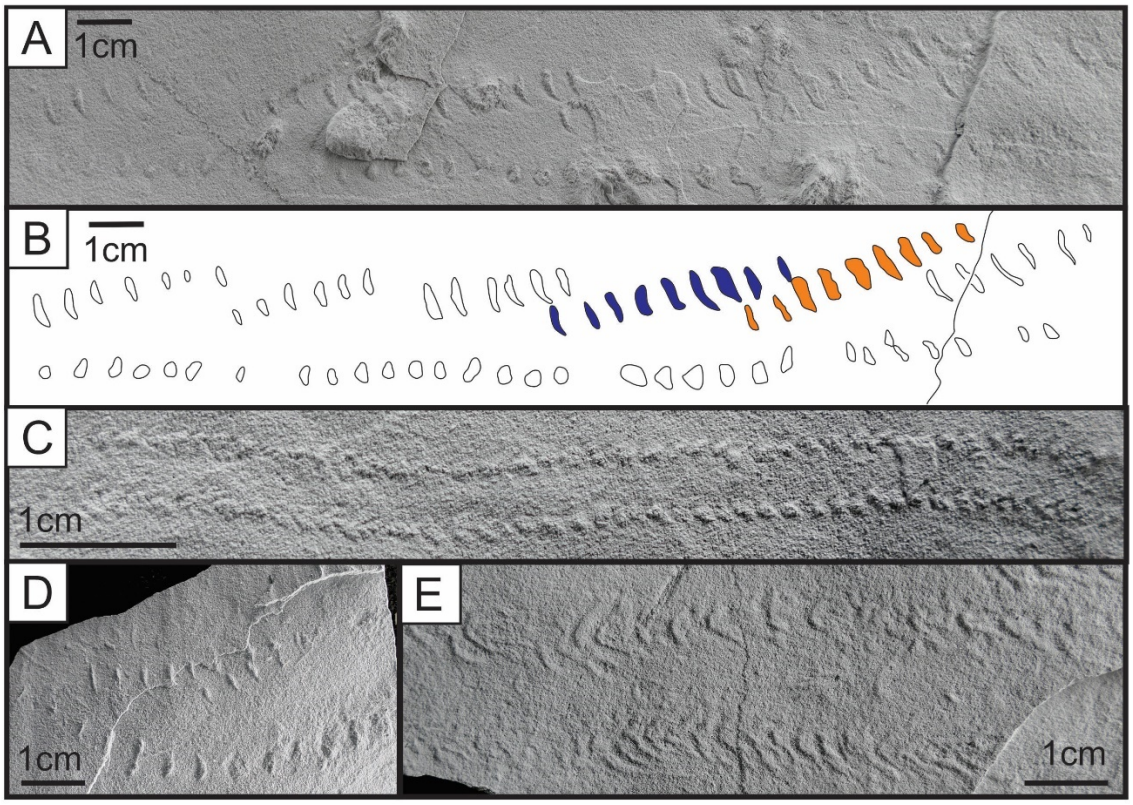


Figure 18 A) *Diplichnites incertipies* from specimen NBMG22626. B) Sketch of trackway A showing morphology and track row series. Two track row series where 9 imprints can be counted are coloured (blue and orange) to distinguish between the separate series. C) *Diplichnites incertipies* from specimen NBMG22626, showing overlapping track row series, making overlapping impressions appear "V" or "Y" shaped, which could be mistaken for the singular bifid impressions of a *Kouphichnium*. D) *Diplichnites incertipies* from specimen NBMG23052 showing separation of track row series at a turning point in the trackway. E) *Diplichnites incertipies* from specimen NBMG22623 through a microbial mat, causing ripples on the trackway surface to give a different trackway morphology.

Protichnites ichsp. Owen, 1852

Fig. 19

Ichnogenus Diagnosis:

Trackways of any external width possessing a single medial longitudinal impression (discontinuous or continuous) and a definite (integer) number of tracks per repeating track series sets, paired (i.e., opposing) across the midline (Owen, 1852).

Description:

Similar to the specimens of *Diplichnites incertipies* described above, the *Protichnites* trackways contain two parallel rows of imprints, divided into track row series. However, these specimens differ from *D. incertipies* with the presence of a drag mark near or at the midline of the trackway. The only specimen with clear enough track rows to count impressions was NBMG 22615 where 7 imprints can be counted. Individual impressions may be punctate, elliptical, crescent, elongate or comma internal. Track row series sometimes overlap, making the impressions appear V-shaped.
The outer width ranges from 3.5 mm to 28 mm, with an average of 8mm. Inner width ranges from 1-10mm with an average of 3 mm. Individual impressions range from overlapping to 6mm between impressions, with an average of 2mm between impressions. Most individual impressions range from ~0.5-2 mm in length/width, with a 1-1.5 mm average. Most track row widths are the widths of an individual impression, although these can reach up to 8.5 mm (in a 17 mm outer width trackway). Track row widths are especially larger at curved points in the trackway. Trackway stride ranges between 1 and 34 mm.

Remarks:

Protichnites was first described by Owen (1852) to describe a type specimen consisting of two rows of well-defined impressions, with a drag mark shown through the midline. Dawson 1873 coined the term *Protichnites carbonarius* to describe the first *Protichnites* ichnospecies from the Carboniferous. However, the type specimen used shows a trackway with changing morphology, part of which shows a clear surface imprint of a *Kouphichnium*. Archer et al. (1995) then erroneously described the ichnogenus *Protichnites* to resemble *Kouphichnium* with bifid and trifid impressions, the difference being that *Protichnites* exhibits a double medial furrow as compared to the single furrow of *Kouphichnium.* This morphological description for *Protichnites* had also not been used previously in literature, and Archer et al. (1995) did not officially amend the diagnosis, so we will be disregarding Archer et al's (1995) use of the ichnotaxon.

Owen (1852) incorrectly grouped 6-7 imprints together into chunks that did not accurately represent the true track row series which Burton (2010) would later regroup into more linear track row series, angled towards the midline, which resemble the track row series seen in the observed specimens at Cape Enrage.

Protichnites resembles *Diplichnites* in that it is a morphologically simple trail consisting of two parallel rows of impressions, the width of which increases on curves corresponding to greater separation of track row series. The main difference that separates *Protichnites* from *Diplichnites* is the presence of a telson drag. The *Protichnites* described here especially resemble the specimens of *D. incertipies,* for the reasons mentioned above, as well as having a similar number of impressions per track row series.

Collett (2012) created a conceptual illustration of arthropod body fossils found in Wisconsin and Quebec and related this animal to be a potential tracemaker for

Diplichnites and *Protichnites.* This animal possesses fewer legs than a myriapod, which aligns with the 7 impressions per track row series of *Protichnites*, as well as a telson that could create the drag mark seen in these specimens.



Figure 19 A) Trackway from specimen NBMG22657 showing a *Diplichnites incertipies* (starting from left) becoming a *Protichnites* at the far-right end with the added presence of a telson drag. B) Trackway from specimen NBMG22657 with visible track row series, especially near the far right. Telson drag is less obvious than in A, due to it overlapping the lower track row of the trackway.

Kouphichnium Nopsca 1923

K. lithographicum Nopsca 1923

Fig. 20

Ichnogenus Diagnosis:

"Oppositely symmetrical, heteropodous and highly variable tracks that consist of up to five impressions in a track row series. Impressions consist of bifurcating, trifid or

quadrifid, oval, or punctate impressions together with variable secondary morphologies; with or without a medial drag impression (modified from Hantzschel 1975; Minter and Braddy 2009)" (King et al. 2019, p. 8).

Ichnospecies diagnosis:

"Oppositely symmetrical, heteropodous and highly variable tracks that typically consist of a series of imprints, often arranged in an echelon fashion of up to five imprints on each side. The imprints consist of a chevron-like series, each of four imprints that may vary in morphology, including punctate, oval or bifid "V" or "Y" shaped impressions that sometimes exhibit bifurcations (also trifid or quadrifid; occasionally on both sides of the impression), scratches or irregular impressions of similar size to one another. Impressions are often parallel to the mid-line, with the bifurcation opening posteriorly. One pair of larger and more deeply impressed bifid or trifid impressions is similar to the smaller, medial proximal impressions and is spaced at regular intervals. With or without medial (continuous or discontinuous) drag marks (Hantzschel 1975; Minter and Braddy 2009)" (King et al. 2019, p. 8).

Description:

Trackways are preserved in both convex hyporelief or concave epirelief. Outer widths range from 5-31 mm, whereas inner widths range from none in trackways with overlapping track row widths, to 10mm. Two different types of imprints are consistently seen in these trackways. The larger imprints (pushers) are usually near the outer edges of the trackway, while the smaller imprints (pedipalps) sit between, closer to the midline. The relatively larger pusher foot impressions are bifid or "Y" shaped perpendicular to the

midline in well preserved specimens but can appear as circular or irregularly shaped in less well-preserved specimens. In these specimens, the pushers are identified by size, as they will be significantly larger than the pedipalp impressions. Pushers range from 1 mm to 13 mm in length, and 1 mm to 6 mm in width.

The pedipalp impressions are smaller and usually punctate or irregular in shape, and rarely more than 1 mm or 2 mm in length and width. Pusher impression width describes the distance between the middle of the large pusher impressions (King et al. 2019) and ranges from 4 mm-26 mm. The repeat distance of the pusher footprint ranges from 1 mm to 18 mm.

Telson drags, although not a defining feature of this ichnospecies (Caster 1938) are sometimes seen in trackways. Many trackways show appearances and disappearances of this drag mark within individual trackways due to preservation changes or layer changes.

Remarks:

The ichnogenus *Kouphichnium* was originally erected as an ichnogenus by Nopsca (1923), who reassigned the previously named *Ichnites lithographicus* as *K. lithographicum.* There are currently 15 recognized species of *Kouphichnium*: *K. aspodon* (Aldrich and Jones 1930), *K. didactylus* (Willard 1935; Caster 1938), *K. scotti* (Caster 1938), *K. arizonae* (Caster 1944), *K. gracilis* (Linck 1949), *K. variabilis* (Linck 1949), *K. walchi* (Malz 1964), *K. rossendalensis* (Hardy 1970), *K. minisculum* (Actenolaza 1978), *K. cordiformis* (Fischer 1978), *K. fernandez* (Romano and Melendez 1985), *K. pentapodus* (Erickson 2005), *K. liulinensis* (Shu et al 2018), *K. minkinensis and K. atkinsoni* (King et al 2019). Many of these ichnospecies names are suspected to be junior

synonyms of each other, and they are therefore in need of revision (King et al. 2019), although this is beyond the scope of this thesis.

Many interpretations have been made of the perceived tracemaker for *Kouphichnium,* with the most accepted being xiphosurans (horseshoe crabs) by Caster (1938). Horseshoe crabs have 10 walking appendages in total, two being larger, "pusher" appendages and the remaining 8 being smaller pedipalp appendages. This corresponds well with the pusher and pedipalp impressions we see in *K. lithographicum* examples. Horseshoe crabs are also known to have existed throughout the fossil record from 480 million years ago to today. Modern horseshoe crabs are also known to be able to raise their telson while traversing (Caster 1938), which could give another explanation for the inconsistent appearance of telson drags in *K. lithographicum.*

The *K. lithographicum* specimens described here show multiple different morphologies (Fig. 20), some of which do not show perfect "Y" shapes. They are nonetheless categorized as *K. lithographicum*, based on the idea that these are most likely underprints, as well as because of the other *Kouphichnium* ichnospecies being in need of revision, as mentioned above. The majority of the focus was placed on whether or not the trackway contained two different types of imprints, one larger, near the outer edges resembling a "pusher" imprint, and other smaller, pedipalp imprints.

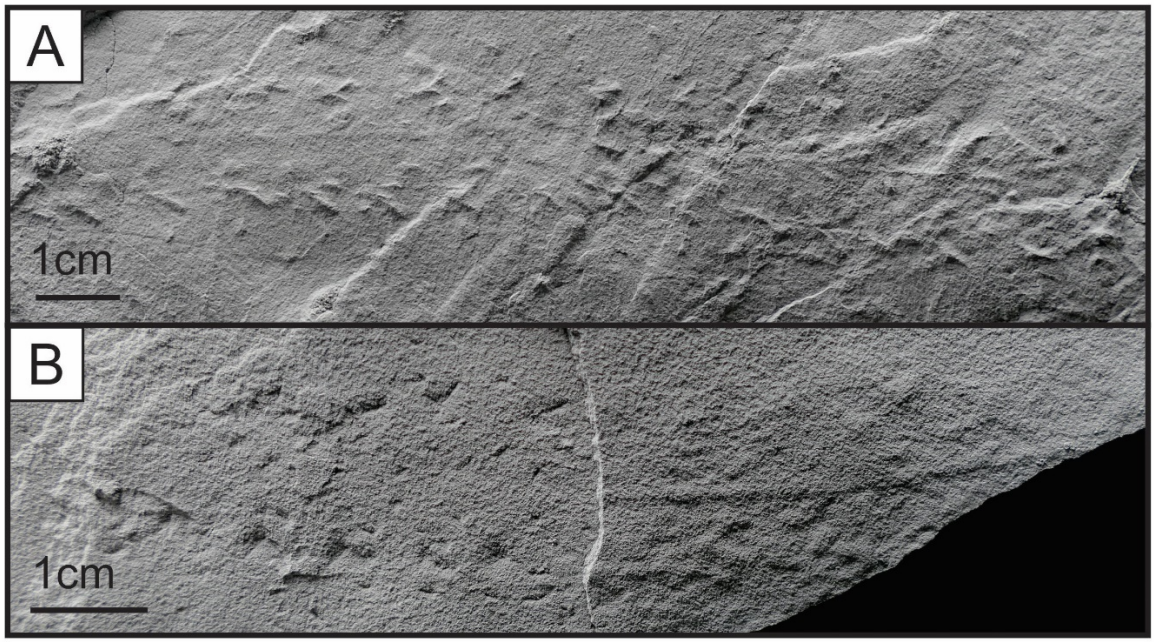


Figure 20. A) *K. lithographicum* trackway on specimen NBMG22765. B) *K. lithographicum* trackway shown crossing through two different layers of rock, changing morphology with the change in layer. Specimen NBMG23163.

Stiaria ichsp. Smith 1909

Fig. 21

Ichnogenus Diagnosis:

"A trackway consisting of a single groove between two rows of imprints which occur in groups of two to four. These groups are set transversely or obliquely to the midline of the trackway" (Walker 1985 p. 290).

Description:

Stiaria trackways contain two parallel rows of imprints divided into groups of three, with opposite symmetry, but are too short to be true track row series. Despite not being true track row series, these groups of three imprints are the most distinctive feature of this ichnospecies. The distance between these groups of imprints ranges from 2.5 mm to 11 mm.

These trackways also usually show a continuous telson drag mark near or at the midline of the trackway. Imprints are usually punctate but can be elongated, crescent, scratch or bifid. The imprint sizes range from 0.5mm in diameter for punctate impressions, to 5 mm long, 0.5 mm wide scratch impressions, usually oriented parallel to the midline. The outer width of the trackways ranges from 7.5 mm to 26 mm. Inner width ranges from 0.5 mm -8 mm. Track row widths range from 2.5 mm -11 mm.

Remarks:

Stiaria was first named by Smith (1909) and later revised by Walker (1985) to include a medial telson drag in the ichnogenus diagnosis. Similarities between *Stiaria* and *Paleohelcura* have been noted in the literature, however Walter (1985) described *Stiaria* as having the potential to have more tracks per set than *Paleohelcura* as well as a greater variety of arrangements of impressions within a set. Buatois et al. (1998) also noted that the arrangements impressions of *Stiaria* show opposite symmetry, while *Paleohelcura* show alternating symmetry. This is one of the main reasons the specimens described here fit *Stiaria.* Although this is a distinctive difference, Getty (2013) noted that symmetry can change with gait, suggesting both traces may have the same tracemaker.

Stiaria have been associated with archaeognathan insects, due to co-occurrence and direct association with the body imprint *Tonganoxichnus* (Buatois et al. 1998, Lucas et al. 2005, Minter and Braddy 2006, Minter and Braddy 2009, Buta et al. 2013, Getty et al. 2013), as well as archaeognathans being the only hexapod known to display opposite symmetry in trackways (Manton 1977, Getty et al. 2013). However, another possibility could be that the *Stiaria* identified at Cape Enrage are underprints of *Kouphichnium* trackways, due to their similarity to "*Protichnites*" described by Dawson (1872) that were

poorly preserved *Kouphichnium* specimens. Goldring and Seilacher (1971) described underprint fallout of *Kouphichnium* and noted that with depth, trackway resolution was reduced leaving only the deepest portions of the impressions. It is possible that the *Stiaria* specimens described herein are the deepest portions of the *Kouphichnium* tracks, akin to digitigrade trackways of tetrapods where only the tetrapod's digit tip (arthropod appendage tips in this case) is preserved. Figure 21 A shows a *Stiaria* that includes imprints on the top half of the trackway that appear to be similar "Y" shapes as seen in *Kouphichnium*, further supporting this interpretation.

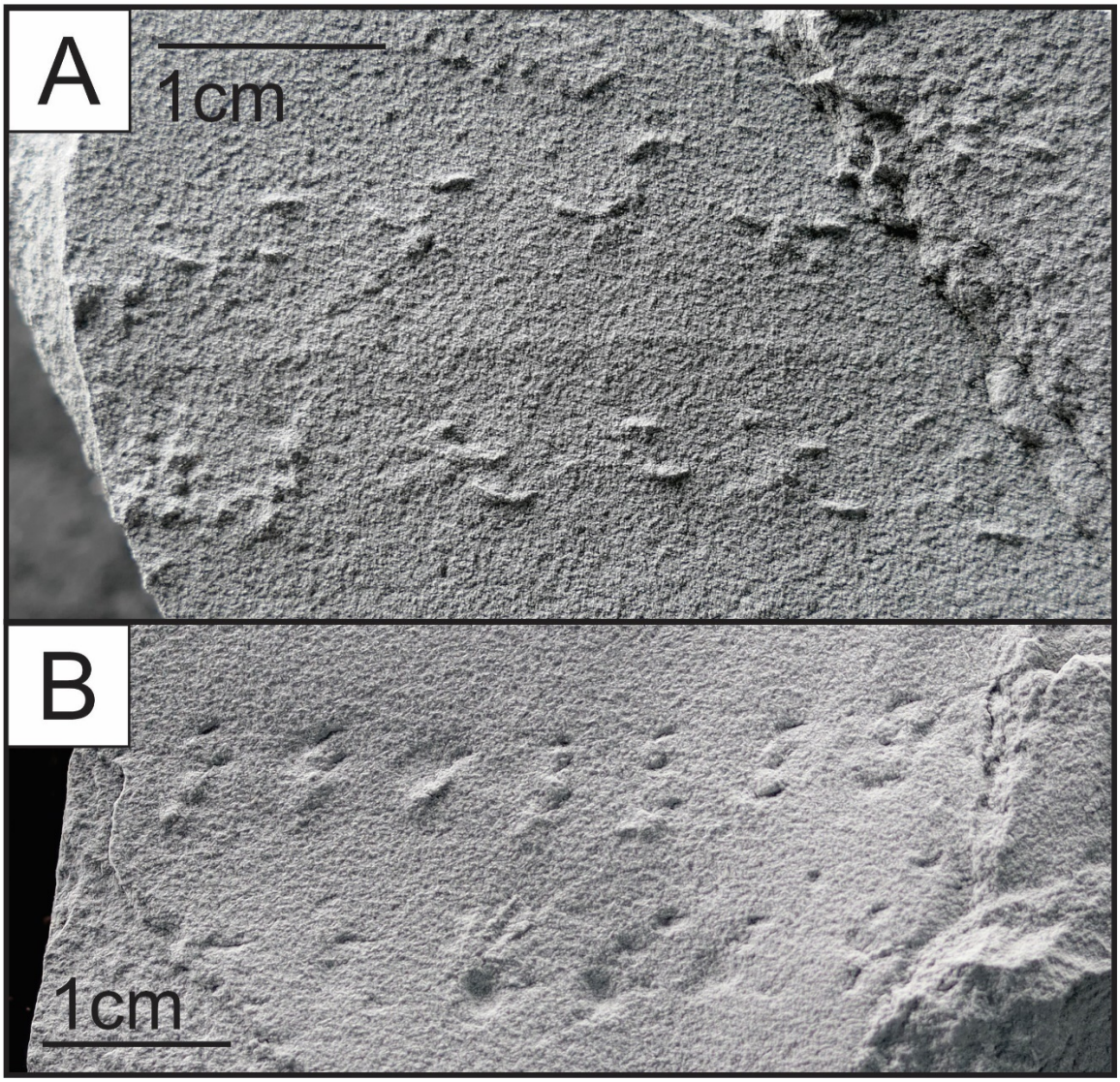


Figure 21. A) *Stiaria* trackway on specimen NBMG23093 showing scratch impressions parallel to midline, with a telson drag impression. B) *Stiaria* trackway on specimen NBMG23077 showing no telson drag impression.

Diplopodicnus Brady 1947

D. biformes Brady 1947

Fig. 22

Ichnogenus Diagnosis:

"Elongate, straight to gently winding, paired furrows (in concave epirelief) or paired ridges (in convex hyporelief). Furrows well-spaced, separated by a distance equal or greater than the width of the individual furrows. Furrows ornamented with indistinct striae or punctate markings (modified from Brady, 1947)" (Keighley and Pickerill 1996, p. 276).

Ichnospecies diagnosis:

"As for emended ichnogenus" (Keighley and Pickerill 1996, p. 277).

Description:

Trackways consist of two parallel continuous grooves. Out of the 7 specimens measured, most are relatively small, with outer widths of 6 specimens ranging from 4-5 mm, inner widths of 1.5 mm-3 mm, and track row widths of 1 mm-1.5 mm. One slightly larger trackway measures 15 mm outer width, 4.5 mm inner width and 4.5 mm track row width.

The grooves often do not differ in width along the trackway or show clear distinction between individual impressions. Occasionally, when they do, the grooves have a slightly "bumpy" texture (Fig. 22 A), where the track rows may increase and decrease in width or elevation at a regular distance (~0.5 mm for 1 mm -1.5 mm wide track rows). These trackways may also include a larger imprint, at a regular distance, that can be used to indicate stride, which ranged between 8 and 15mm for the four specimens where stride could be measured.

Remarks:

The name *Diplopodichnus biformis* was coined by Brady (1947) to describe traces from Arizona consisting of a continuous double groove, with part of the description being

the absence of individual impressions. This, however, is not entirely accurate as Brady (1947) did note faint individual imprints in his description of *D. biformis* from Massachusetts. Keighley and Pickerill (1996) later emended the diagnosis to two grooves separated by a distance equal to or greater than one groove width, to better distinguish the ichnospecies from *Didymaulichnus.*

Potential tracemakers for *D. biformis* include millipedes or small beetles (Brady 1947), but more recent literature interprets these traces to be underprints of *Diplichnites,* or traces of similar tracemaker origin through soupy sediment, causing individual imprints to merge together into a continuous track row groove. This can be seen in Figure 22 B, where a *Diplopodichnus* trackway changes morphology into a *Diplichnites* trackway.



Figure 22. A) *Diplopodichnus* trackway from specimen NBMG23255, showing two continuous grooves. Slight changes in width can be seen throughout these grooves, in the form of small "bumps", however individual impressions cannot be made out. B) From left to right: *Diplopodichnus* trackway changes morphology into a *Diplichnites* trackway after a change in sedimentary layer on specimen NBMG22704.

Selenichnites Romano and Whyte 1987

Selenichnites rossendalensis **Hardy 1970**

Fig. 23

Ichnogenus Diagnosis:

"Shallow, sub-oval traces occurring as isolated or in a series. Traces are semi-lunate in morphology and are generally slightly wider than long, with a rounded anterior margin and are strongly convex (in hyporelief) or concave (in epirelief) lunate or are paired crescent-shaped lobes directly anterolaterally with or without scratch marks and an anterior ridge (Romano and Whyte 2015; Buhler and Grey 2017)" (King et al. 2019, p. 16).

Description:

Large crescent shape impressions ranging from 11 mm to 23mm in width and 8 to 17mm in length. These crescent shapes sometimes include an elongated (telson) imprint (Fig. 23).

Remarks:

The ichnogenus *Selenichnites* was coined by Romano and Whyte (1987) who later further divided *Selenichnites* into more ichnogenera (Romano and Whyte 2015); however, King et al. (2019) suspected these subdivisions to be "extra morphological variants", and therefore in need of revision, which is beyond the scope of this thesis. *Selenichnites* has been associated with *Kouphichnium* trackways (Romano and Whyte 1987), as well as *Cruziana* and *Dendroidichnites (*King et al. 2019). The ichnogenus has widely been interpreted to be a resting trace of a xiphosuran, or horseshoe crab, which has buried its head shield into the sediment, leaving a crescent shape trace (Hardy 1970; Romano and Whyte 1987; Lerner and Lucas 2015; Buhler and Grey 2017), much like

modern day horseshoe crabs do today, but they have also been interpreted to be made by trilobites (Gibb et al. 2011, King et al. 2019).

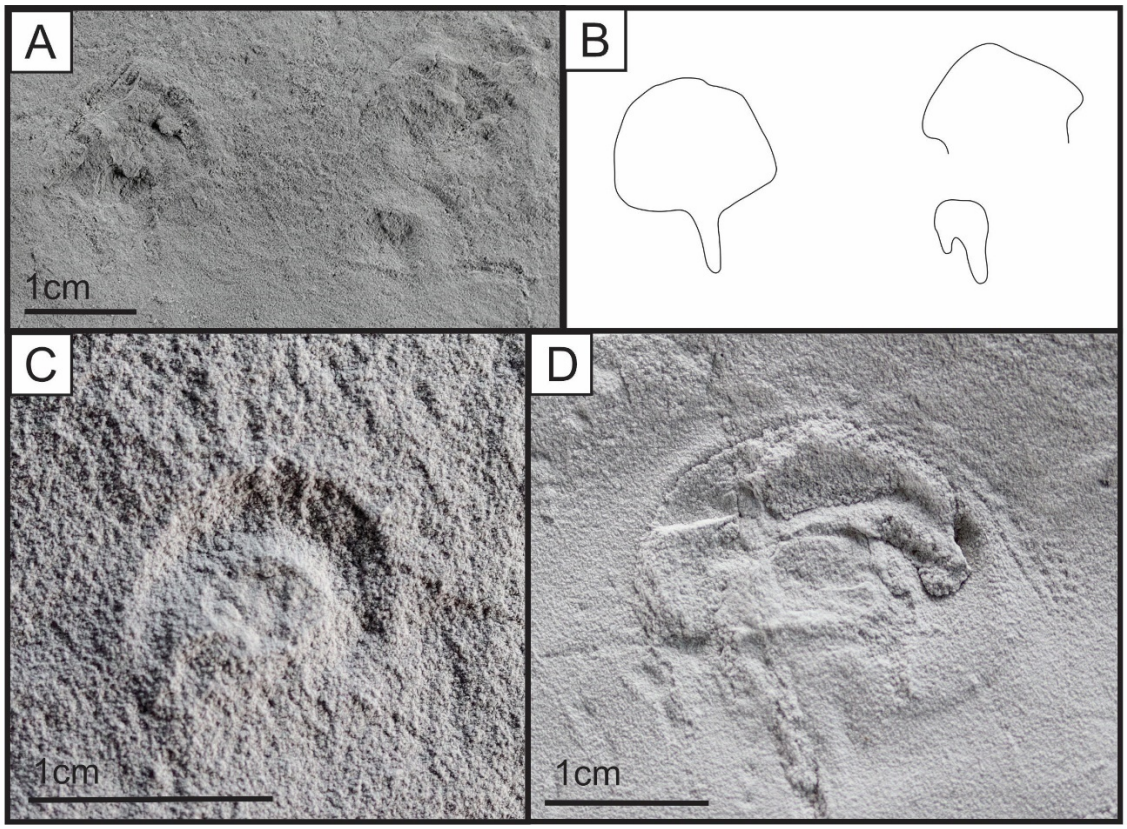


Figure 23. A) Three *Selenichnites* imprints from specimen NBMG22690. B) Rough sketch of A, showing locations of traces. C) *Selenichnites* imprint from specimen NBMG22730. D) *Selenichnites* imprint from specimen NBMG22632.

"Eurypterid resting trace"

Fig. 24

Referred specimens (Material): NBMG22657

Description:

A roughly bilaterally symmetrical impression is preserved in concave epirelief at the end of an invertebrate trackway identified as *Palmichnium mcdonaldi*. The trace is

comprised of one large bilaterally symmetrical oval impression that is blunt and rounded on one side (interpreted to be anterior) and tapers on the other side (interpreted to be posterior) into an elongated impression. The oval impression has a maximum length and width of 22 mm and 8 mm respectively, and an aspect ratio of 2.75. Projecting from both the right and left elongated sides of the oval, in roughly the mid-point are two lateral traces that project perpendicular to the long axis of the oval and acutely recurve posteriorly, with the distal end of the curved back towards the midline, but do not cross or come in contact with the medial oval impression. Both perpendicular and recurved impressions are similar but asymmetrical.

Remarks:

Unlike *Selenichnites,* this trace contains multiple parts, the largest being longer than wide, whereas a *Selenichnites* usually shows a singular large crescent shape, usually wider than it is long. This trace resembles that of a eurypterid body, specifically *Adelophthalmus,* which is known to have lived in the Carboniferous (Waterston 1968). No eurypterid resting trace fossils have been named to date in literature, but nonetheless this trace will not be given a new name in this thesis, as only one specimen of this type has been found, and although proof of eurypterids has been found within Atlantic Canada from the Carboniferous period (Dawson 1863,1894; Matthew 1888), no eurypterid body fossils have been found from Cape Enrage. Therefore, despite interpreting this resting trace as that of a eurypterid the official taxonomic assignment will be left in open nomenclature until more information is found on the topic.

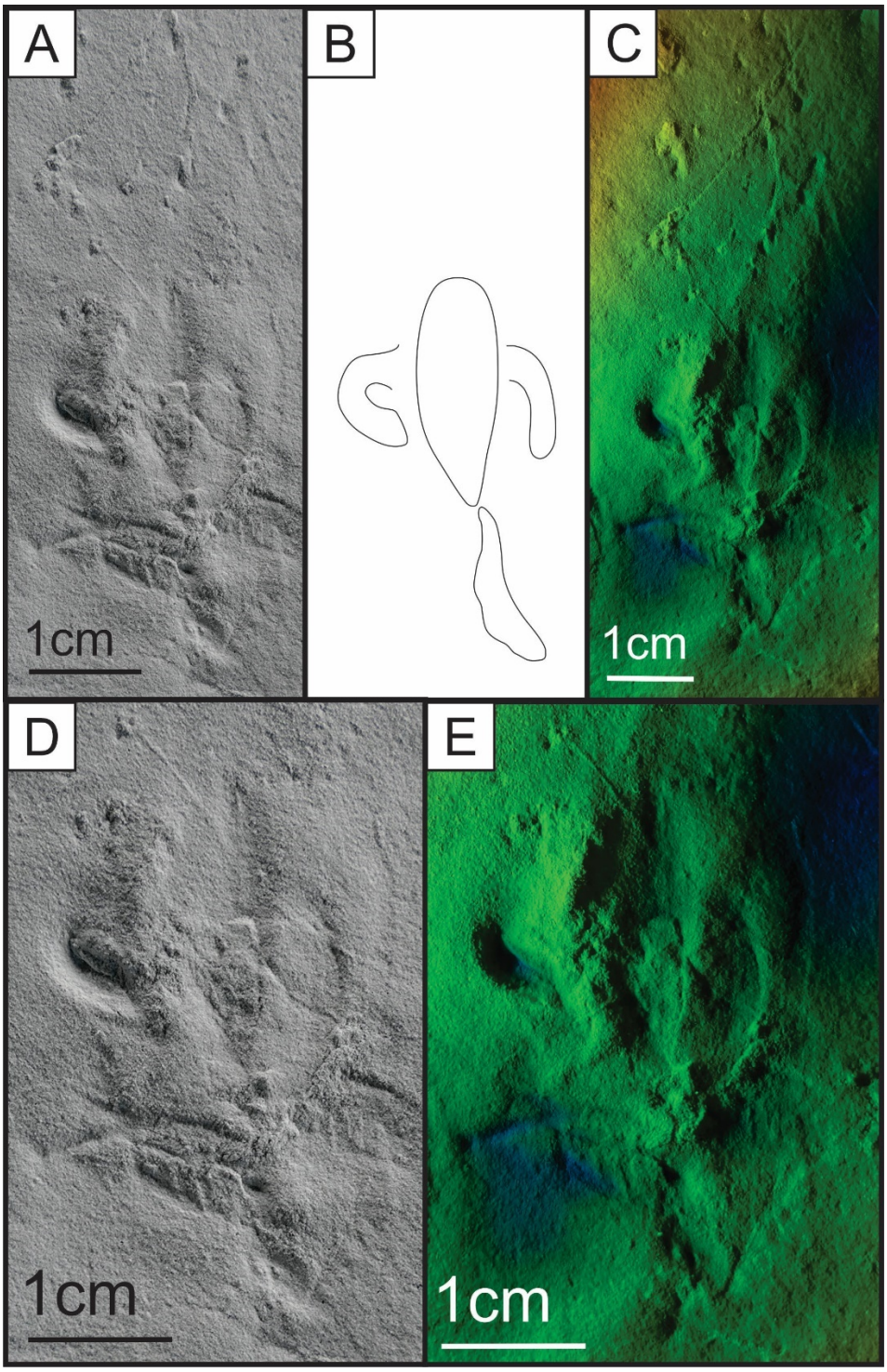


Figure 24. A) An interpreted eurypterid resting trace at the end of a *Palmichnium mcdonaldi* trackway from specimen NBMG22657. B) Sketch of interpreted eurypterid resting trace. C) 3D model of image A. D) Zoomed-in image of euryptid impression from photo A. E) 3D model of image D.

Numerical Results

An interesting difference can be seen in the outer widths of *D. incertipies* between the two horizons where *D. incertipies* were most commonly found (Fig 25, 26). For Horizon 2, the size range for *D. incertipies* was relatively consistent, resembling that of a bell curve, with the most common outer width being 6.5 mm - 8 mm, and fewer outer widths being found further from this range (Fig. 26). Horizon 3, however, showed two visible groups of size ranges: a relatively large proportion of trackways measured were extremely close to a 5 mm outer width, while another proportion showed outer widths of around 20 mm to 24 mm (Fig. 25, 26). While a larger size range is expected for the larger sample size collected (n=451 for Horizon 3, n=76 for Horizon 2), the unique part for Horizon 3 was how few *D. incertipies* were found ranging from ~8mm to 13mm in outer width.

Unfortunately, statistics cannot be reasonably run on this data to show precise significance values of these ranges, as samples were not collected randomly. Samples were collected based on quality, usually corresponding to morphology and clearness of trackway, and may therefore contain human bias. However, it is an interesting detail worth noting, as this size range could be due to differences in life stages for the trace maker. This will be expanded on within the discussion section.

Other common trackways did not show this same phenomenon. *Protichnites* trackways were more common at the smaller end of the outer width range, although the larger end contained very few trackways, and did not show the same split range as *D. incertipies* in Horizon 3 (Fig. 27). Both *K. lithographicum* and *Stiaria* outer width ranges

resemble a bell curve when graphed, with most trackways being near the middle of the size range, becoming less common at either end (Fig. 28, 29).

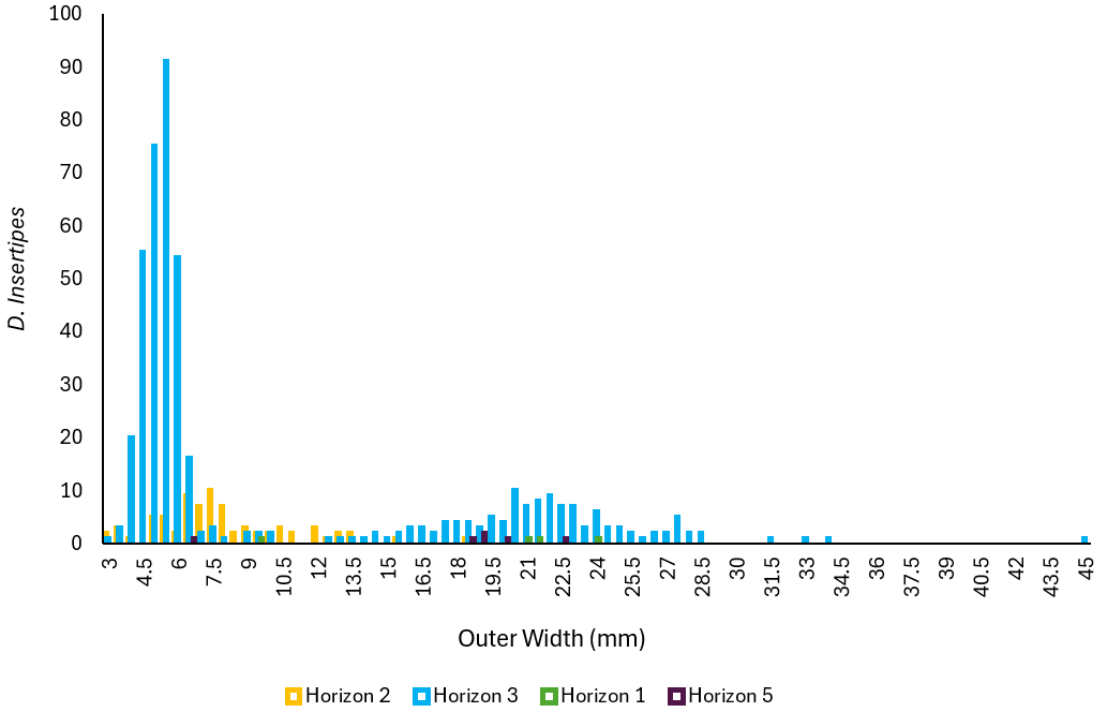


Figure 25. Bar graph showing numbers of trackways by outer widths (mm) for *D. incertipes* trackways at four different stratigraphic horizons at Cape Enrage.

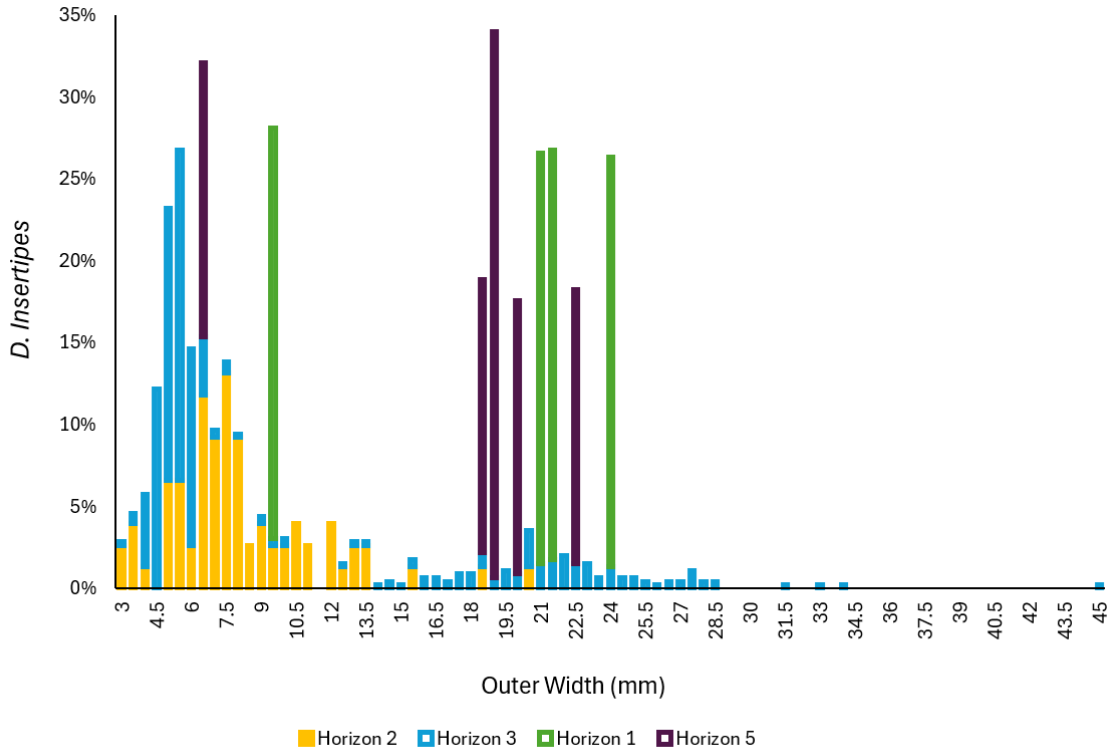


Figure 26. Bar graph showing percentages of *D. incertipes* trackways of different outer widths (mm) within each stratigraphic horizon.

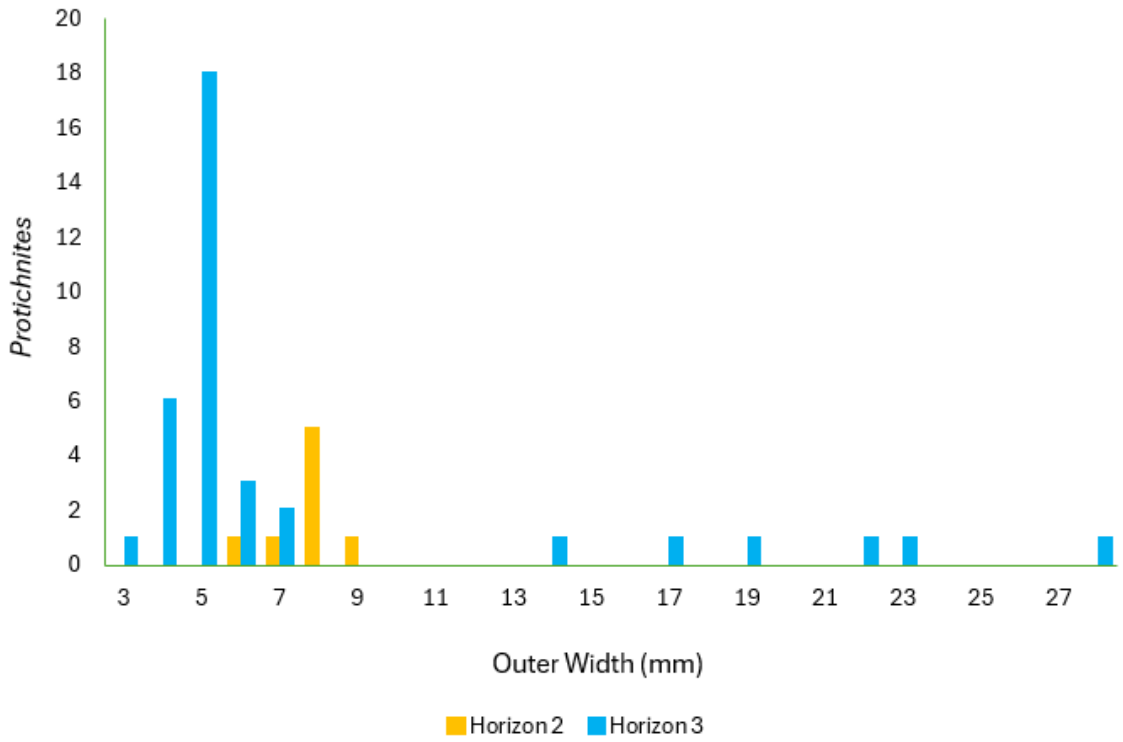


Figure 27. Bar graph showing outer widths (mm) of *Protichnites* trackways at two different horizons at Cape Enrage: yellow representing the Horizon 2 of site 2 and blue representing the Horizon 3 of informally named "Horseshoe Cove" (sites 3 and 4).

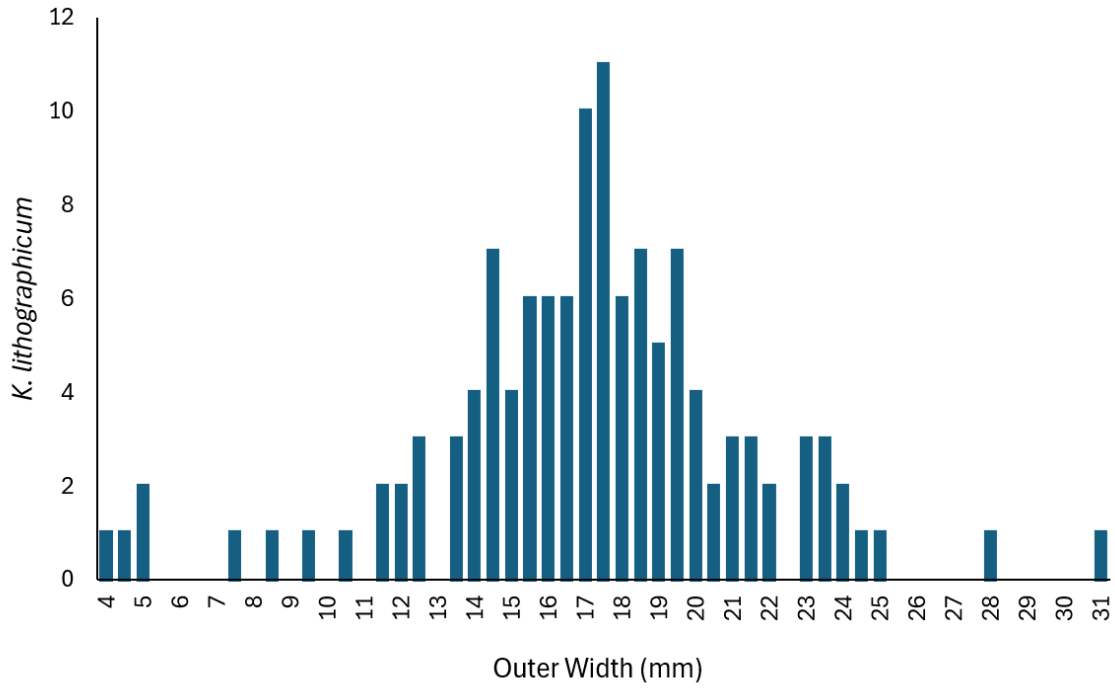


Figure 28. Outer widths (mm) of *K. lithographicum* trackways.

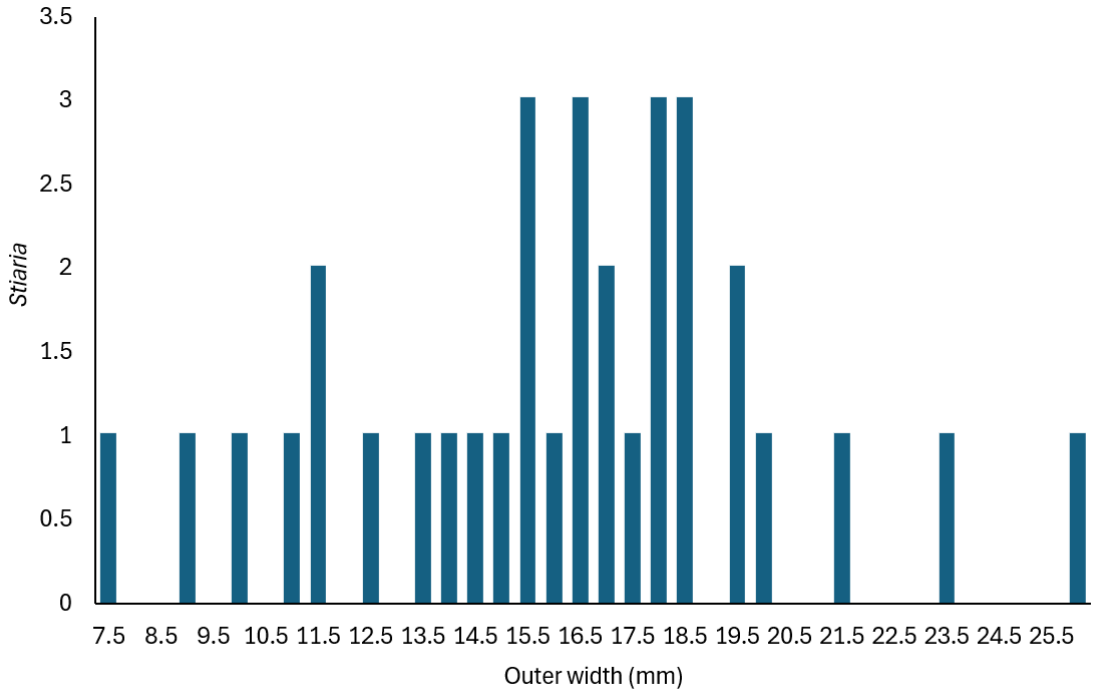


Figure 29. Outer widths (mm) of *Stiaria* trackways.

Discussion

Although we often cannot tell exactly what trace maker was responsible for making a trace fossil unless a body fossil has been preserved at the end of a trackway, we can compare unknown trackways to similar trackways found both in the fossil record and from the current day, to draw conclusions and interpretations of potential trace makers.

Trace makers:

Diplichnites cuithiensis has widely been interpreted to have been made by the giant myriapod, *Arthropleura* (Briggs et al. 1979, Schnieder et al. 2010, Prescott et al. 2014, Davies et al. 2022), especially traces with large widths, such as the trackway described in this thesis. *D. cuithiensis* also possesses track row series with up to 23 impressions (Getty 2017), indicating 23 pairs of walking legs, which would correspond to that of the *Arthropleura* (Trewin and McNamara 1994).

The *Arthropleura* would have been the largest known terrestrial arthropod during the Carboniferous, with lengths of up to 2.6m and widths of up to 55cm (Davies 2022), while *D. cuithiensis* have been found with widths of up to 47cm (Pearson 1992; Whyte 2018). One 36cm wide *D. cuithiensis* trackway was found in early Carboniferous strata in England by Davies (2022) within the same regional sedimentary succession as a large *Arthropleura* body fossil and they are therefore interpreted to be correlated.

Evidence suggests that *Arthropleura* would have lived in terrestrial forested environments (Pearson 1992, Lucas et al. 2005, Schneider et al. 2010, Getty et al. 2017, Pearson and Gooday 2019, Davies et al. 2022) and they are often found in similar environments associated with tetrapods (Falcon-Lang et al. 2006, Martino and Greb

2009, Schneider et al. 2010, Minter et al. 2016, Getty et al. 2017, Dernov 2019, Davies 2022). *Diplichnites cuithiensis* are often found in similar environments as described above (Pearson 1992, Whyte 2018, Davies 2022), despite trace fossils and body fossils having different ideal preservation environments.

One of the main ways *Diplichnites incertipes* is distinguished from *D. cuithiensis* is its track row series. The track row series of *Diplichnites incertipes* contain ~8 impressions, which is far less than the >20 impressions per track row series that *D. cuithiensis* is known for. The difference in size, although prominent in this study, is not a good distinguishing feature for ichnotaxonomy (Bertling et al. 2006, Buatois and Mángano 2011), as sizes of trackways can vary based on the age of the trace maker, as well as sexual dimorphism, or general size variation between individuals. The difference in track row series, however, can give us a good indication of how many pairs of appendages the trace maker would have used for walking, meaning the trace maker for the *D. incertipes* likely had at least 9 walking appendages, as 7-9 impressions have been counted for track row series. The trace maker could easily have more appendages than impressions in track row series, as most trackways are likely underprints to some level, and therefore may only show the deepest impressions made. Track row series impressions are therefore more reliable as a minimum number of walking appendages, as opposed to an exact amount, although the number is likely close. It should be noted however, that this assumes that the track row impressions are made by walking appendages, which may not always be the case, as impressions can also be made by dragging of the carapace, or other parts of the body as we commonly see with telson drag impressions.

Diplichnites trackways have also been interpreted as trackways of trilobites (Crimes 1971, Getty 2017), but evidence of rivers throughout the Boss Point Formation, including Horizon 1, where *D. incertipes* is commonly found, suggests that this is an unlikely trace maker for these trackways. Trilobites are known to inhabit marine environments (Fortey 2014), likely requiring a higher salinity than the more brackish environment that is interpreted as the depositional setting for these strata.

Another trace maker possibility for *Diplichnites incertipes* are eurypterids, but the only known eurypterid from the Carboniferous is the *Adelophthalmus,* which has four pairs of walking legs, as seen in Figure 30. If the track row series of *D. incertipes* show impressions made by walking appendages, that would be too few to match these 7-9 impressions. Although track row series may not always correspond directly to pairs of legs (as mentioned above), the depth, consistency and organization of these imprints make it unlikely to be a drag impression. At this point, more research and data would be needed to make a confident interpretation of the specific trace maker of *D. incertipes.* Despite not knowing the specific trace maker, it can be assumed that *D. incertipes* trackways found at Cape Enrage are made by the same animal as *Protichnites,* as the two trackway types share all other features besides presence of tail drag. Tail drags have been shown to appear and reappear within singular trackways (Fig 19), opening the possibility of a telson being present for *D. incertipes* trace makers, yet this telson rarely creates a tail drag due to poorer preservation conditions, or the animal lifting its telson out of the sediment while walking. *Diplopodichnus* is another example of morphological variation from *D. incertipes* as seen in Figure 22 and is therefore likely made by the same trace maker.

Kouphichnium traces, including *K. lithographicum*, are widely interpreted as being made by xiphosurans (Caster 1938, 1944; Linck, 1949; King et al. 2019) or horseshoe crabs, which have existed from the late Ordovician period (~445 million years ago; Rudkin et al. 2008, Gradstein et al. 2020) until present. Evidence of horseshoe crabs from the Pennsylvanian Carboniferous period have been commonly found throughout Atlantic Canada (Copeland 1957, Calder 1998, Falcon-Lang et al. 2006, Falcon-Lang and Miller 2007, Buhler and Grey 2017, Stimson et al. 2010). Since there has been little evolutionary change from Carboniferous xiphosurans to present day horseshoe crabs, it can be assumed that they would have inhabited similar environments as today. Present day horseshoe crabs are known to have a wide salinity tolerance, however there are still limits to this range. Laughlin (1983) interprets this salinity tolerance range as allowing them to survive changes in ocean salinity over time, but that their ability to survive in drastically different salinity environments means that although they may inhabit brackish waters, they would not survive a strictly freshwater environment. This contradicts Plint and Browne's (1994) interpretation for the Boss Point Formation being strictly lacustrine and fluvial sediments. Horseshoe crabs are known to migrate towards beaches, and occasionally travel upstream into brackish waters to mate and lay eggs, but they would still require access to open ocean (Button 2010).

Selenichnites is also interpreted to have been made by horseshoe crabs (Hardy 1970, Romano and Whyte 1987, Lerner and Lucas 2015, Buhler and Grey 2017, King et al. 2019) although, instead of representing a trackway, *Selenichnites* is interpreted to represent a resting trace, where the horseshoe crab may have stopped walking and dug

itself into the sand, leaving a large crescentic or semi-circular, horseshoe-shaped imprint in the sediment.

Stiaria trackways have previously been interpreted as being made by archaeognathan insects, however, the interpreted marine environment of the horizons these trackways were found in would not be suitable for this trace maker. It is more likely that this trackway represents an underprint, or different morphological form of a *Kouphichnium* trackway, and was made by horseshoe crabs, unless this trackway was made by a trace maker not yet known in literature. More research would need to be done to form a more confident interpretation of this trackway.

The only trace specimen described in this study that has not been assigned a name is the interpreted eurypterid resting trace (Fig. 24, 30). This resting trace does not fit the description of other known resting traces of similar time periods and environments in literature, such as *Selenichnites*, as previously described, and appears to take the shape of a eurypterid, more specifically, *Adelophthalmus*. There are no currently named eurypterid resting traces in literature, therefore we leave this specimen in open nomenclature while noting that it may represent a new ichnotaxon.

Eurypterids are an extinct order of arthropods known to have existed from the Ordovician period (Lamsdell et al. 2015) to the end-Permian (Poschmann 2022). The only known eurypterid from the Carboniferous period is the genus *Adelophthalmus*. As seen in Figure 30, an *Adelophthalmus* fossil described by James Hall (1884) is shown with five pairs of appendages, four of which are interpreted to be used for walking and one of which is often enlarged into swimming paddles.

A side-by-side comparison of an *Adelophthalmus* (Hall 1884) specimen and the interpreted eurypterid imprint from Cape Enrage is shown in Figure 30. The larger oval in the resting trace shows a similar shape to the eurypterid body, with the anterior side (prosoma) being flatter than the elongated anterior end, which appears to become a telson imprint. The four walking appendages are not visible on the resting trace; however, two relatively large, curved imprints can be seen extending from the "body", which resemble the swimming legs in Figure 30B. Evidence of eurypterids has been found within the Carboniferous Maritimes including fossilized cuticles, found in Joggins (Dawson 1863,1894) and Fern Ledges (Matthew 1888). Eurypterids are also known to inhabit a wide range of habitats, including both freshwater and marine (Braddy 2001), further supporting this interpretation of them being a potential trace maker for this resting trace.

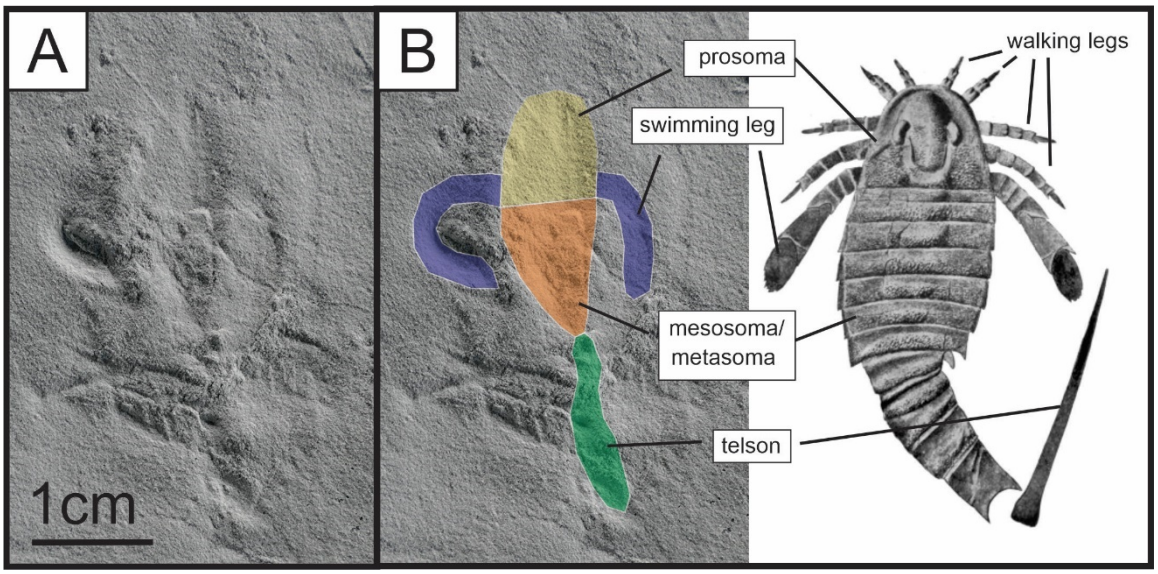


Figure 30 A) Interpreted eurypterid resting trace on specimen NBMG22657. B) Rough sketch of interpreted eurypterid body parts correlated with parts of resting trace, with fossil specimen of *Adelophthalmus* (Hall 1884) for comparison.

Biostratigraphy

Trace fossils were categorized based on horizon instead of fossil site, since this gives a better indication of a change of environment. Distinctive beds of sandstone are continuous though sites 3, 4 and 5 and therefore represent the same stratigraphic horizon. Beds of different stratigraphic horizons, however, show vastly different sedimentary features fossils, and ichnofossils which are interpreted to represent different depositional environments, for instance, from a muddy, low energy floodplain shown by flat beds of mudstone to a high energy riverbed shown by coarse grained trough-bedded conglomerate. A few sequentially stacked layers of sediment can represent many years of time, and therefore, large changes in depositional setting.

It should be noted that biodiversity is not directly correlated with ichnodiversity, as multiple ichnospecies can be made by the same tracemaker. This is seen above with trackways that change morphology based on preservation, for example *Diplopodichnus* becoming a *Diplichnites* trackway as seen in Figure 22B. This can also be seen by tracemakers showing different behaviours, such as the walking trace (*Kouphichnium*) and resting trace (*Selenichnites*) both interpreted to be made by horseshoe crabs. It can also rarely be stated with confidence what animal may have made what trace fossil unless the body fossil is shown at the end of the trackway. However, we can use such examples (known as mortichnia, or “death march” (Seilacher 2008)), such as horseshoe crabs found at the end of *Kouphichnium* trackways (Lomax and Racay 2012), to help solidify interpretations of these trace fossils, and use these trace fossils to help create a clearer picture of ancient geological environments.

Horizon 1 (Fig 31, 32)

Horizon 1 is represented by the stratigraphy of trace fossil site 1 (see Figures 6,7 and 8). This horizon represents a low energy river system and is the environment that best matches that described by Browne and Plint (1994), since they describe much of the Boss Point Formation as made up of fluvial sediments and interpret a portion of the formation to represent low energy rivers. Trace fossils we see from this site are exclusively *Diplichnites incertipes*. Unfortunately, *Diplichnites incertipes* does not give us more information on the environment of this horizon, as we do not have a confident interpretation of the trace maker of this trackway. However, the lack of *Kouphichnium* trackways at this site is noticeably different from Horizons 2 and 3 described below and could be due to this Horizon representing a paleoenvironment that was too far upstream and high energy for horseshoe crabs to occupy since, as stated earlier, horseshoe crabs are not likely to be found in fully freshwater environments such as rivers.

Horizon 2 (Fig 31, 32)

Horizon 2 represents the stratigraphy of trace fossil site 2. The beds of this site are predominantly sandstone containing prevalent interference ripples. Interference ripples show no singular direction of water motion, indicating movement of water in multiple directions, which is common for coastal, bay areas as opposed to unidirectional movement of water in rivers (although freshwater rivers could have added influence to motion of coastal water). The abundance of these ripples indicates an aquatic environment shallow enough to be affected by continuous surface level wave action. Tidal rhythmites have also been noted from this site, indicating rhythmic tidal conditions

(Williams 1991, Kvale 2003), which supports the interpretation that this environment was either marine, or at least affected by tidal action, as opposed to being a large freshwater lake.

Trace fossils of this horizon include the trackways *D. incertipes, Diplopodichnus, K. lithographicum* and *P. septanensis.* Similar to horizon 1, despite being the most common trackway identified, *D. incertipes* and with it, *Diplopodichnus,* and *P. septanensis* (as these have been interpreted to be made by the same trace maker), cannot give us much information on the environment of this horizon, as we do not yet have a clear idea of the trace maker responsible for these trackways. *K. lithographicum* however is widely known to be associated with horseshoe crabs, which are known to breed on beaches during high tides (Rudloe 1980). This supports the interpretation that the sediments deposited at this horizon were deposited within a bay area and is further strengthened by the fact that horseshoe crabs are not known to inhabit freshwater. The tidal rhythmites, as well as the prevalent interference ripples, also indicate a shallow, marine, bay environment.

Horizon 3 (Fig 31, 32)

Like Horizon 2, this horizon shows tidal rhythmites, as well as an abundant amount of *Kouphichnium* trackways, indicating a similar bay area. However, this horizon is made up of finer-grained siltstone/shaley beds and lacks the same prevalence of ripples that is seen in Horizon 2. This indicates a lower energy environment, likely a similar bay, but slightly further from shore, deep enough for surface level waves to not have strong effects on the sediment, allowing sediment of smaller grain size to settle.

The trackway assemblage of this horizon is similar to that of Horizon 2, showing *D. incertipes, Diplopodichnus, K. lithographicum* and *P. septanensis* with the only added difference being presence of *Stiaria.* The *Stiaria* in this context, however, will be assumed to be underprints of *K. lithographicum,* as this would be the wrong environment for archaeognathans. Although in this thesis I am not describing burrow traces, it is worth noting that, of all the fossil horizons, the burrow assemblage is largest in this horizon, and most notably includes *Augerinoichnus,* which is known to be associated with tidal flat settings (Minter et al 2008, Voigt et al 2021).

Due to the large numbers of trackways collected from this horizon, trends in size ranges of trackways were easier to see. When measuring outer widths of *D. incertipes* trackways, it was observed that this horizon showed a large proportion of *D. incertipes* with an outer width of around 5 mm, a lower proportion of trackways at around 20 mm - 24 mm, and few to no trackways with an outer width in between these two groups (Figs. 25, 26). Two possible explanations for this size division could be, firstly, that the site may be near a breeding site of the trace maker, and the two size groupings are two separate stages of the trace maker's life: young, newly hatched stage, and an older, mature stage, where fully developed members of the species return to their place of birth to lay eggs , which would be similar to the reproduction cycle seen in horseshoe crabs (Rudloe 1980). This would explain the size distribution seen, specifically the relatively large number of trackways on the smallest end of the size range, as the majority of juveniles would not reach adulthood to return to the breeding site, as well as the lack of trackways found with a size in between the interpreted juvenile and mature size, as the animal would not have reason to return to the breeding site unless it has reached maturity.

An alternate explanation could be that the graph may show two separate animal species creating similar looking *D. incertipes* trackways of two different sizes. To make a more confident interpretation would require further research and data.

Horizon 4 (Fig 31, 32)

Horizon 4 contains no tidal rhythmites and is interpreted to be a terrestrial environment due to the presence of *D. cuithensis*, widely interpreted to be made by the giant *Arthropleura*, which is known to be a terrestrial arthropod. The horizon also contains abundant fossilized *Calamites* and lycopod roots preserved in life position, which further supports this terrestrial interpretation.

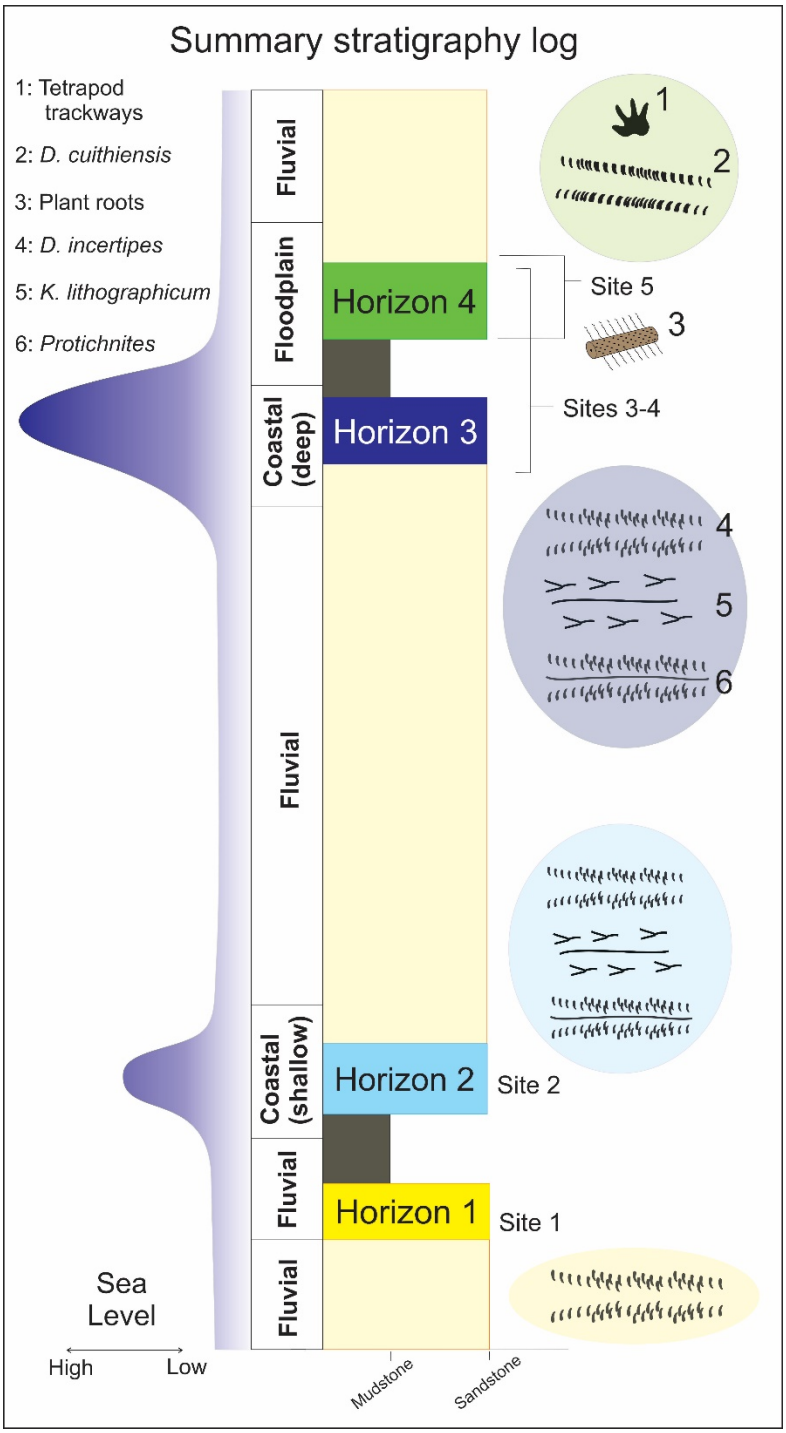


Figure 31. Summary stratigraphic log showing horizons relative to each other (not to scale), and geologic structures and trackways found at each horizon, as well as relative interpreted sea level at the period of each horizon.

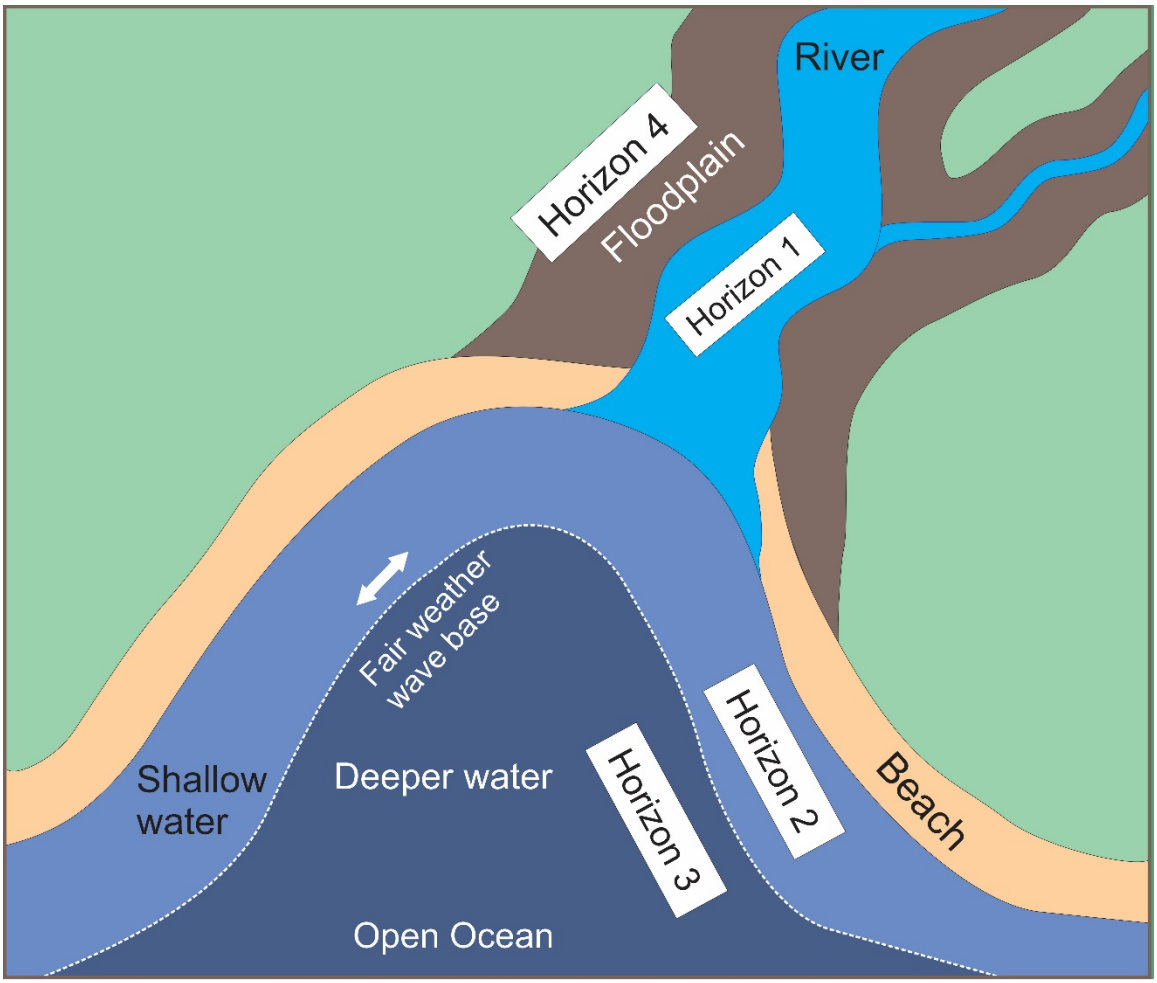


Figure 32. Sketch showing interpreted paleoenvironments of each of the four horizons listed in Figure 31.

Conclusion

The most common trackway found at Cape Enrage was *Diplichnites incertipes.* Unfortunately, since the trace maker for these is unknown, they could not be used for interpretation of environments. However, certain other trackways were able to change our interpretations of some environments and help paint a picture of rising and falling of sea levels which would not have been considered were it not for the ichnofossils found, and the implications of the presence of the interpreted trace makers concerning the environment. An example of this is the ichnogenera *Kouphichnium* and *Selenichnites*.

Without having found any animal body fossils at Cape Enrage, we were able to interpret certain environments as habitats of horseshoe crabs due to the presence of both *Kouphichnium* and *Selenichnites* ichnofossils. This then challenged previous literature on the Boss Point Formation which had interpreted the sediments as coming from strictly fluvial sources such as lakes and rivers. By looking at the habitats and salinity tolerances of horseshoe crabs today, we were able to assume the area must have had at least some contact with the ocean, and after this, we were able to choose stratigraphic horizons to research in detail, leading to us finding more evidence of these habitats being marine, such as the presence of tidal rhythmites.

Are ichnofossils a reliable source of information on paleoenvironments and their biodiversity? Though this is highly variable to each fossil site, and ichnobiodiversity will rarely correlate to biodiversity, it can however help give insight, and clues to environments that may not have been previously considered, with this study being a perfect example. I therefore suggest ichnology should more often be considered in future studies of paleontology and paleontological environments. One animal will only have one (or very few in the case of molting) chance to create a body fossil, which can then be transported to a new environment after death, but ichnofossils will always be preserved in place, and are often far more abundant than body fossils, such as the case at Cape Enrage. I conclude that it is beneficial to take advantage of this, to help paint a richer paleontological picture of ancient environments.

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Appendices

Appendix 1: Halokinetics in the Cumberland Subbasin

Waldron and Rygel (2005) and Waldron et al. (2013) interpreted extensive seismic surveys of the Cumberland Basin in Nova Scotia. They concluded that the Athol syncline seen in Cumberland County, Nova Scotia is the result of extensive salt withdrawal of Windsor Group evaporites below the Joggins Fossil Cliffs and surrounding area. This withdrawal sourced the salt-diapirs in the Minudie Anticline including those that are mined by 'Sifto-Salt' in Maccan Nova Scotia. The rapid down-warping strata from the salt evacuation at depth allowed for accommodation space at surface for the deposition of 7-9 km of strata deposited during the Langsettian (Bashkirian) (Waldron and Rygel 2005, Waldron et al. 2013, Craggs et al. 2015).

In New Brunswick, similar halokinetic salt evacuation can be observed in the Cape Enrage area. Recent mapping by Park and Hinds (*In Preparation*) has demonstrated that secondary salt welds are present along an unnamed "fault zone" west of Cape Enrage (Fig. 5). Exposed in outcrop along the coast near Owls Head, the strata of the Boss Point Formation are juxtaposed against Mississippian Hopewell Cape Formation along a salt weld in the Harvey Hopewell Fault (Fig. 5). Inland, in the Long Marsh Creek Fault zone, enclaves of entrained Windsor Group limestone have been preserved within the fault zone where the evaporites have long been removed by dissolution giving the appearance of a fault zone along a secondary vertical salt weld (Park and Hinds 2024 – *In Preparation*). The vertical strata at Cape Enrage are the result of down-warping in the basin center and the diapirism further to the west, as well as involving asymmetric

folding verging eastward, producing the folds and shallow-dipping cleavage seen across the zone from Owls Head, Munson Pond and Cape Enrage (Park and Hinds 2024 – *In Preparation*) (Fig 5).

Comparison to previous literature

Horizons 1 and 4 support Browne and Plint's (1994) interpretation of the Boss Point Formation's paleontological environment being largely fluvial, with Horizon 1 representing a low energy river system with some evidence of possible estuary conditions, and Horizon 4 likely representing a vegetated floodplain. However, both Horizons 2 and 3 suggest a tidally influenced, likely coastal open water environment, which has not yet been considered for the Boss Point Formation.

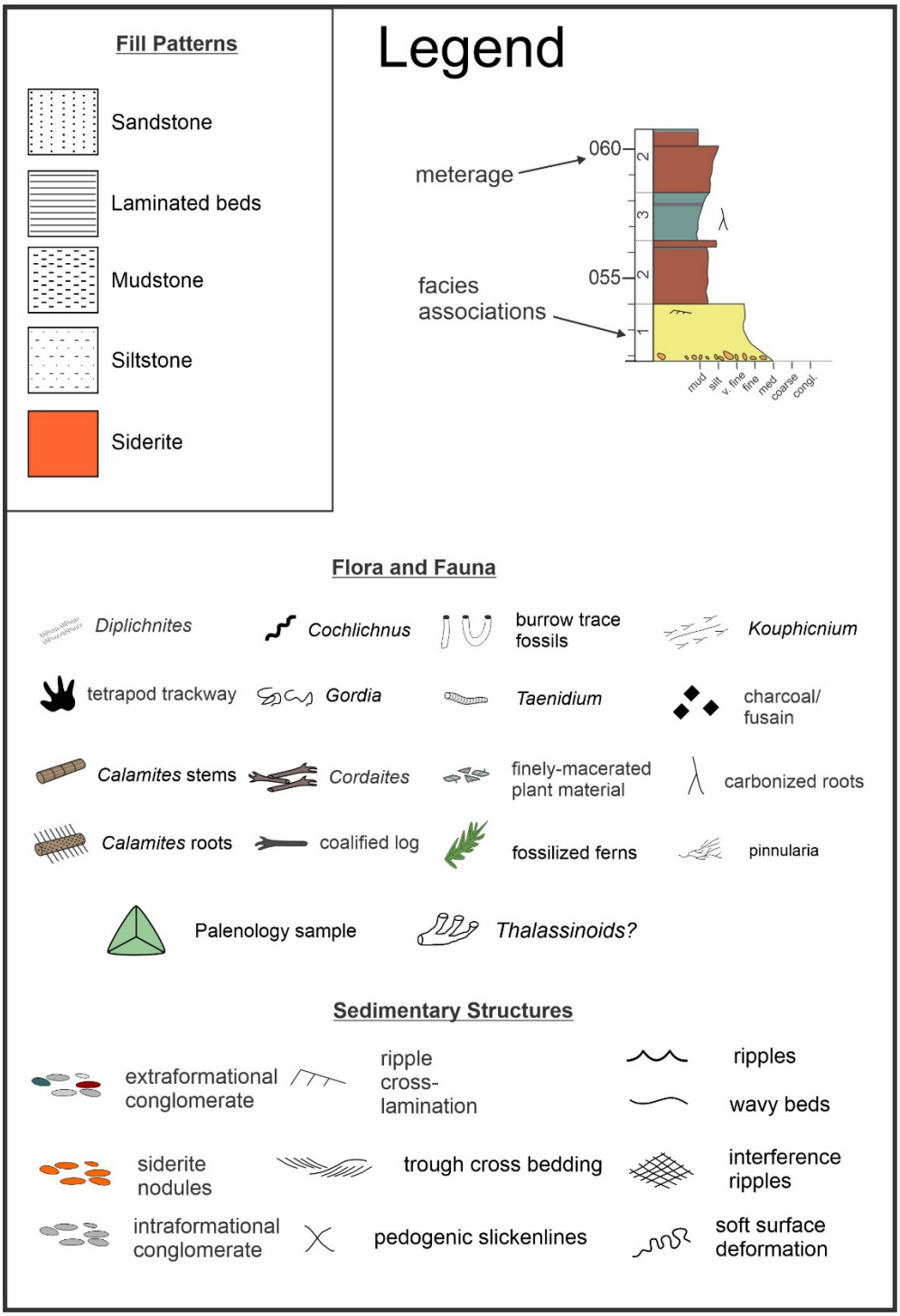
Sea level changes from the late Mississippian to early Pennsylvanian have been attributed to changes in glacial-interglacial periods (Belt et al. 2011) and can provide an explanation for the changes in environment seen at Cape Enrage. Interglacial periods are the likely explanation for the marine paleoenvironments seen at Cape Enrage, with the melting of glaciers causing a rise in sea level dramatic enough to cause an area to change from a river system, such as that seen in Horizon 1, to a beach (Horizon 2), and an even a relatively deeper marine habitat (below the fair-weather wave base; Horizon 3). Periods of glacial formation would then take up large enough large amounts of water to lower global sea level, allowing for previously marine habitats to become dry again, as seen by the transition of Horizon 3 into Horizon 4.

Appendix 2: Boss Point Formation (Nova Scotia)

The four main lithologies that describe the Boss Point Formation in Nova Scotia are major channel bodies, open water facies association, poorly drained facies association and well drained facies association. Channel bodies refer to a sedimentary structure created after a channel of water is infilled with sediment. As mentioned previously, major channel bodies are described by Rygel et al. (2015) as being over 4m thick and are very common, mostly composed of sandstones and calcite cement (Rygel et al. 2015), making up 60% of the Boss Point Formation. Open water facies are associated with calm, fresh to brackish water, and make up far less (2%) of the total formation (Rygel et al. 2015). These intervals range from 1.5-9.1 m thick and are composed of greyish-black to grey mudrock, often containing siderite nodules and black organic-rich limestones. Poorly drained facies are interpreted as being made in anoxic swampy environments in low-lying areas. The facies are often found above multistory channel bodies and are identified by the green/grey mudrocks and often contain siderite nodules and preserved vegetation such as *Calamites*. The beds are up to 2 m thick and make up 5% of the total Boss Point Formation of the area. “Well drained facies” can be distinguished by Rygel et al. (2015 p. 18) from poorly drained facies by their reddish colour due to the oxidation of iron after drainage, matching the conditions of interpreted floodplains. These facies make up 17% of the Formation’s thickness and consist of mainly mudrocks with grain sizes ranging from silty claystone to siltstone. The lithologies show alternating fluvial, floodplain, and potentially brackish bays/lagoon environments with occasional and often regional changes of water level, speed of flow and oxygen levels throughout the Boss Point Formation of Nova Scotia (Rygel et al. 2015, Ryan and Boehner 1995).

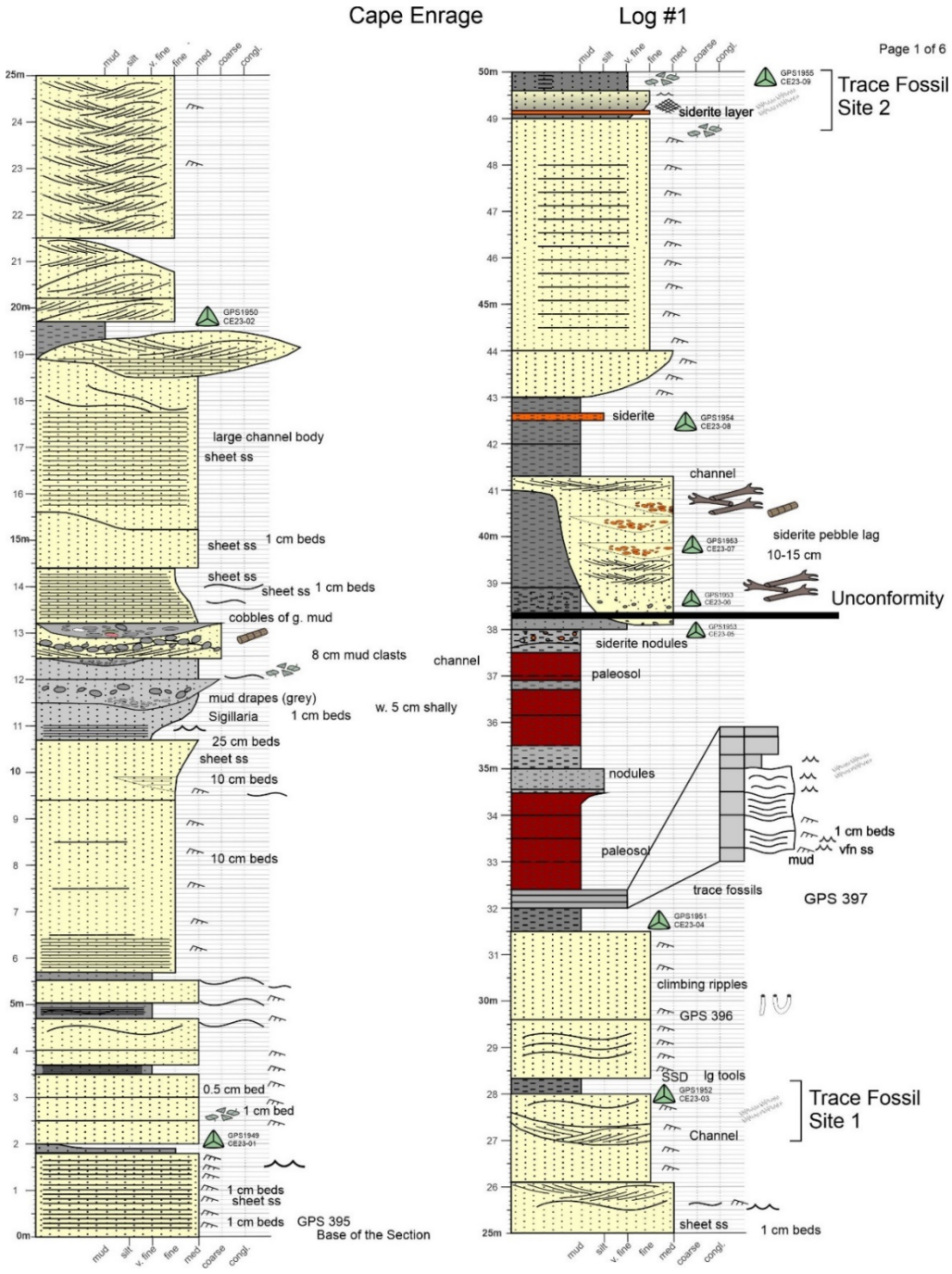
The Boss Point Formation in Nova Scotia is divided into three main members (Fig. 3C). These members are described by Rygel et al. (2015) as follows: The Chignecto Bay Member makes up the first 91.5m from the base and formed in a semi-arid environment which is dominated by redbeds containing fine-grained, reddish sandstone channel bodies composed of lithic arenitic sandstone (Rygel et al. 2015). The overlying Ward Point Member is the thickest of the three members and is interpreted to have been formed during a sub-humid floodplain/fluvial environment, with multistory channel bodies of thicknesses varying from 4-126m, consisting of mostly grey sandstone, as well as floodplain deposits of mudrocks of various colours as well as thin coal seams, *cordatian* logs and preserved roots. Certain open-water deposits have even shown organic rich limestones and evidence of ostracods which Rygel et al. (2015) interprets as potentially a brackish bay/lagoon environment. The North Reef Member is the uppermost member of the formation in Nova Scotia and consists of only two sandstone channel bodies, with the upper limit of the highest channel body defining the upper contact with the overlying Little River Formation (Fig. 3). The presence of redbeds distinguishes this member from the Ward Point Member below and is interpreted to represent increased seasonality (Rygel et al.2015).

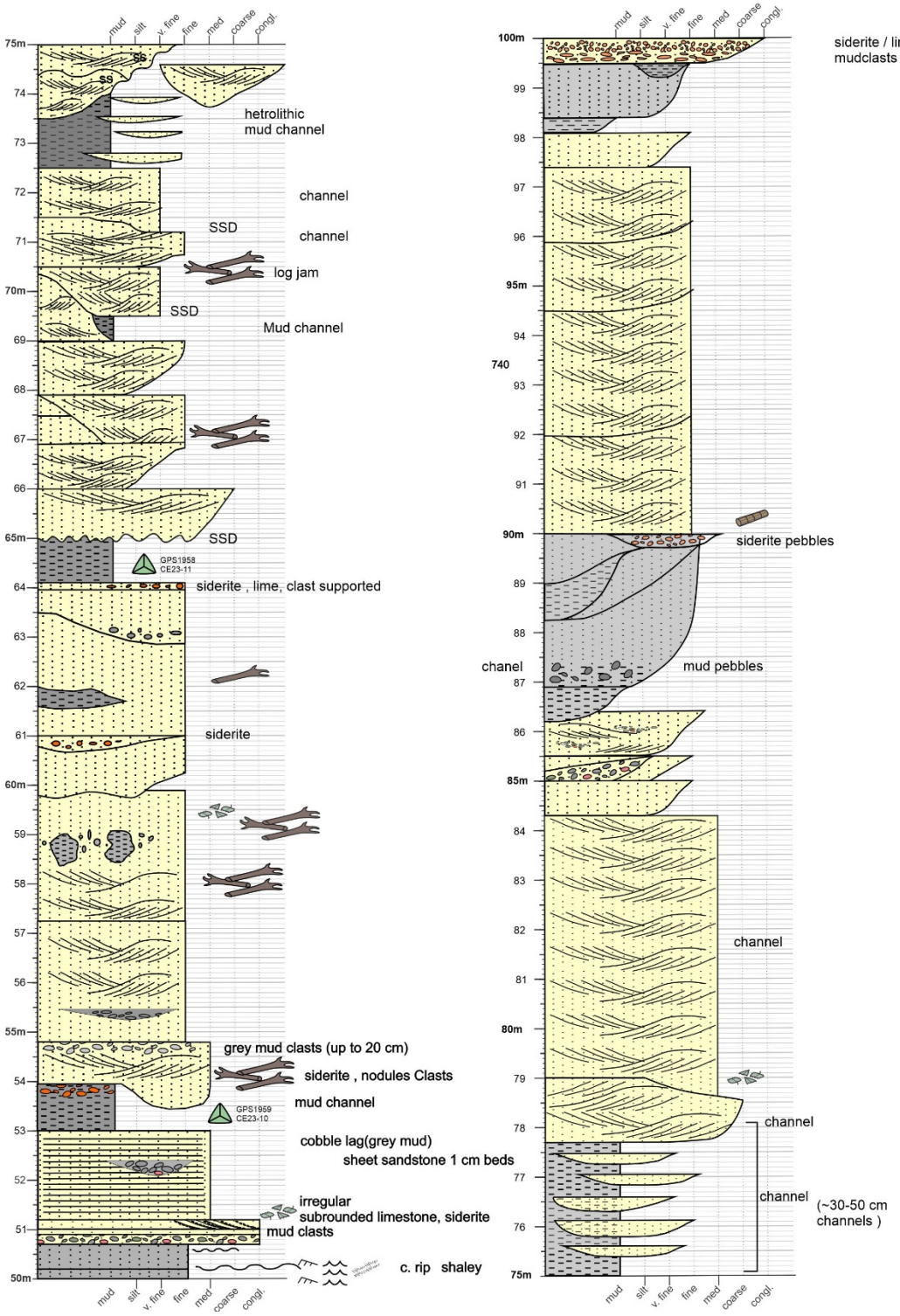
Appendix 3: Legend

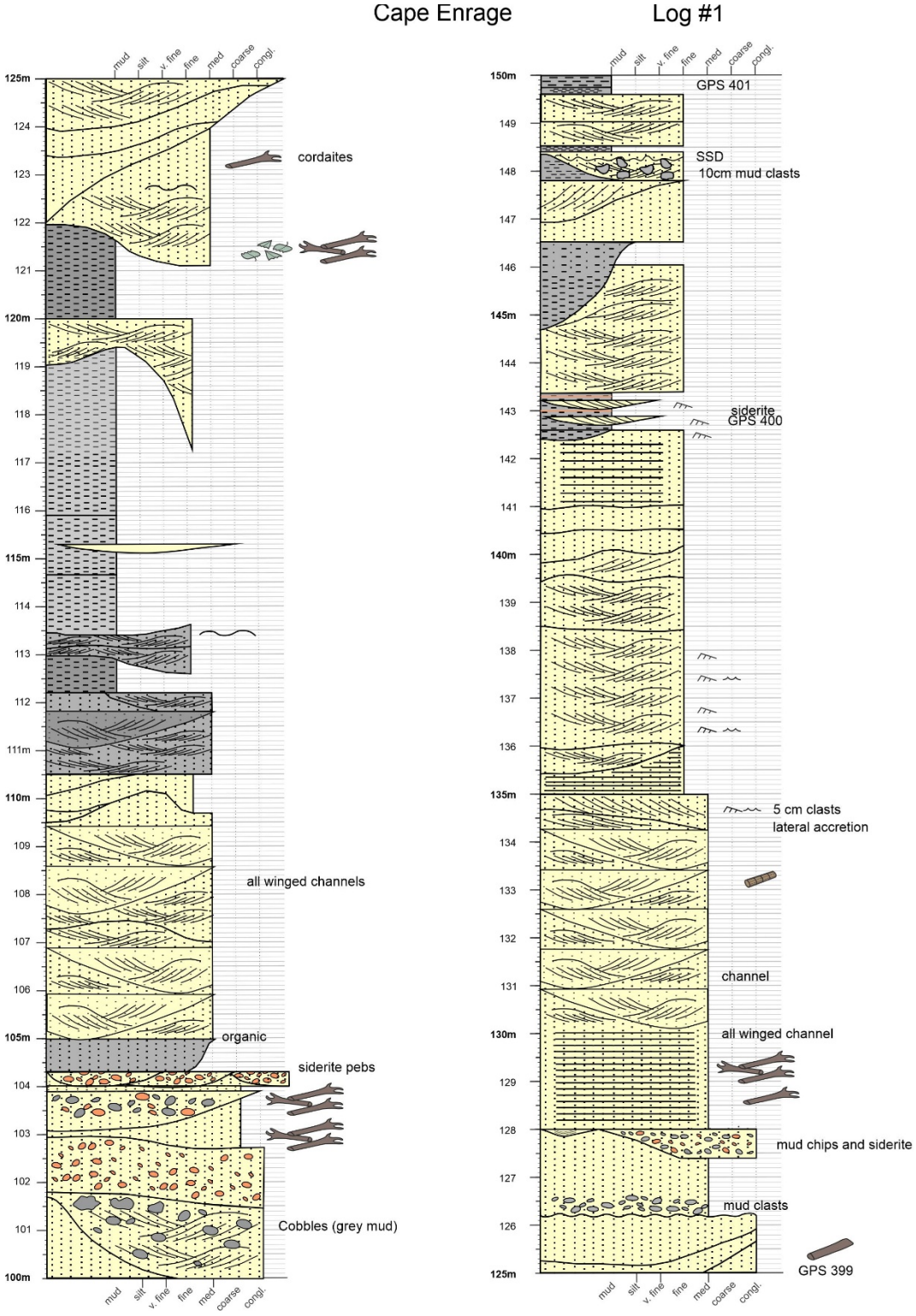


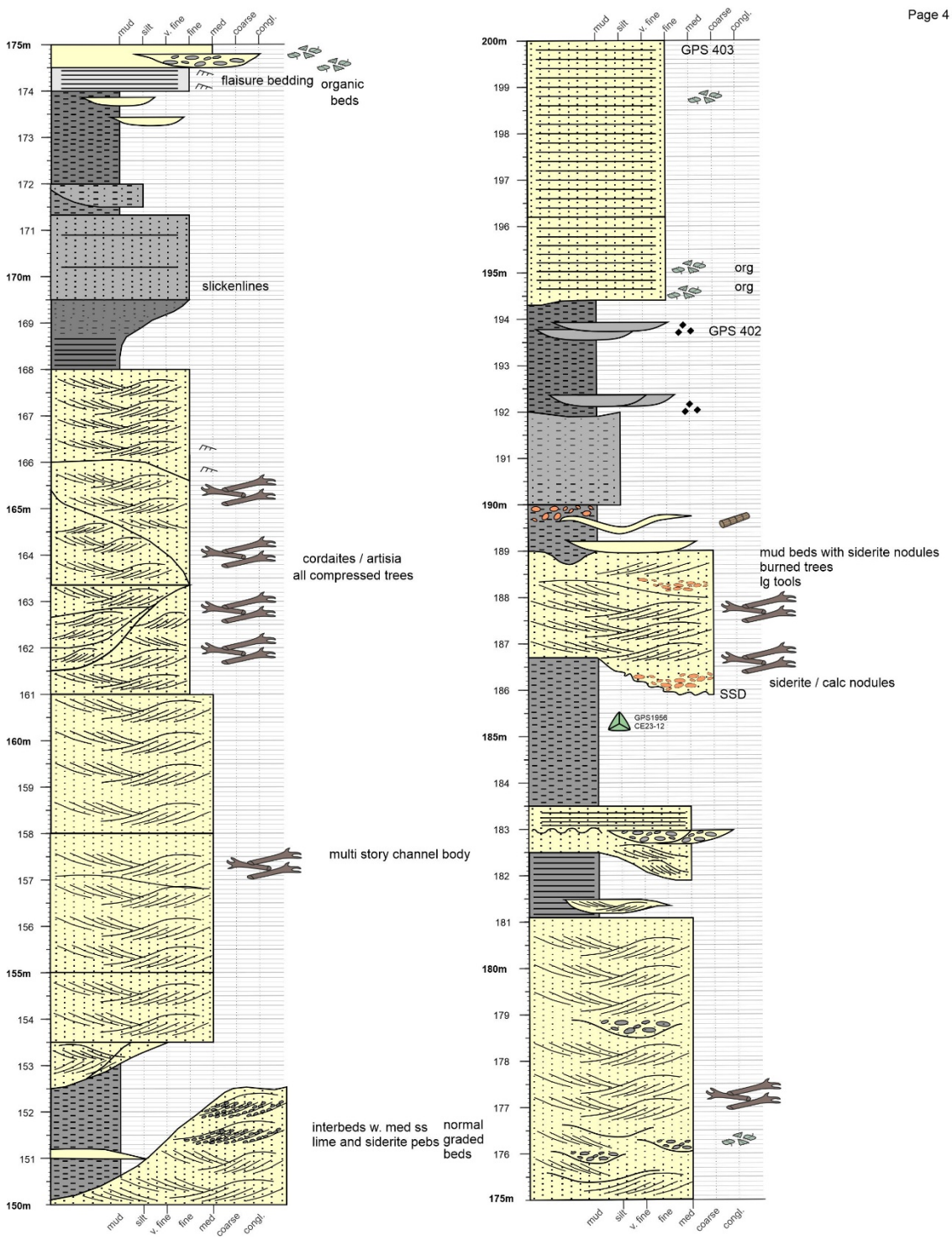
Appendix 4: Logs 1 and 2

(Drafted by Matthew Stimson and Olivia King, 2018)

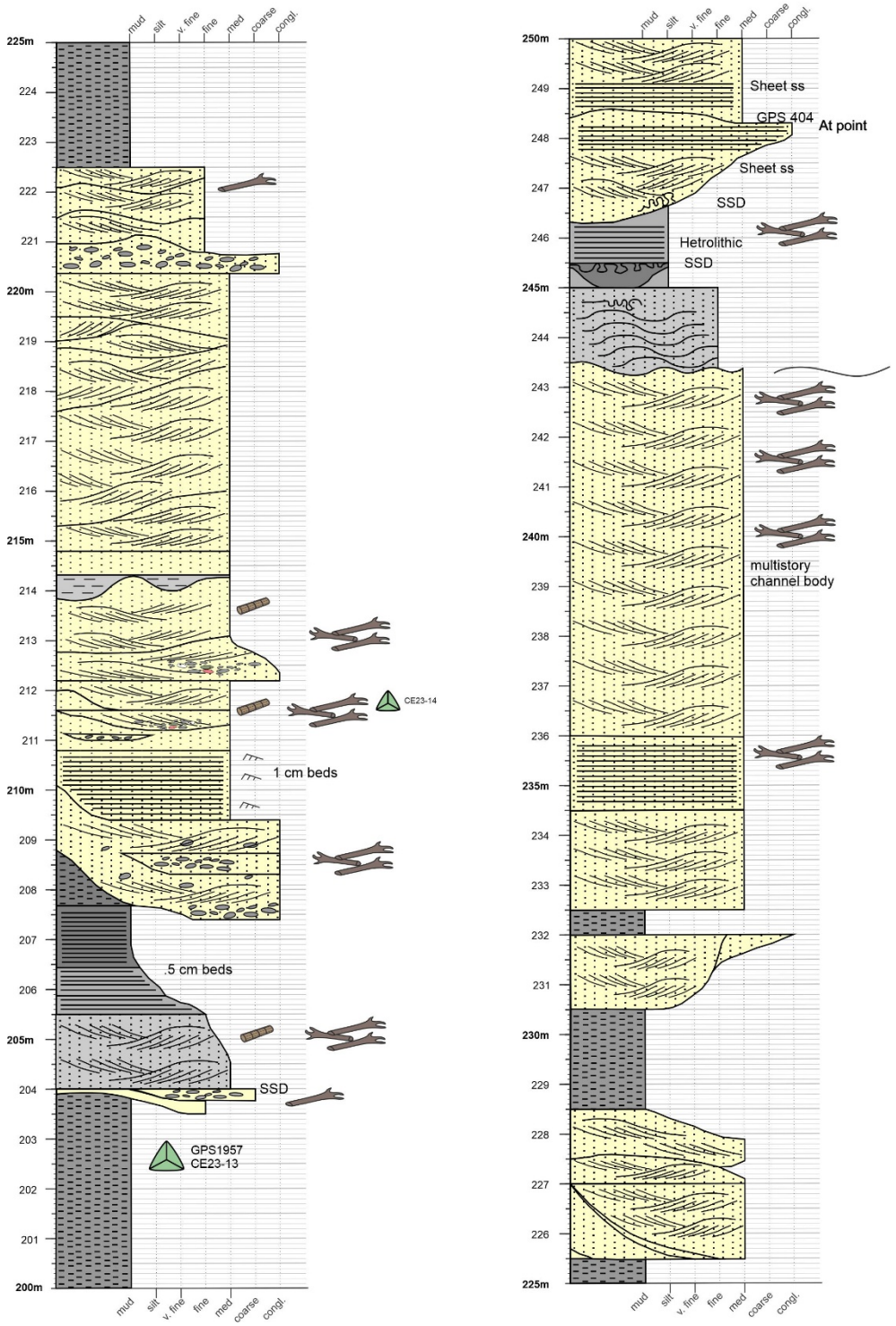



Cape Enrage
Log #1
mud
silt
v. fine
fine
med
coarse
congl.
hetrolithic
mud channel
channel
SSD
channel
log jam
SSD
Mud channel
SSD
GPS1958
CE23-11
siderite , lime, clast supported
siderite
grey mud clasts (up to 20 cm)
siderite , nodules Clasts
mud channel
GPS1959
CE23-10
cobble lag(grey mud)
sheet sandstone 1 cm beds
irregular
subrounded limestone, siderite
mud clasts
c. rip shaley
siderite / limestone
mudclasts
siderite pebbles
chanel
mud pebbles
channel
channel
channel
(~30-50 cm
channels)

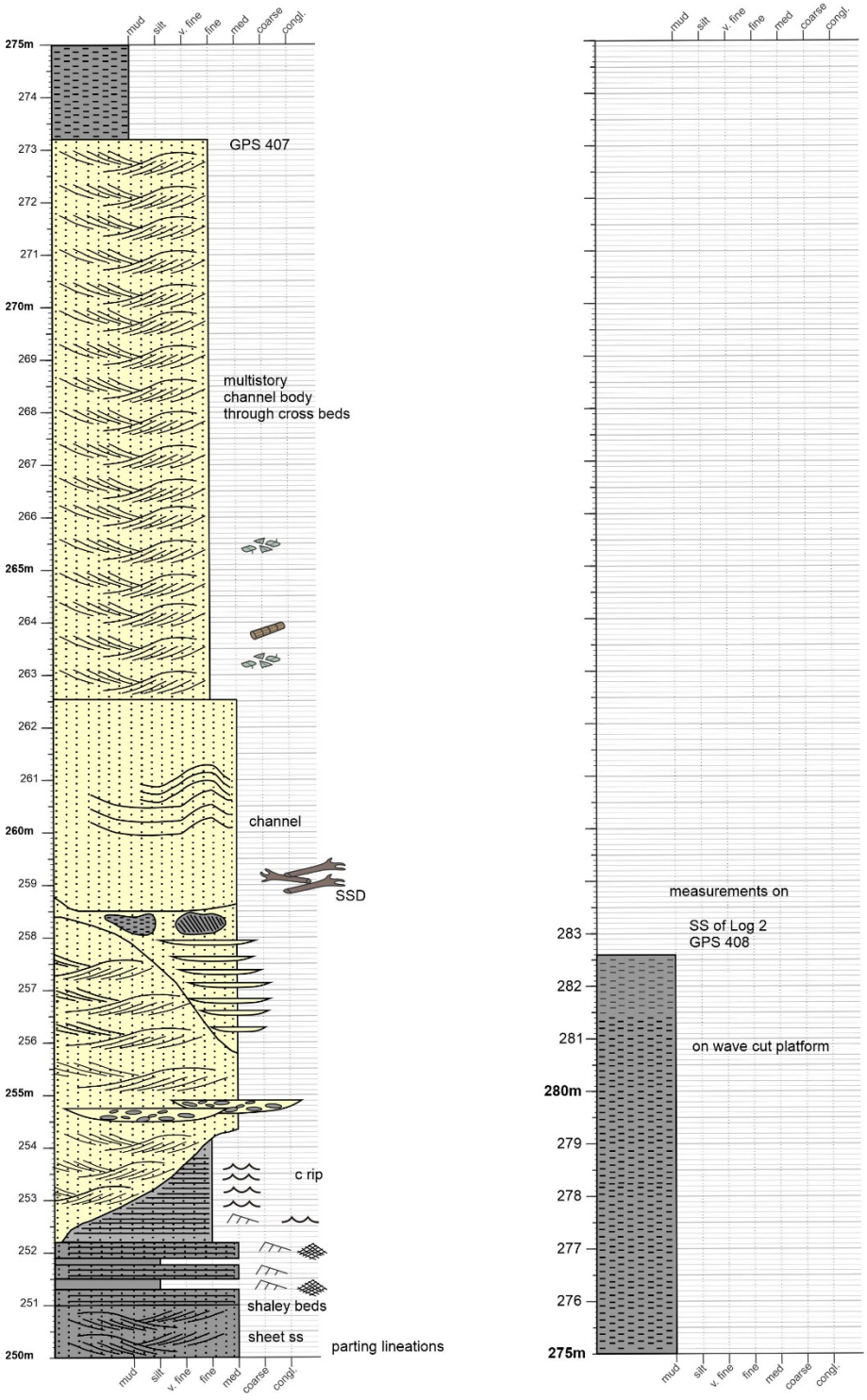

Cape Enrage
Log #1
mud
silt
v. fine
fine
med
coarse
congl.
125m
124
123
122
121
120m
119
118
117
116
115m
114
113
112
111m
110m
109
108
107
106
105m
104
103
102
101
100m
cordaites
all winged channels
organic
siderite pebs
Cobbles (grey mud)
150m
149
148
147
146
145m
144
143
142
141
140m
139
138
137
136
135m
134
133
132
131
130m
129
128
127
126
125m
GPS 401
SSD
10cm mud clasts
siderite
GPS 400
5 cm clasts
lateral accretion
channel
all winged channel
mud chips and siderite
mud clasts
GPS 399


Cape Enrage
Log #1
mud
silt
v. fine
fine
med
coarse
congl.
flaisure bedding
organic beds
slickenlines
cordaites / artisia
all compressed trees
multi story channel body
interbeds w. med ss
lime and siderite pebs
normal graded beds
GPS 403
org
org
GPS 402
mud beds with siderite nodules
burned trees
lg tools
siderite / calc nodules
SSD
GPS1956
CE23-12

Cape Enrage Log #1

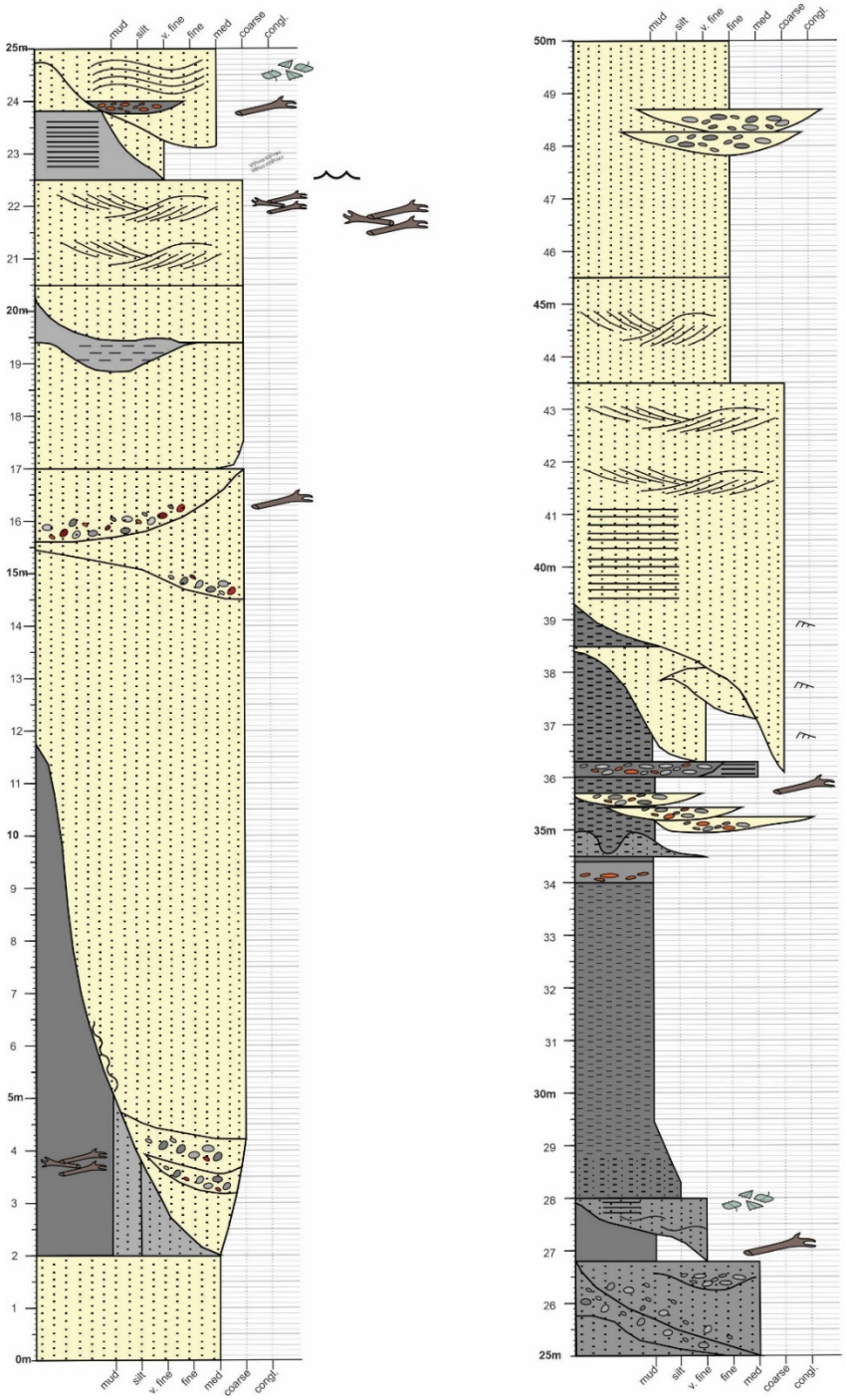


Cape Enrage Log #1



Cape Enrage Log #2

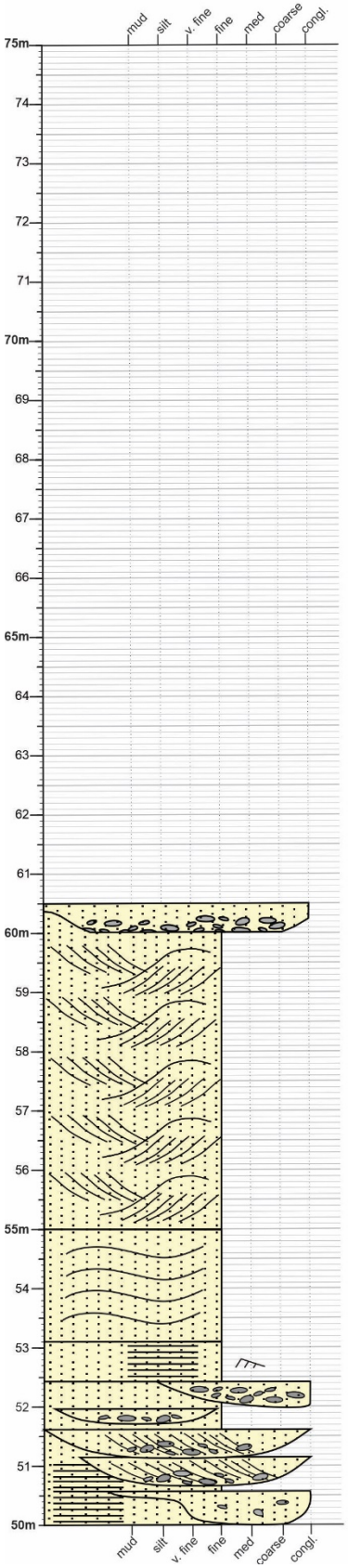
Date: 2018/07/29



Cape Enrage

Log #2

Date: 2018/07/29



Appendix 5: Description of Logs 1 and 2

Log 1 was measured at Cape Enrage where ~420m of strata is exposed between Barn Marsh Beach to south of the lighthouse; however, only ~282.5m can be easily described and measured into stratigraphy logs (Fig. 6) as the upper 100 m are exposed along the wavecut platform and are covered in gravel and seaweed.

The base of Log 1 (Fig. 6, 7) section, up to an interpreted unconformity, preserves a 5m thick red paleosol that is uncharacteristic of the Ward Point Member of the Boss Point Formation and is hence assigned to the Chignecto Member of the Boss Point Formation.

The lowest stratigraphic unit of Log 1 (below the interpreted unconformity) is dominated by sandstone channels that include winged channels that taper into grey mudstone/siltstone units. Two successive 1.9 m and 3.2 m thick sandstone beds are dominated by shaly fine-grained sandstones that preserve abundant ripple bedforms and unidirectional cross-bedding in cross-section. Bedding planes often contain trackways of invertebrates (see Fossil Site 1) on both the ripple crests and ripple troughs.

A cryptic unconformity is observable along the eastern outcrop of Barn Marsh Beach at the base of the overlying grey unit Boss Point Formation which is assignable to the Wards Point Member (45°35'48.97"N, 64°46'51."W; Fig. 6, 7). Here, a variance in the strike and dip can be observed. The 30cm thick sandstone (38 m above the base of the measured section) is truncated by a stratigraphically higher sandstone bed. Further, both sandstones and the overlying siltstone shale unit are truncated by an incising 3.2 m channel body that contains abundant Pennsylvanian-aged plant axes (i.e. *Calamites, Lepidodendron, Sigillaria*, cordaitalean, pteridosperm).

A second sandstone similar to trace fossil site 1 (Site 2) is preserved 21m above site 1 and exhibits similar sedimentary features, but traces are less abundant yet include higher ichnobiodiversity. Here ripple bedforms are well developed on several bedding planes. Ripple bedforms are multidirectional as interference ripple bedforms exhibiting both symmetrical and asymmetrical bedforms and commonly climbing ripples (Fig. 8B). Organic debris tends to fill the troughs of many ripples and commonly preserves trace fossils interpreted to be made by arthropods, vermiform worms, and the ventral fins of fish.

Although soft sediment deformation is commonly observed at the junction between sandstone channels and underlying mudstone – siltstone units within the section, a single outlier of meter scale soft-sediment deformation can be observed as load pouches and load casts at 186.5 m above the base of the section. Here both small scale (1-2 cm) and large scale (~1 m) deformation can be observed.

The majority of middle and upper stratigraphy of Log 1 is dominated by sandstone channel bodies with conglomerate lags as described above with trough cross-bedding and internal ripple cross-bedding. Plant fossil axes are common within the sandstone channels and often form log jams that were interpreted by Ielpi et al. (2014) as the oldest log jams in the fossil record from the Boss Point Formation type locality at Joggins. Locally, mudstone and siltstone beds interpreted as interfluvial deposits can be observed with channels incising into the upper beds or lateral to channel bodies (252-254 m above the base of the section). The measured section ends at the top of a 9.5-10m thick mudstone unit that is overlain by 70 m of seaweed-covered sandstone interpreted to be channel bodies where details cannot be observed (Fig. 6).

This single, laterally traceable fine-grained mudstone-siltstone unit can be traced along strike from the wave-cut platform below the lighthouse (45°35'31.23"N, 64°46'49.40"W; Fig 6), through Log 2, to a small headland 240 m North-East (45°35'43.56"N; 64°46'41.58"W; Fig. 10). This ~10 m thick mudstone and siltstone unit varies in thickness along its length. Near the Cape Enrage lighthouse the unit is mostly buried and exposed in the floor of the wavecut platform. The unit is exposed at a small headland (at 45°35'43.66"N, 64°46'41.21"W; Fig. 12D) where the sediments are grey siltstones and mudstones that are mostly featureless at the base but exhibit fine laminations that are rhythmic at the stratigraphic top of the fine-grained unit. A second fine-grained mudstone can be observed (at 45°35'50.33"N, 64°46'38.39"W; Fig. 12F). Although these 2 units appear to be laterally continuous, tectonic deformation is observed along the sandstone wall (45°35'48.44"N, 64°46'39.77"W; Fig. 12B, E) and they are lithologically distinct. The bases of both units are variable where the mudstone adjacent to the lighthouse has a sharp contact between the grey mudstone and intraformational (grey mud chip) conglomerate. This contact at the second mudstone unit exhibits a sheet sandstone overlain by a cross-bedded (with local cross trough bed scours) sandstone unit with a thick (1 m) cross-bedded, light grey finely bedded, very fine sandstone unit that is overlain by a mudstone unit here (45°35'49.23"N, 64°46'39.24"W, Fig 12F). This unit expresses abundant mottled red/grey mudstone beds, large (5-10 cm) siderite and calcrete nodules and interbedded and discontinuous sandstone beds up to 20 cm in thickness. This same mudstone unit can be traced on resistant small sandstone headlands for 1200m to the informally named ‘Horseshoe Cove’ (Logs 3, 4) and adjacent strata at Log 5 ‘Horseshoe Cove’ stratigraphy (Fig.12A).

Three sections were measured at an unnamed cove that is here informally referred to as ‘Horseshoe Cove’, that are 1380m (45°36'17.05"N, 64°46'22.93"W), 1430m (45°36'18.35"N, 64°46'22.10"W), and 1600m (45°36'24.38"N, 64°46'17.85"W) respectively along the beach from the top of the measured section in Log 1 (45°35'49.41"N, 64°46'52.21”W) at Cape Enrage lighthouse (Fig. 6). The 3 sections are 29m, 46m, and 47m in thickness respectively (Appendices 4-6) and can be loosely tied back to the main stratigraphic log (Fig. 11).

All 3 sections commence with a laterally continuous sandstone body that can be traced the length of the Cape Enrage coastal section (Unit 1; Fig. 15). The sandstone is fine to medium grained buff coloured sandstone with intraformational mudstone conglomerates at the base of trough cross-beds. The uppermost bed of the sandstone at fossil site 5 preserves large scale (0.5-1cm wide) *Cochlichnus* trails in concave epirelief (Fig. 15).

Immediately overlying the sandstone in all 3 sections is a 3-4 m thick grey, very fine-grained sandstone and siltstone unit (Unit 2; Fig. 15). Very fine sandstones are cross-bedded and preserve ripple bedforms. Very fine sandstones are laminated with submillimeter scale mudstone and sandstone that form cross-bedding in cross section with no evidence of desiccation or pedogenic sedimentary features. The laminations are rhythmic in thickness and commonly preserve subaquatic surface repichnia (locomotory tracks), and infaunal invertebrate trace fossils. Unit 2 (trace fossil bearing zone) is composed of 0.5 to 1 cm beds of siltstone and very fine sandstone. These units preserve abundant small (5 mm to 2 cm) *Diplichnites / Acripes* trackways and *Kouphichnium* traces (Fig. 15).

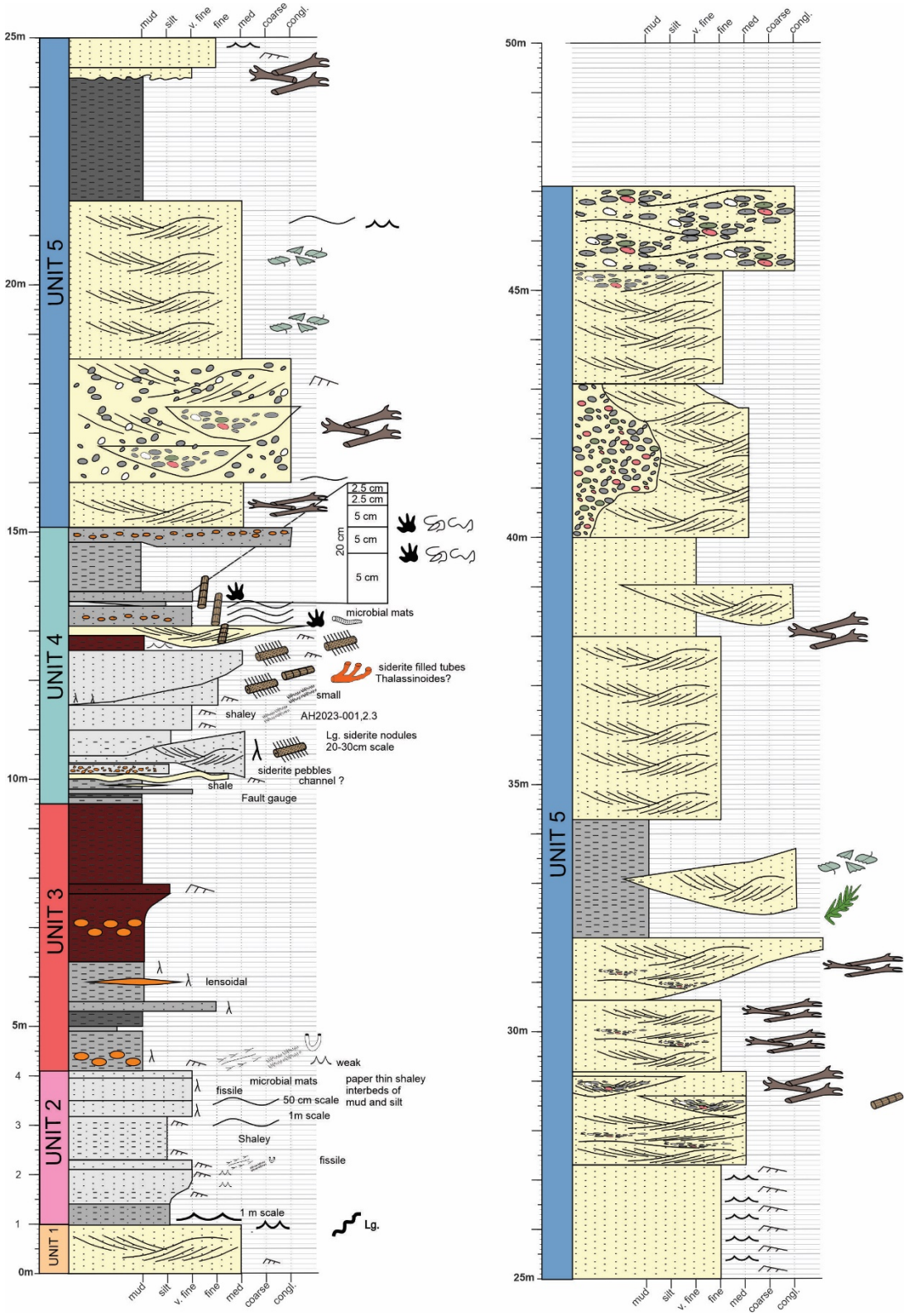
Siltstone units commonly exhibit 1-5 mm diameter rooting structures crossing bedding planes. The uppermost bedding plane in this unit in Log 3 is a fine-grained, brown sandstone that varies in thickness from 10 cm to 20 cm. This sandstone bed is not expressed laterally in Logs 4 or Log 5 (Fig. 15). The surface commonly contains 1-3 cm scale calcrete nodules that formed post-depositionally as well as terrestrial repichnia ichnofossils including tetrapod tracks and large *Arthropleura* derived *Diplichnites* trackways.

The successive 5 - 6.5 m of the section is comprised of fine-grained siltstone and mudstones that can be correlated back to the Lighthouse strata (Unit 3; Fig. 15). The same unit laterally changes between Logs 1 and 2 to 3 from alternating grey and mottled red/maroon with siderite horizons and rhizoconcretions as paleosols to grey siltstones with interbedded dark grey mudstone laminations. Tectonic disturbance near the Cape Enrage Beach access may have structurally offset the beds, casting doubt on the correlatability between Logs 1 and 2 with Logs 3-5, which is corroborated by the lithological difference between these two logs.

The strata overlying the pedogenetically altered mudrock unit (Unit 3) at Trace Fossil Site 5 (Log 5) are unique (Unit 4) in that they commence with a heterolithic unit that preserves small (1 m) back-filled sandstone channel thalwags and interdistributary floodplain deposits of grey shale and mudstones and crevasse splay deposits (Fig. 15). The basal sandstone preserves abundant 5-10 cm siderite nodules, some of which appear to form a network of cylindrical structures that might be interpreted as either burrow activity or rhizoconcretions. Invertebrate repichnia are known from these strata. The overlying fluvial and interfluvial unit commonly preserves *in situ Stigmaria* roots that

penetrate the backfilled channels and the grey mudstones. Some 3-5 cm diameter *Calamites* are observed in life position crosscutting strata including those that preserve tetrapod and invertebrate repichnia. This is unique as virtually all paleobotanicals at the Cape Enrage site and commonly observed in the Boss Point Formation more generally are preserved as transported stem axes within channel bodies and in log jams (Ielpi et al. 2014). The trace fossil bearing section is incised by a carbonate clast-rich conglomerate and overlain by thick successions of sandstone channels with intraformational conglomerates as seen elsewhere in the formation at the Cape Enrage site (Unit 5). The fluvial tetrapod trackway-bearing unit (Unit 4) is not seen elsewhere in the section (Fig. 15) but is represented by grey fine-grained sediments that stratigraphically overlie the oxidized well drained pedogenetically overprinted Unit 3 and are truncated by larger channels of Unit 5.

Appendix 6: Log 3



The basal 1.5 metre sandstone unit commences as a buff colour, medium-grained sandstone that is 75 cm thick (Unit 1). The sandstone transitions into a 25 cm thick intraformational conglomerate comprised of grey mudstone intraclasts. The upper 50 cm of Unit 1 is buff coloured medium sandstone that exhibits trough-cross-beds with wavey bedding which preserves localized grey mudstone intraclast lags. This unit preserves transported *Calamites* stems.

Unit 1 is overlain by a grey fine sandstone to siltstone unit that preserves abundant ichnofossils (Unit 2; 1.5 m to 5 m above the base of the measured section; Fig. 15, Log 3). This section commences with a 90cm thick light-grey, fissile, trough-cross-bedded, fine-grained sandstone. The sandstone preserves abundant internal cross-bedding and ripple bedforms. The upper half of the bed preserves abundant rooting structures and pyrite. Invertebrate trackways (*Diplichnites* and *Kouphichnium*) have been observed within the upper portion of this stratum.

The sandstone is overlain sharply by a grey siltstone with 0.5 cm beds that preserve abundant ripple bedforms and internal crossbedding. This siltstone contains rooting structures, transported plant axes, abundant invertebrate trackways along with vertical U-shaped burrows. A 30cm sandstone channel can also be found 25cm above the base of the siltstone (2.65m above the base of the measured section). The siltstone package is sharply overlain by a 60 cm thick sandstone package that is divided into 3 distinct beds. The lower 2 beds include a grey and dark grey very fine-grained sandstone that preserves ripple bedforms, internal cross-bedding interference ripple bedforms, and wavey bedding. Rhizoconcretions and calcrete nodules are found in the bottom of this unit. Invertebrate trackways (i.e. *Diplichnites, Kouphichnium*), and U-shaped burrows are

common. The uppermost 10-20 cm of this unit is a brown to dark grey sandstone that contains calcrete nodules. The bottom contact with the underlying sandstones is wavey and the upper bedding surface exhibits mudcracks. Tetrapod tracks and large *Arthropleura* scale (19-25cm wide) *Diplichnites cuithiensis* tracks are preserved on this surface.

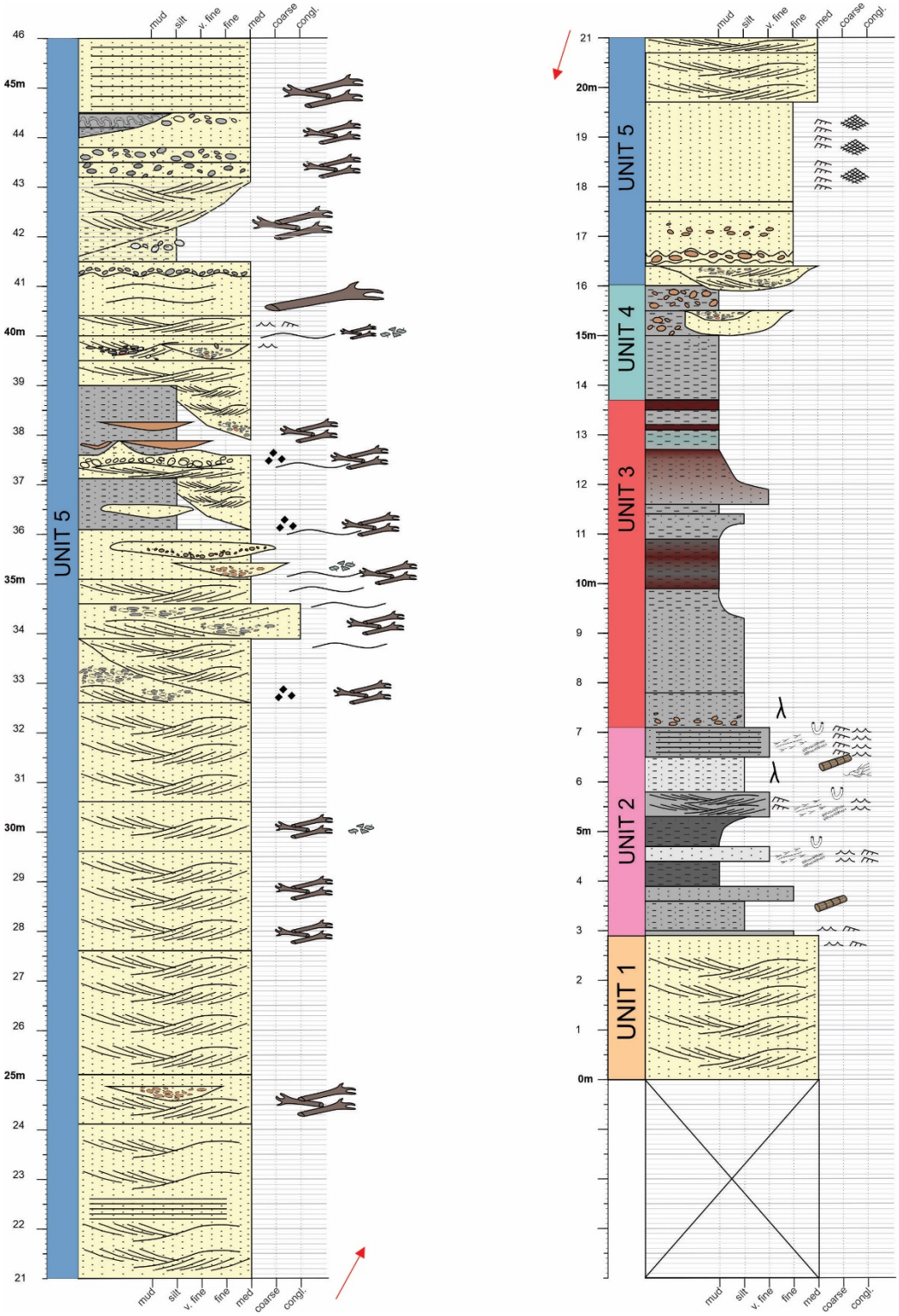
The trace fossil zone is sharply overlain by a siltstone that rapidly grades to a 7.6-metre thick package (Unit 3) that is overlain by mudstone. The fine-grained mudstone package initiates as a fissile, grey-coloured silty mudstone with rooting structures and rhizoconcretions but the facies quickly changes to oxidized mudstone that preserves pedogenic slickenlines within the first metre of the unit, although given the amount of bedding-adjustment deformation in these rocks, these could also be tectonically derived. The mudstone alternates between a red/ maroon and grey or (mottled grey/red) in colour. This unit contains 20-30 cm thick sandstone channels and preserve horizons of siderite nodules up to 10 cm in diameter. The top of the oxidized and mottled grey-red zone that exhibits pedogenic features (12.6 m above the base of the section) is marked by a buff coloured 30 cm thick very-fine sandstone bed, which marks the transition to the overlying Unit 4.

The overlying 5 m of fissile grey mudstone (Unit 4), contains indeterminant plant matter and transported *Calamites* stems. The upper 0.5 m of the unit contains a 10cm thick fine sandstone with grey intraformational mudstone intraclasts, as well as 10cm siderite nodules, and thin, 10cm discontinuous siderite layers.

The grey beds of unit 4 are truncated by a buff, coarse-grained sandstone that displays trough cross-bedding with grey-mudstone and siderite nodule lags (Unit 5).

These coarse sediments also preserve transported tree trunks of various types as well as indeterminant plant matter. A polymictic conglomerate is observed at 20m above the base of the log. The remaining 9 metres of the section can be summarized as being comprised of medium-grained sandstone with cross-bedding, indeterminant plant matter and tree trunks, and a rare grey mudstone layer (20 cm thick).

Appendix 7: Log 4



The basal sandstones of Unit 1 have an unknown thickness with only the upper 3 m being exposed in outcrop along the shoreline. The medium-grained, buff-coloured basal sandstones contain trough cross-bedding throughout, and internal cross-bedding with ripples near the top of the uppermost bed.

The sandstone unit is overlain by a 4-meter grey bed unit that contains abundant ichnofossils (Unit 2). The unit is comprised of alternating fine-grained grey (6-12 cm thick) sandstone and grey to dark grey siltstone/mudstones that locally grade upwards into fine-grained sandstone. Fissile siltstones within this unit contain transported *Calamites* stems, occasional *Calamites* roots (*Pinnularia*) and other rooting structures. The sandstones of this section are commonly cross-bedded or laminar bedded which locally preserve wavey and trough cross-bedding. These sandstones preserve ripple bedforms on their upper and lower bedding surfaces and are commonly comprised of sub-millimetre alternating laminations of light grey siltstones and dark grey mudstones in a rhythmic pattern. Unit 2 contains the main ichnofossil assemblage of the site. The light grey, very fine sandstone (4.5m, 5.5m, and 6.5m above the base of the measured section) contains multiple invertebrate trackways (i.e. *Diplichnites, Kouphichnium*), U-shaped burrows and ripple marks.

The fossiliferous strata are conformably overlain by a fine-grained, dominantly mudstone and siltstone unit that is 6.6 m thick (Unit 3). The basal part of this fine-grained unit consists of grey siltstone and is marked with 1-2 cm siderite and calcrete nodules associated with rooting structures. A red, maroon, mottled red/grey package of mudstone with minor siltstone and minor very fine-grained sandstone sits at 3-7 m above the base of the unit (10-14 m above the base of the section).

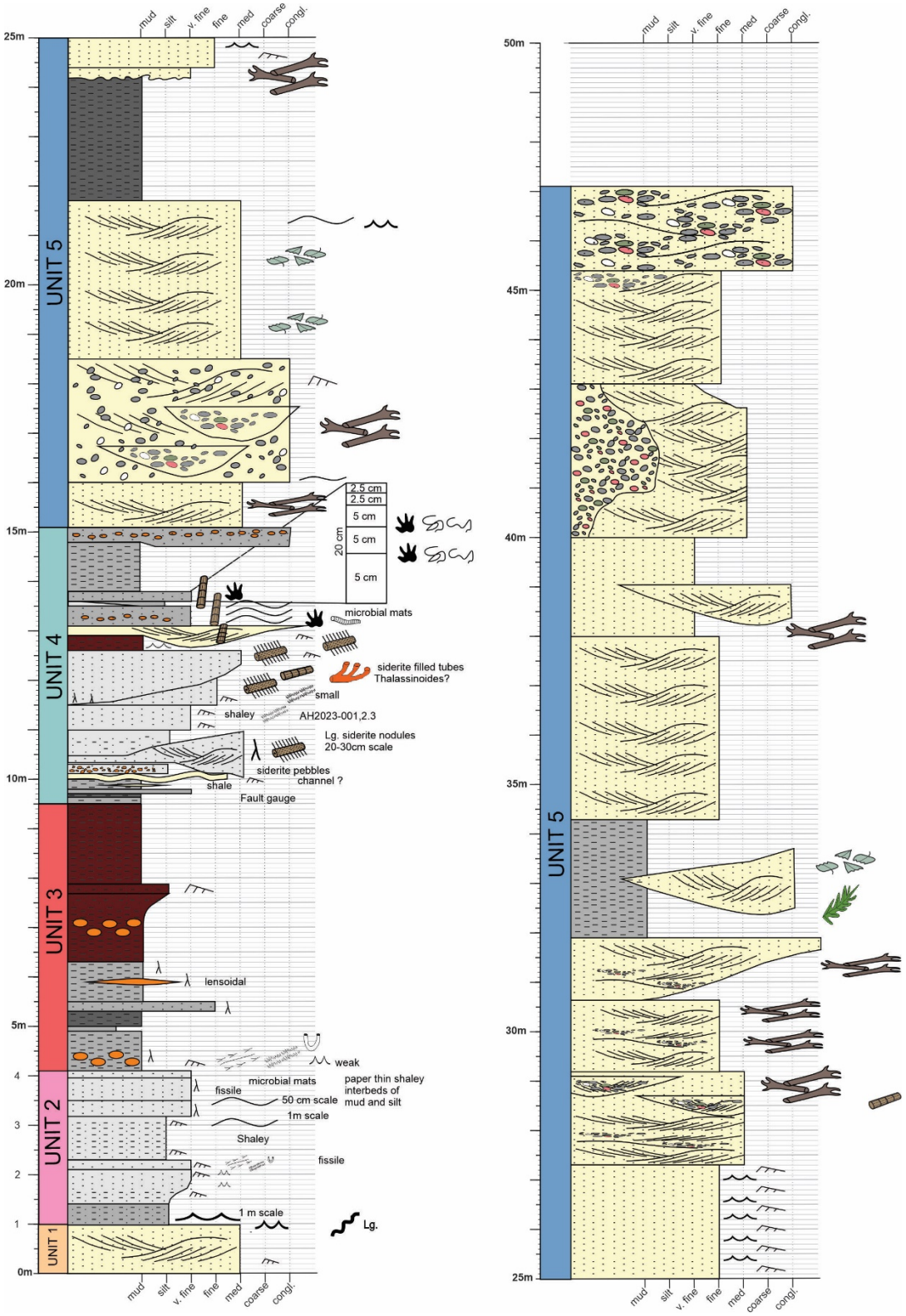
Unit 4 sits conformably above unit 3 and is characterized by grey mudstones with large (10 cm) siderite nodules and localized 50 cm thick channel bodies with erosive bases into the underlying mudstone. Channels contain gravel lags at the base of troughs.

The upper 30 m of the section consists of a predominantly medium buff coloured sandstone with trough cross-bedding and abundant transported, coalified logs (Unit 5). The base of this unit begins with a 50cm thick sandstone channel with trough cross-bedding and conglomerate lags that erodes into the upper mudstone of Unit 4. This is overlain by a 20-40cm thick unit of fine sandstone containing siderite nodules, with wavy bedding near the bottom of the unit. The remainder of the fine sandstone unit contains internal cross-bedding and interference ripples. A 15.5 m sequence of medium, buff sandstone comprises the middle of this section as a multistory channel body unit. All sandstones and channel bodies preserve trough cross-bedding, local siderite and gravel lags, and abundant coalified logs arranged into log jams (Ielpi et al.2014). The upper 3.5 m of this section has more abundant gravel lags at the base of 0.5-2 m channel bodies with wavey beds and the presence of fusain (a fossilized carbon deposit). The next sequence consists of 3 metres of grey siltstones with incising sandstone filled channels (0.5-1.5 m thick) and local discontinuous sandstone and siderite lenses commonly preserved through cross-beds, gravel lags, fusain and abundant transported logs.

This is overlain by a 3.5 metre thick medium-grained sandstone channel made up of trough cross-bedding and containing conglomerate at the bottom. The upper 1 m of the channel exhibits wavey bedding with ripple bedforms, cross-beds, indeterminate plant matter, and transported logs which include up to 3-4m cordaite logs. The uppermost portion of this unit has wavy beds that contain grey mud chips intraclasts. A locally

deformed 0.5 m thick grey mud-filled channel is present at the top of the section which is overlain by laminar bedding of 2-5 cm thick beds that once again preserve abundant coalified logs before the section is lost under the wave cut platform.

Appendix 8: Log 5



The basal stratum of Trace Fossil Site 5 is a trough-cross-bedded, medium grained sandstone with smaller scale internal cross-bedding that has an unknown thickness as only the uppermost meter of this unit is exposed in outcrop (Unit 1). The top of this unit contains ripple bedforms and large *Cochlichnus* surface burrows (Fig. 16F).

Conformably above Unit 1 is a 3.1m thick unit that consists of grey siltstone and very fine sandstones. This unit begins with 40cm of grey siltstone containing 1m scale ripple marks which is overlain by a lighter grey siltstone that increases in grain size to a ~50cm thick very fine-grained sandstone, containing internal cross-bedding, ripples, and invertebrate trackways and burrows. This in turn is overlain by a 90cm thick very fine, fissile, light grey sandstone section containing paper thin shaly interbeds of mud and silt. The style of the beds changes from 1m scale waves at the bottom to internal cross-bedding at the uppermost portion. This section contains rooting structures and microbial mats, as well as invertebrate trackways and burrows (Fig. 16J,K) within weak ripple marks at the top of the section. This unit is comparable to and is the lateral continuation of unit 2 that was measured within logs 3 and 4 at Horseshoe Cove.

Unit 2 is overlain by 5.4m of grey, changing to a red and maroon and mottled reg-grey mudstone to siltstone package of Unit 3 (Fig 16A-C). This unit does not contain any ichnofossils, but contains abundant rooting structures in the lower half, as well as the occasional siderite nodules, and compressed woody plant fragments. There is a 1-3 cm wide, bedding parallel fault gouge zone which indicates minor displacement was accommodated within the uppermost fine-grained mudstone unit at the contact with the overlying Unit 4.

Unit 4 commences with a grey mudstone and very fine grained sandstones that are overlain by a 10cm thick wavy, buff coloured fine sandstone with internal cross-bedding 10m above the base of the log. Log 5 is unique among the Horseshoe Cove stratigraphic logs in that Unit 4 in logs 3 and 4 is dominated by grey mudstone where Unit 4 of Log 4 is characterized by a 5.6 m thick package of mostly grey sandstone and siltstones that preserve *Calamites* and *Stigmaria* lycopod roots in life position (Fig. 16 G,H) and various continental vertebrate (Fig. 16 I) and invertebrate (Fig. 16 J,K) ichnofossils. Ichnofossils are preserved in the late channel fills and within floodplain deposits on the flanks of channel bodies.

The basal 2.5 m of Unit 4 is characterized by 1 m channel bodies. The lower 1 m thick channel body contains abundant siderite nodules that range from pebble scale to 20-30 cm cobble scale. Sediments also preserve rooting structures including 3-dimensional *Stigmaria* roots (Fig. 16H). A single 50 cm thick very fine-grained, grey sandstone bed with fine bedding preserves small (0.5 cm wide) *Diplichnites* trackways. The upper 1.5 m is dominated by very fine-grained to medium-grained, grey sandstone with *Stigmaria* roots. The uppermost portion of the sandstone channel (12.5 m above the base of the section) preserves a network of siderite-filled tubes that may represent a burrow network (Fig. 16E).

A red-maroon mudstone (12.5 m above the base of the section) is incised by a 50 cm fine-grained sandstone. This channel sandstone preserves in-situ *Calamites* (Fig. 16 G) and *Stigmaria* roots (Fig. 16 H) in life position. Short (<20-30 cm) segments of *Calamites,* preserved in life position, continue to cross-cut strata for nearly a meter of strata. The lower 40 cm includes wavey beds of grey finely bedded to shaley very fine-

grained sandstones and contains pebble sized siderite nodules. As well, this bed preserves abundant *Taenidium* burrows and tetrapod trackways that will be described in a concurrent paper (Allen et al. *In Preparation*) some of which are associated with what is interpreted as microbial mats expressed as micro-wrinkles. The uppermost 20 cm of this unit comprises 5 individual beds. The lower 3 beds have a thickness of 5 cm each while the upper 2 beds are 2.5 cm thick. Trace fossils have been recorded from the two upper 5 cm thick beds in the middle of the 20 cm thick package. Traces include abundant tetrapod tracks (Fig 16 I) that will be described in a concurrent paper (Allen et al. *In Preparation*), and invertebrate surface burrows (Fig. 16 J) and traces that are described elsewhere in this manuscript. *Calamites* stems are documented throughout this unit but are not observed within the overlying 1 m of grey mudstone. The grey mudstone unit is capped by a 30-40 cm coarse sandstone to conglomerate that leads into the overlying multistory channel bodies of unit 5.

Unit 5 of this section begins at 15m from the base of the measured section and consists of 3 multistory channel body packages of buff coloured, mostly fine-grained sandstone to conglomerates. There are two ~2.5m grey mudstone intervals at 21.7m and 31.9m from the base of the measured section. The remainder of unit 5 consists of trough-cross-bedded buff-coloured, fine- to medium-grained sandstone, with the occasional ~0.5-1m sandstone channels and gravel lags. This unit contains abundant transported logs and occasional indeterminant plant matter. Fossil ferns have been found in the second mudstone section, 31.9m above the base of the log, and have been identified as *Alethopteris*. There are two thick conglomerate intervals at 16m and 45.4m above the base of the log, the first containing trough cross-bedded sandstone channels and

transported logs with the latter making up the stratigraphically highest section of the log contained under the wave cut platform. A sandstone channel body is observed 40 - 43 m above the base of the section and incises into a conglomeratic interval with the channel's cut-bank being observed in cross-section.

Glossary

Basin: A large low-lying area, that often collects sediment from the erosion of surrounding highlands. Subbasins are smaller basins within a larger basin.

Biostratigraphy: The branch of stratigraphy that correlates fossils to specific sedimentary depositional successions. This is often used as a relative age dating method with fossils of a specific known time.

Carboniferous: A geological time period, also known as "The Coal Age" spanning from ~360 mya to ~300 mya. This period succeeds the Devonian period and precedes the Permian (Gradstein et al. 2020).

Devonian: A geological time period spanning from ~420 mya to ~360 mya. This period succeeds the Silurian and precedes the Carboniferous. (Gradstein et al. 2020).

Geological formation: A unit of rock from a specific period of time, with characteristics that make it identifiable from the underlying and overlying units of rock.

Fluvial: Relating to rivers.

Halokinesis: The movement of large layers of salt within the earth, which can lead to disruption of surrounding strata.

Ichnogenus: a taxon based on the fossilized work of an organism.

Ichnology: The study of trace fossils.

Ichnotaxa: Traces that have been described in literature and given taxonomic names.

Infaunal burrow: Burrows created within sediment.

Interference ripple: Two sets of ripples within the same area forming right-angles to each other, as the result of two or more paleocurrents moving at different directions.

Lacustrine: Relating to lakes.

Palynology: The study of plant pollen, spores, and microscopic plankton.

Repichnia: Walking trackways.

Sedimentary beds: Layers of deposited sediment that are in some way (grain size, structures, etc.) distinguishable from other layers within a larger sedimentary rock unit.

Stratigraphic log: A graph describing sedimentary beds in a unit of rock with the oldest beds at the bottom and the youngest beds at the top. The Y-axis measures thickness of each bed, and the X-axis measures its grain size.

Tetrapod: A four-footed vertebrate.

Xiphosuran: An order of arthropods, also known as horseshoe crabs.