



GAC
Newfoundland
and Labrador

**Geological Association of Canada
Newfoundland and Labrador Section**

FALL FIELD TRIP

September 18-20, 2015



The Ediacaran fossils of the Avalon Peninsula

Alex Liu and James Conliffe

with contributions from Liam Herringshaw, Jack Matthews, and Duncan McIlroy

Field Trip Guide and Background Material

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Cover photo: Overview of the fossil bearing bedding planes at Mistaken Point, with insets showing some of the diverse Ediacaran macrofossils present at Mistake Point (photo: A. Liu)



Ediacaran macrofossils from the Mistaken Point 'E' Surface.

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INTRODUCTION AND OVERVIEW

The Mistaken Point Ecological Reserve (Fig. 1) is home to some of the world's most impressive Ediacaran fossil assemblages. Large bedding planes covered in thousands of exceptionally preserved specimens can be found *in situ* throughout a continuous ~2 km succession of sedimentary strata. We will work through the stratigraphy, from the first appearance of the classic soft-bodied “Ediacaran biota” anywhere in the world, via the spectacular fossil assemblages of Mistaken Point, and up to outcrops of the Fermeuse Formation in the vicinity of Ferryland, where the nature of the biotic assemblages changes completely as we enter shallower depositional environments. We will also examine specimens considered to represent the earliest traces of metazoan locomotion in the Ediacaran record. You are free to take photographs at any of the localities we will visit, but please respect the fact that these outcrops are currently under study by ourselves and other research groups.

ACKNOWLEDGEMENTS

The authors would like to thank Tina Leonard, Jeri Graham and Erika Pittman of the Department of Natural Resources, Government of Newfoundland & Labrador; and Tony Power and the interpreters of the Mistaken Point Ecological Reserve for their assistance in organising permits to run this trip. Carol-Ann Devereaux and the staff of the Trepassey Motel are thanked for providing accommodation and sustenance in Trepassey. Editorial assistance from Chris Pereira with the final version of this field trip guide is greatly appreciated.

The support of the Geological Survey of Newfoundland and Labrador (part of the Department of Natural Resources) in terms of time and organization, support for participation, and assistance with vehicle support is gratefully acknowledged. Without this, such ventures could rarely happen. The Department of Earth Sciences at Memorial University provided valuable subsidies to encourage student participation, which is an important aspect of these excursions. GAC-NL also wishes to acknowledge direct financial support for the 2015 trip from the Geoscience Education Trust of Newfoundland and Labrador (GET-NL), established from revenues accrued from National GAC-MAC meetings in 1988, 2001 and 2012. GET-NL previously operated under the name “St. John's 88-01 Trust Fund” but has now been rebranded.

SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

The weather in Newfoundland in September is unpredictable, and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, and sturdy footwear are essential at almost any time of the year. Gloves and a warm hat could prove invaluable if it is cold and wet, and a sunhat and sunscreen might be just as essential. It is not impossible for all such clothing items to be needed on the same day.

Above all, field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

Specific Hazards

All of the sites we will visit require off-road walking across uneven and often wet terrain. Sturdy hiking boots, preferably with some ankle support, are therefore recommended for all stops. A walking pole may be useful for some participants. Since many localities are on or near the coast, please keep away from cliff edges, and stay on the trails. This is especially important if fog descends on Mistaken Point (hopefully it won't at this time of year). Also be aware of slippery rock surfaces, especially those coated in black or green algae. Large waves are common all along the Newfoundland coastline, so be alert to these when examining outcrops close to the water's edge. Take care when descending to localities down small, rubble-covered slopes. Follow the instructions of trip leaders at all times, and stay with the group.

At Mistaken Point Ecological Reserve, you will be provided with 'Bama Booties' to wear while on the outcrops (in order to protect the fossil surfaces from erosion). Please remember to return these to the trip leaders when boarding the bus back out of the reserve.

You have a responsibility to your fellow participants to behave in a safe manner. This is particularly relevant when hammering (though note that **HAMMERS ARE NOT PERMITTED WITHIN THE MISTAKEN POINT ECOLOGICAL RESERVE**); if you must hammer an outcrop, please warn those near you prior to starting, and wear safety goggles.

Finally, more specific guidance about the hazards associated with particular stops will be provided later in the guidebook, under each stop description. These will be reiterated by the field trip leaders upon arrival at each locality. Field trip participants are advised to read these sections carefully, and to take necessary precautions to maintain both their own safety, and the safety of fellow participants.

MISTAKEN POINT ECOLOGICAL RESERVE (MPER)

Strict rules laid down by the provincial government exist to protect the fossils of MPER.

PLEASE NOTE:

- 1) Within MPER **the use of hammers, casting of fossils, or collecting specimens of any kind without a valid permit is prohibited** under the protection of the Newfoundland and Labrador Wilderness and Ecological Reserves Act and applicable Fossil Ecological Reserve Regulations (2009).
- 2) Self-guided geological excursions are **not** permitted within MPER.
- 3) Public access to the fossil-bearing surfaces within MPER is **by guided tour ONLY**.
- 4) Permits (issued without charge by the Parks and Natural Areas Division of the Newfoundland and Labrador Department of Environment and Conservation) must be obtained in order to conduct scientific research at Mistaken Point or visit the Reserve with an educational/academic tour group. Permit application information and forms are available by following the links at: http://www.env.gov.nl.ca/env/parks/wer/r_mpe/permits.html

Since the Mistaken Point Ecological Reserve is a protected location, we are not permitted to provide detailed locality information about the fossil sites. If you would like more information, please contact the Reserve Manager (currently Tony Power; powert@gov.nl.ca ; 1-709-438-1012).

SPECIFIC SAFETY ISSUES AT MISTAKEN POINT

In addition to the general safety guidelines discussed at the front of this guidebook, please:

- Stay away from cliff edges.
- Be alert for rogue large waves.
- Be careful with your footing on wet/muddy rocks.
- Dress accordingly for the conditions, but ensure you have additional warm clothes, waterproofs, sunscreen, water, and some food with you – weather conditions can change suddenly within the reserve, and we will be some distance from the vehicles.
- Be aware that mobile phones will not work within the reserve. The trip leaders carry first aid kits, and a satellite phone.

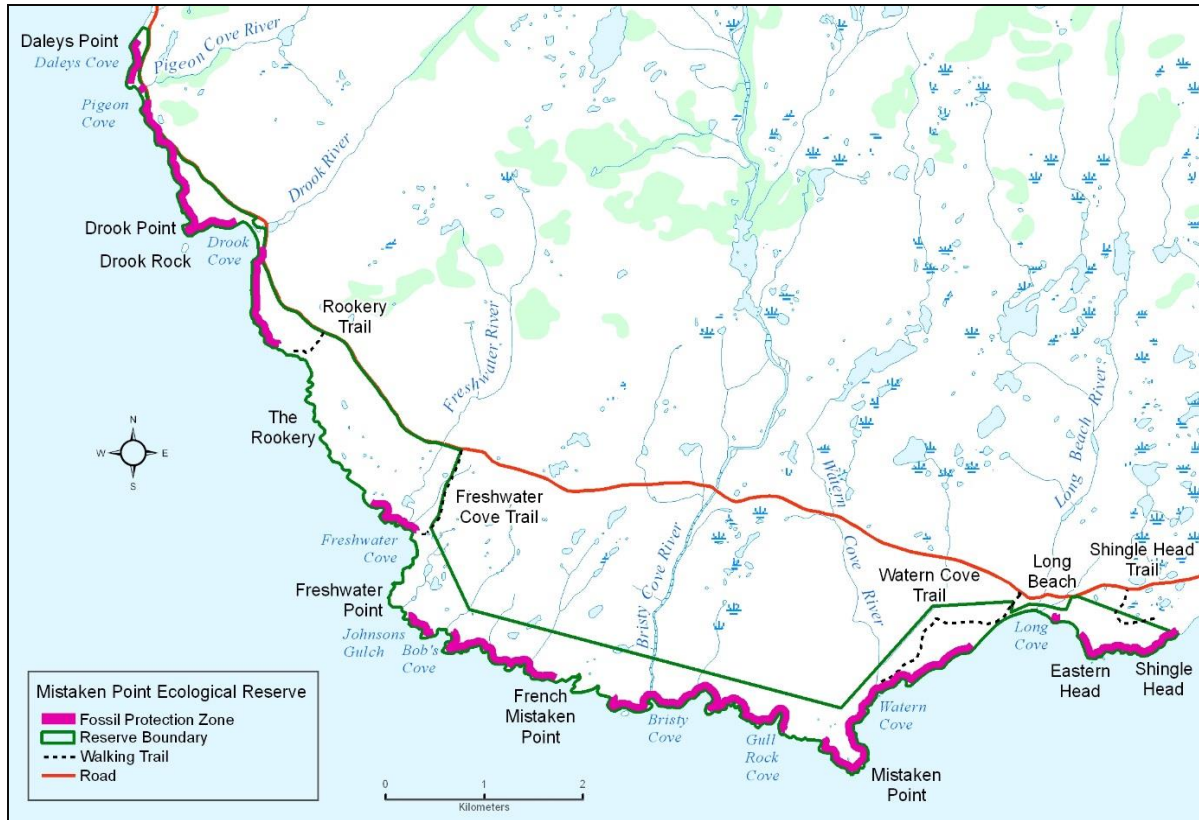


Figure 1. The Mistaken Point Ecological Reserve, showing the reserve boundaries (green), and the Fossil Protection Zone (pink). Map provided by the Parks and Natural Areas Division of the Newfoundland and Labrador Department of Environment and Conservation.

PART 1: BACKGROUND MATERIAL

INTRODUCTION

INTRODUCTION TO THE NEOPROTEROZOIC–PHANEROZOIC TRANSITION

The late Neoproterozoic Era was an interval of immense change in the biosphere. In addition to the development of biological innovations that would culminate in the appearance and dominance of metazoans in marine ecosystems, numerous chemical and physical changes were also taking place.

Thick glacial diamictites with striated dropstones, deposited on multiple continents at both high and low paleolatitudes, suggest that widespread and long-lived glacial events affected the planet both before and during the Ediacaran Period (*e.g.*, Hoffman *et al.*, 1998). There are postulated to have been three of these events; the Sturtian (~717–660 Ma), Marinoan (ending ~635 Ma) and Gaskiers (~583–582 Ma) (Knoll *et al.*, 2004; Rooney *et al.*, 2015), although the latter has not yet been convincingly shown to be a truly global event (*cf.* Chumakov, 2009; Herbert *et al.*, 2010). The most extreme interpretation of the glacial observations envisages the planet being enveloped in ice for millions of years at a time in so-called ‘Snowball Earth’ events, with the Earth only released from glacial conditions after a gradual increase in atmospheric CO₂ (perhaps caused by global volcanism) passed a threshold level and triggered a runaway greenhouse effect (*cf.* Kirschvink, 1992; Hoffman *et al.*, 1998). Contrary to this view, a raft of data incompatible with a full ‘Snowball’ hypothesis has emerged in recent years, with a less severe but equally influential ‘Slushball’ model, positing extreme polar glaciations but not full global ice coverage, gaining support (*e.g.*, Kilner *et al.*, 2005; Dobrzinsky & Bahlburg, 2007; Allen & Etienne, 2008; Etienne *et al.*, 2009; Sansjofre *et al.*, 2011), and true polar wander also invoked by some (*e.g.*, Hofmann, 1999).

While debate over the spatial extent and correlation of these Neoproterozoic glaciations remains ongoing (*see* Rooney *et al.*, 2015 *for the most recent discussion*), their long durations (on the order of 10⁵–10⁶ years; Kilner *et al.*, 2005) and associated physical and chemical changes recorded in marine sediments imply that they may have had a significant effect on the biosphere. A biological ‘bottleneck’ during the ‘Snowball Earth’ events, with

climatic changes proposed to have reduced global biotic diversity (*e.g.*, Hoffman *et al.*, 1998; Narbonne & Gehling, 2003), seems unlikely given that numerous eukaryotic clades appear to have survived through these events (*e.g.*, Porter, 2004; Ye *et al.*, 2015).

The glaciations coincided with a period of prolonged supercontinental rifting, with Rodinia (McMenamin & McMenamin, 1990) and Pannotia (Scotese, 2009) breaking apart during the late Neoproterozoic (Li *et al.*, 2008; Scotese, 2009). Such rifting events have been postulated to be causally linked to both the glaciations (*e.g.*, Dalziel, 1997), and to the Ediacaran and Cambrian biological radiations (*cf.* McIlroy & Logan, 1999; Brasier & Lindsay, 2001).

Late Neoproterozoic geochemical data show multiple large negative excursions in stable carbon isotopes, including the largest in the geological record (the Shuram/Wonoka excursion, $>10\text{‰}$; *e.g.*, Le Guerroue, 2010; EN3 of Fig. 2). These excursions reveal large-scale perturbations to the global carbon cycle, perhaps related to revolutions occurring in the biosphere, but global chemostratigraphic correlation is not straightforward (*see* Halverson *et al.*, 2005; Bristow & Kennedy, 2008), and the precise relationships between the chemical shifts and the glaciations, and more importantly with the biota, remain to be determined.

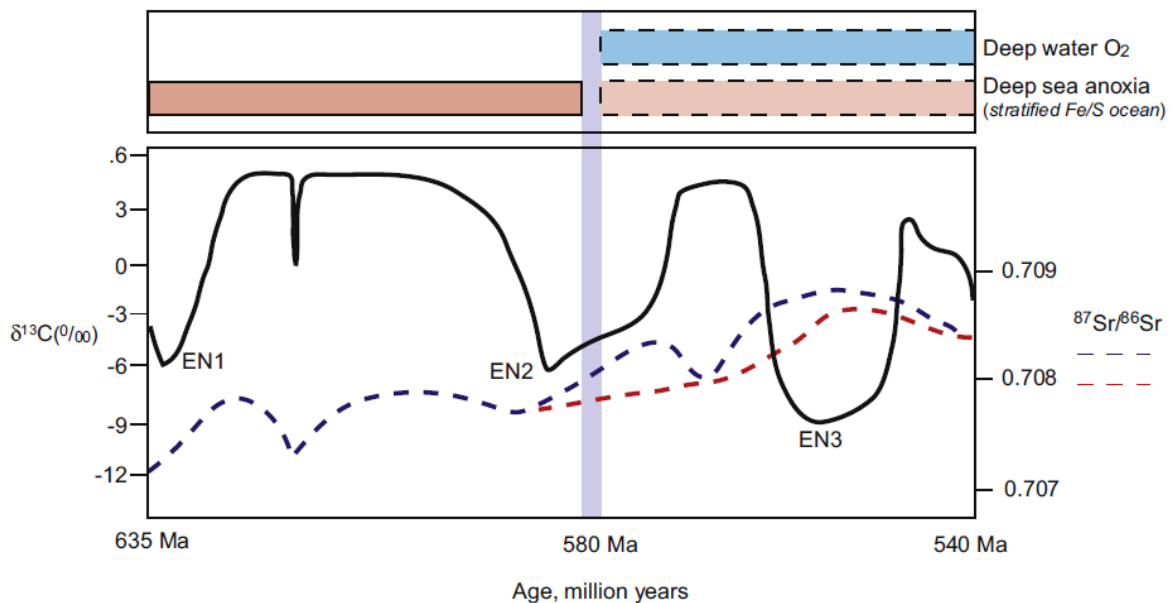


Figure 2. Summary of Ediacaran ocean chemistry, including generalized strontium and carbon isotope curves, and ocean redox evolution (based on iron speciation data). From Narbonne *et al.*, 2012, fig. 18.5, and references therein.

Carbon and sulfur stable isotopes indicate a significant rise in marine oxygen levels through the Ediacaran Period (Fike *et al.*, 2006), while iron speciation studies reveal a ferruginous and sometimes sulfidic water column at depth (Canfield *et al.*, 2008). An apparent pulse of oxygenation to the deep oceans is thought to have immediately followed the Gaskiers glacial event (Fig. 2; Canfield *et al.*, 2007; *see also* Shen *et al.*, 2008), and has previously been proposed as a causal factor for the appearance of the first large macro-organisms, seen here in Newfoundland (Stop 2.1) just three million years later (Cloud Jr., 1968; Narbonne & Gehling, 2003; Catling *et al.*, 2005; Canfield *et al.*, 2007). This link between oxygen and the evolution of large and complex multicellular macro-organisms is not without criticism (*e.g.*, Budd, 2008; Butterfield, 2009b), and further isotopic records from other basins are required to determine its assumed global extent. The most recent studies of Ediacaran marine oxygenation suggest fluctuation of oxygen concentrations, and intermittent/transient oxic and anoxic conditions in deep marine environments (*e.g.*, Wood *et al.*, 2015).

Dramatic changes to the biosphere also occurred through the late Neoproterozoic. Pre-Ediacaran microfossils include bacterial rods and spheres, fungi, algae, and the acritarchs (a group of spherical organic-walled forms whose biological affinity remains uncertain; *e.g.* Vidal & Moczydlowska-Vidal, 1997). Multicellularity was already widespread prior to the Ediacaran Period (*e.g.* Butterfield, 2009a), and eukaryotic microfossils, including testate amoebae and ciliates (Bosak *et al.*, 2011a, b), were reasonably diverse (*e.g.*, Sergeev & Schopf, 2010). Biomineralization may have evolved in some eukaryote lineages at roughly 750 Ma (Porter *et al.*, 2003), and possible foraminifera have been identified within Cryogenian cap carbonates (Bosak *et al.*, 2012). These findings demonstrate that despite the absence of macroscopic organisms, there was a substantial amount of biological diversity present within the early Ediacaran oceans.

Possible macroscopic algae are now known from Marinoan deposits just prior to the base of the Ediacaran in the Nantuo Fm. of South China, ~635 Ma (Ye *et al.*, 2015), while the mid-Ediacaran Lantian biota of South China contains abundant algal fossils of a few centimetres in length (*e.g.*, Yuan *et al.*, 2011). However, the Avalon assemblage of the Ediacaran soft-bodied biota (found mostly in the United Kingdom, and in Newfoundland), marks the point at which “life got big”, and individual organisms reached dimensions of >10 cm (Narbonne & Gehling, 2003). Avalonian assemblages (~580–560 Ma) are followed chronologically by the shallower-marine deposits of the White Sea and Nama assemblages of

Australia, Russia, and Namibia (Fig. 3; *cf.* Waggoner, 2003). Those later assemblages possess evidence for early stem group metazoans (e.g. *Kimberella*; Fedonkin *et al.*, 2007b), alongside macroscopic biomineralizing organisms (e.g. *Cloudina* Germs, 1972), and simple horizontal locomotory traces (e.g., Seilacher, 1999). The enigmatic “Ediacaran biota” of soft-bodied macro-organisms thrived for ~40 million years, but do not appear to have survived into the Cambrian (Fig. 3; though *see* Conway Morris, 1993; Jensen *et al.*, 1998). Preliminary examination of their extinction suggests ecosystem engineering, resulting from behavioural innovations, is the most likely cause of their demise (Laflamme *et al.*, 2013).

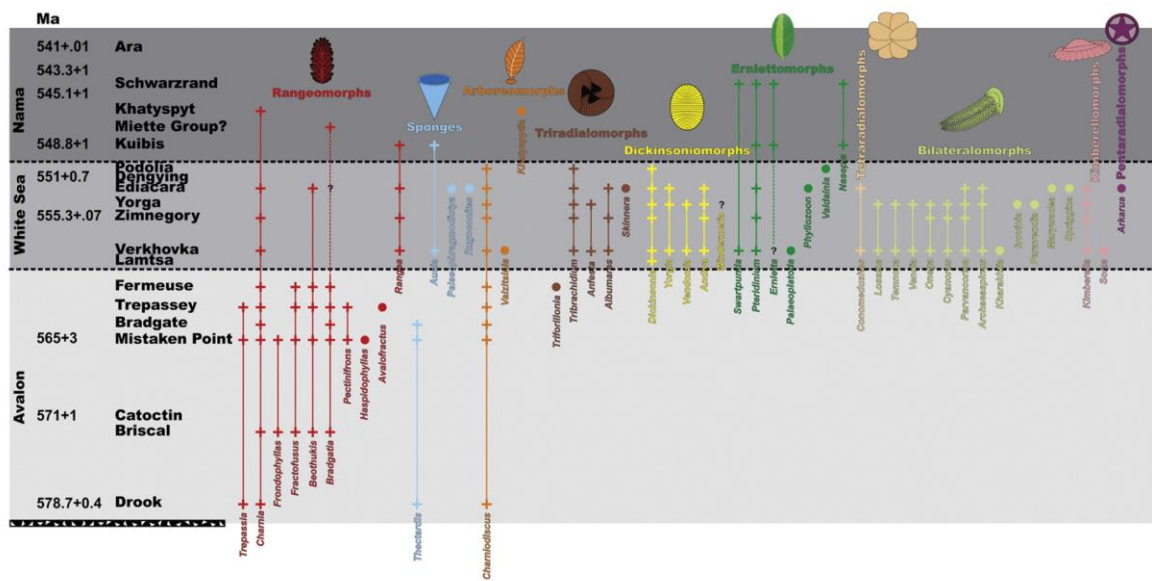


Figure 3. The temporal distribution of Ediacaran macrofossils and their main geographic occurrences. Clade designations follow Erwin *et al.*, 2011. Avalon, White Sea and Nama assemblages follow Waggoner, 2003. See Laflamme *et al.*, 2013, fig. 3, for references to source data.

Although the relationships between many of the enigmatic Ediacaran organisms and those of the Phanerozoic remain to be determined, what is clear is that the Ediacaran Period records a key transition from a Proterozoic, microbially dominated world, to a Phanerozoic biosphere where metazoans exert a significant impact on global ecosystems (*cf.*, Clapham *et al.*, 2003). As we cross the Ediacaran–Cambrian boundary and encounter fossils more akin to extant organisms, we observe changes in macroecology (McIlroy & Logan, 1999; Erwin & Tweedt, 2012), the chemistry and mineralogy of the sediment–water interface (e.g., Brasier, 2009), and even in the nature of fossil preservation (Callow & Brasier, 2009a). Many of these

changes are related to the advent of vertical bioturbation, the breakdown of microbial matgrounds, and the liberation of buried nutrients, generation of new ecospace, and engineering of new ecosystems (*e.g.*, McIlroy & Logan, 1999; Mángano & Buatois, 2014).

The Ediacaran–Cambrian transition is thus considered to be one of the most important intervals in the history of life on Earth. Identifying and understanding the evolutionary events that occurred at this time, and determining the intrinsic and extrinsic feedbacks and driving forces that initiated them, are the ultimate goals of current Ediacaran research.

Stratigraphy, Structural Geology, and Depositional Environment of the Avalon Peninsula

During the latest Neoproterozoic Era, eastern Newfoundland lay just offshore from Avalonia (Murphy & Nance, 1989), a micro-continent that lay at low southern latitudes (Pisarevsky *et al.*, 2011). Avalonian fossil-bearing deep-marine facies, dated at between ~580 and 555 Ma (Van Kranendonk *et al.*, 2008; Noble *et al.*, 2015), can be seen on both the Avalon and Bonavista Peninsulas of Newfoundland (Misra, 1969; Hofmann *et al.*, 2008), and also in Charnwood Forest in Leicestershire, U.K. (*e.g.*, Wilby *et al.*, 2011). Shallow-marine to fluvial Ediacaran successions, with completely different biotic assemblages, occur in Shropshire and Carmarthenshire in the U.K. (*e.g.*, Cope, 1977; McIlroy *et al.*, 2005), and in the Ferryland area of Newfoundland (Gehling *et al.*, 2000). Interested readers are referred to the following publications for further discussions of the sedimentology, stratigraphy, history and paleontology of these shallow-water U.K. regions (Salter, 1856, 1857; Cope, 1977; Pauley, 1991; McIlroy *et al.*, 2005; Callow *et al.*, 2011; Liu, 2011a).

In Newfoundland, a >10 km-thick sedimentary succession of Neoproterozoic rocks is observed, showing a gradual shallowing-upwards trend from deep-marine basin floor paleoenvironments (Ichaso *et al.*, 2007), to shallow-marine and fluvial siliciclastic units (*see* Fig. 4). These sedimentary rocks are believed to have been deposited in a tectonically active basin associated with island-arc volcanism (Myrow, 1995) prior to Avalonia separating from the Amazonian craton (Nance *et al.*, 2002; Wood *et al.*, 2003). This setting provided episodic influxes of volcanic material, which were integral to macrofossil preservation, and provide important horizons for geochronological studies. Numerous sedimentological studies have

been undertaken on the rocks of Mistaken Point, most of which support a deep-water basin floor to slope depositional environment for the Conception Group (*e.g.*, Misra, 1971; Benus and Anderson *in* Landing *et al.*, 1988; Wood *et al.*, 2003; Liu *et al.*, 2010b; *although see* Retallack, 2010, 2014 *for an alternative view*). This interpretation is supported by similar studies of outcrops in the Spaniard’s Bay and Bonavista Peninsula regions (Ichaso *et al.*, 2007; Hofmann *et al.*, 2008).

The Ediacaran siliciclastic deposits of the Avalon Peninsula comprise the Conception, St. John’s, and Signal Hill Groups (Fig. 4). Below these lie the rocks of the Harbour Main Group, comprising rhyolites and basalts as well as some red to grey tuffs and agglomerates (Papezik, 1970; Nixon & Papezik, 1979). The Conception Group, which possesses the bulk of the fossils we will see on this trip, comprises mainly thick-bedded green to grey turbiditic siltstones and sandstones. However, one notable unit is the ~582 Ma Gaskiers Formation, near the base of the Group, which is composed of grey to red diamictites, and minor siltstones and sandstones. This unit is interpreted to be a glaciogenic mass-flow deposit (Williams & King, 1979), and other glacial deposits of similar age worldwide indicate that it may record a significant global event (*cf.* Hoffman *et al.*, 1998).

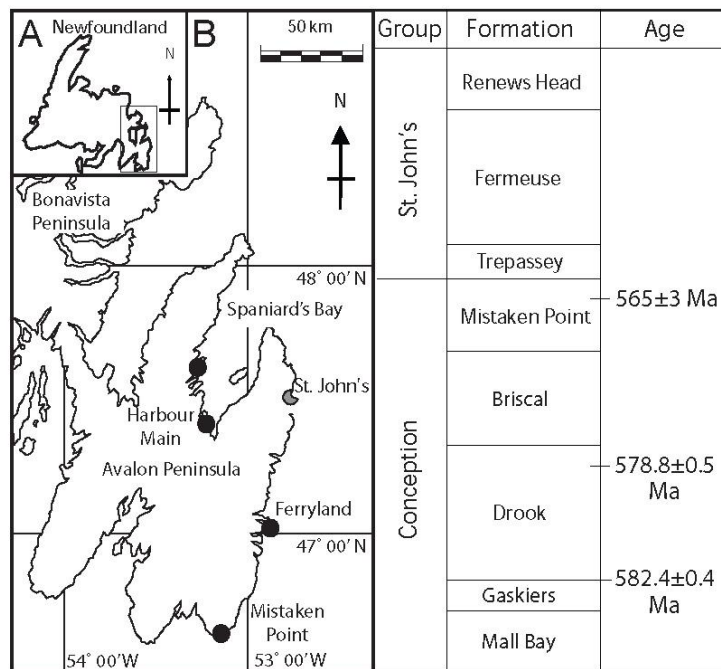


Figure 4. Late Neoproterozoic localities and stratigraphy of the Avalon Peninsula to be visited on this trip Dates are from Benus *et al.*, 1988, and Van Kranendonk *et al.*, 2008.

The Conception Group is interpreted as a basin floor to slope succession (Wood *et al.*, 2003; Ichaso *et al.*, 2007; Mason *et al.*, 2013). Turbidite packages are punctuated by occasional tuffs and tuffaceous beds, which are associated with the exceptional preservation of Ediacaran biotic communities such as those seen Mistaken Point (*see* Narbonne *et al.* in Fedonkin *et al.*, 2007a). Progressively shallower sediments of the St. John's Group are recorded by the Trepassey, Fermeuse and Renew's Head formations, which conformably overlie the Conception Group. The St. John's Group is mainly composed of grey sandstones, siltstones and occasional shales, and in comparison to the Conception Group, there are fewer beds of tuff and tuffaceous material. Slump structures are found throughout the Group, most notably within the Fermeuse Formation. The St. John's Group is considered to have been deposited on a prograding delta slope (King *et al.*, 1988; Matthews, 2011).

Finally, the Signal Hill Group represents the shallowest deposits of the Ediacaran succession on the Avalon Peninsula, and the final infill of the Neoproterozoic basin. Grey to red siltstones and sandstones with occasional carbonate and phosphatic nodules characterise the group, with coarse fluvial conglomerates at the top of the succession. Evidence of shallow-marine and fluvial environments, including wave ripples, desiccation cracks, and fluvial cobble conglomeratic facies, becomes increasingly common up-section. Paleoenvironmental reconstructions suggest this Group represents a southwards-prograding deltaic and fluvial/alluvial deposit (King *et al.*, 1988; Matthews, 2011).

EDICARAN PALEONTOLOGY OF THE AVALON PENINSULA

Ediacaran fossils from Avalonia represent some of the oldest and most spectacularly preserved macroscopic organisms in the geological record. In Newfoundland, 28 distinctive Ediacaran macrofossil taxa have been formally described, many of which are not known outside the Avalonian micro-continent. The fossil assemblages are dominated by frondose ‘rangeomorph’ fossils (*e.g.*, *Charnia*, *Bradgatia*), and discoidal forms (*e.g.*, *Aspidella*, *Hiemalora*), alongside several miscellaneous taxa (Fig. 5; reviewed in Liu *et al.*, 2015). Recent studies have revealed that in many cases, the former two groups are associated, with the discoidal forms comprising the attachment structures of fronds, tethering them to the seafloor (*e.g.*, Laflamme & Narbonne, 2008; Burzynski & Narbonne, 2015; Fig. 5D, F).

The biological affinities of many members of the soft-bodied Ediacaran biota remain to be determined. The Ediacaran macrofossil taxa of Avalonia may include algae (Hoffman *et al.*, 2008), extinct phyla (Seilacher, 1992), fungi (Peterson *et al.*, 2003), and protists (Antcliffe *et al.*, 2011). Of greatest significance is the possibility that some taxa represent stem- or crown-group animals (*e.g.*, Jenkins, 1985; Narbonne, 2005; Sperling *et al.*, 2011). Regardless of whether animals were present in late Ediacaran marine ecosystems, they should be considered as diverse, and often densely-populated, assemblages (Darroch *et al.*, 2013; Liu *et al.*, 2015).

Preservation of Ediacaran macrofossils

At Mistaken Point, fossils are preserved on over 100 bedding planes beneath volcanic ash deposits of millimetre to decimetre thickness (Clapham *et al.*, 2003). The ash is considered to have either sunk through the water column to smother the organisms *in situ* on the seafloor (in a manner similar to an ‘Ediacaran Pompeii’; Narbonne, 1998), or to have been washed down-slope in volcanoclastic turbidity currents (Narbonne, 2005). These mechanisms of preservation has been termed Conception-type (Narbonne, 2005), distinguishing them from the preservational styles seen at other global Ediacaran fossil assemblages.

While studying Ediacaran fossils from South Australia, Gehling (1999) suggested that microbially mediated pyritization during the early stages of diagenesis may have formed a ‘death mask’ around deceased Ediacaran organisms, forming an accurate representation of their external surfaces prior to decay of the organic tissues. Experimental taphonomy provides evidence in support of this model (Darroch *et al.*, 2012), while petrographic studies confirm the original presence of a pyrite veneer in Australia (*cf.* Mapstone & McIlroy 2006).

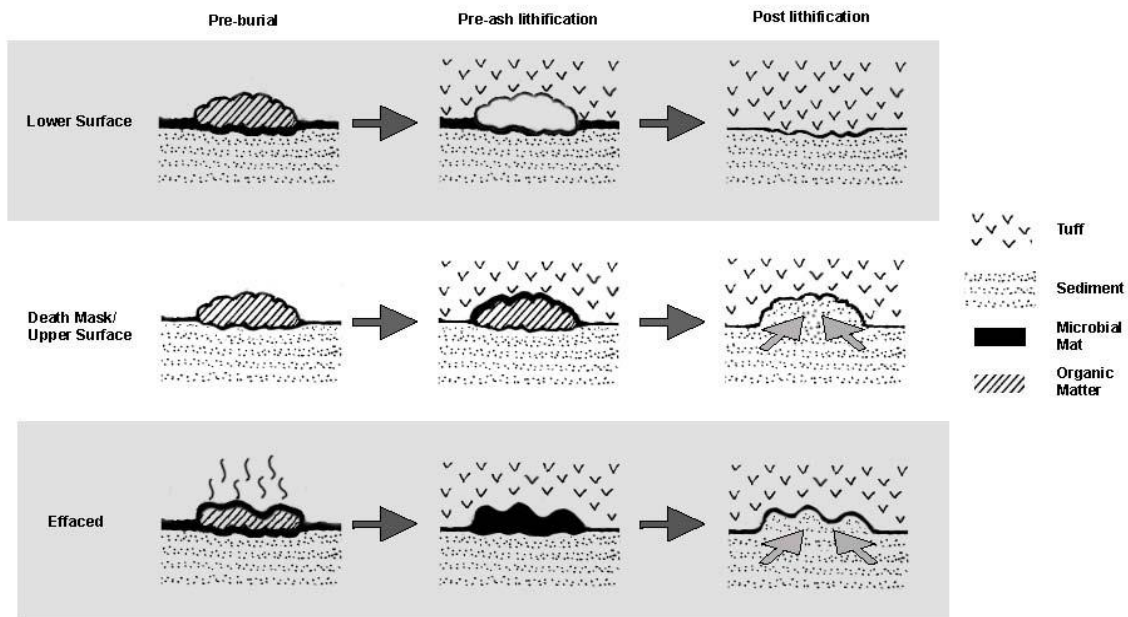


Figure 5. The three most common modes of fossil preservation observed in the Conception Group. Death mask preservation was named by Gehling (1999), Lower and Upper surface are variants of the Conception-type preservation of Narbonne (2005). Figure taken from Liu *et al.*, 2011, fig. 12.

Different taxa, and sometimes even different parts of individual specimens, can be preserved in both negative and positive epirelief on Avalonian bedding planes (here referred to as ‘lower’ and ‘upper’ surface preservation respectively, following Liu *et al.*, 2011; Fig. 5). Lower surface preservation is typically of high fidelity, and is inferred to occur when ash collapses in to fill the void left by a buried organism once it decays away (Narbonne, 2005).

In contrast, upper surface preservation is explained by a pyritic ‘death mask’ forming and rapidly lithifying on the upper surface of the buried organisms, such that once the organism decays, tuff above does not collapse in from above, and the void is instead filled by sediment injected in from beneath (Gehling, 1999; Narbonne, 2005).

Until very recently, it was considered that the fossil assemblages at Mistaken Point preserved snapshots of Ediacaran communities that were alive at the time of burial (*e.g.*, Clapham *et al.*, 2003). In 2011, analysis of Ivesheadiomorph fossils (see Stops 2.1 and 2.3) led to the suggestion that some of the fossils preserved on the bedding planes may represent organisms that had been dead and decaying on the seafloor for some time prior to burial, and thus the communities we now see are significantly time-averaged (Liu *et al.*, 2011). Since there is a striking lack of evidence for predation, scavenging, and pervasive bioturbation in the late Ediacaran rocks of the Conception Group (*e.g.*, McIlroy & Logan, 1999; Seilacher, 1999; Bottjer *et al.*, 2000; Jensen *et al.*, 2006), microbial degradation and autolysis are envisaged to have been the only available biological mechanisms capable of removing large concentrations of organic matter from the seabed (Liu *et al.*, 2011). More recent studies by Wilby *et al.* (In Press) reveal that time averaging of communities also results from small influxes of sediment that can be lethal to small organisms, but not to larger individuals.

The Avalon Assemblage

Research into the Ediacaran fossils of Newfoundland began in 1872 with the description of the discoidal fossil *Aspidella terranovica* from Precambrian rocks in downtown St John's (Billings, 1872). No further discoveries occurred until the late 1960s, when a graduate student at Memorial University, S. B. Misra, found the spectacular fossil bedding planes at Mistaken Point (Anderson and Misra, 1968; Misra, 1969). Considerable exploration of the region followed, aided in part by the mapping exploits of Williams and King (1979).

Since the millennium, paleontological research into Avalonian fossils has enjoyed a period of unparalleled growth, initially led by the work of Guy Narbonne and his students at Queen's University in Ontario, and more recently supplemented by researchers from McGill, the University of Oxford, Memorial University of Newfoundland, the British Geological Survey, and the University of Cambridge. The enigmatic nature of the biota has attracted public attention, with the sites visited by NASA Astrobiology researchers, and BBC and CBC camera crews in recent years. Major Ediacaran fossil localities have been described from the Catalina Dome of the Bonavista Peninsula (O'Brien & King, 2004; Hofmann *et al.*, 2008), and at Spaniard's Bay (Narbonne, 2004). Both of these sites have provided significant

insights towards our understanding of Ediacaran paleobiology, with several new taxa described (Hofmann *et al.* 2008; Narbonne *et al.*, 2009), including evidence for metazoans with preserved impressions of muscular tissue (Liu *et al.*, 2014a).

The United Kingdom houses three significant Ediacaran fossil localities, namely Charnwood Forest (Leicestershire), the Long Mynd Hills (Shropshire), and the Llangynog Inlier (Carmarthenshire). Despite these being deposited at broadly the same time in the late Ediacaran Period (~560 Ma), these three regions contain rather different biotic assemblages. This taxonomic variability is likely to be related to differences in facies, with each region recording a different depositional environment. Charnwood possesses the closest similarities to Mistaken Point, and was the original site at which iconic forms such as *Charnia masoni* were first discovered (Ford, 1958). Recent casting projects by the British Geological Survey reveal that at least 60% of the Charnwood taxa are shared with Mistaken Point, suggesting that endemism between the two localities is not as marked as has previously been suggested (Wilby *et al.*, 2011). Geochronological dating has also confirmed a similar age for the Charnian Supergroup (~569–556 Ma; Noble *et al.*, 2015).

The Long Mynd Hills of Shropshire record a shallow-water sedimentary succession of late Ediacaran age (566.6 ± 2.9 – 555.9 ± 3.5 Ma; Compston *et al.*, 2002), and lay claim to the first description anywhere in the world of a Precambrian body fossil (erroneously interpreted as an ichnofossil at the time; *Arenicoloides didyma* Salter 1856). The shallow-marine slope to fluvial and alluvial facies of the Long Mynd are dominated by microbial mats and mat-related sedimentary structures (McIlroy *et al.*, 2005; Menon *et al.*, In Press). Meanwhile, the Llangynog Inlier in Carmarthenshire preserves a respectable number of discoidal Ediacaran macrofossils, previously assigned to the genera *Cyclomedusa* and *Medusinites* (Cope, 1982), alongside rare *Hiemalora* and *Palaeopascichnus* specimens. Small horizontal surface traces may also be present (Cope, 1977). As with the Long Mynd, this shallow-water succession is not currently known to contain any frondose taxa.

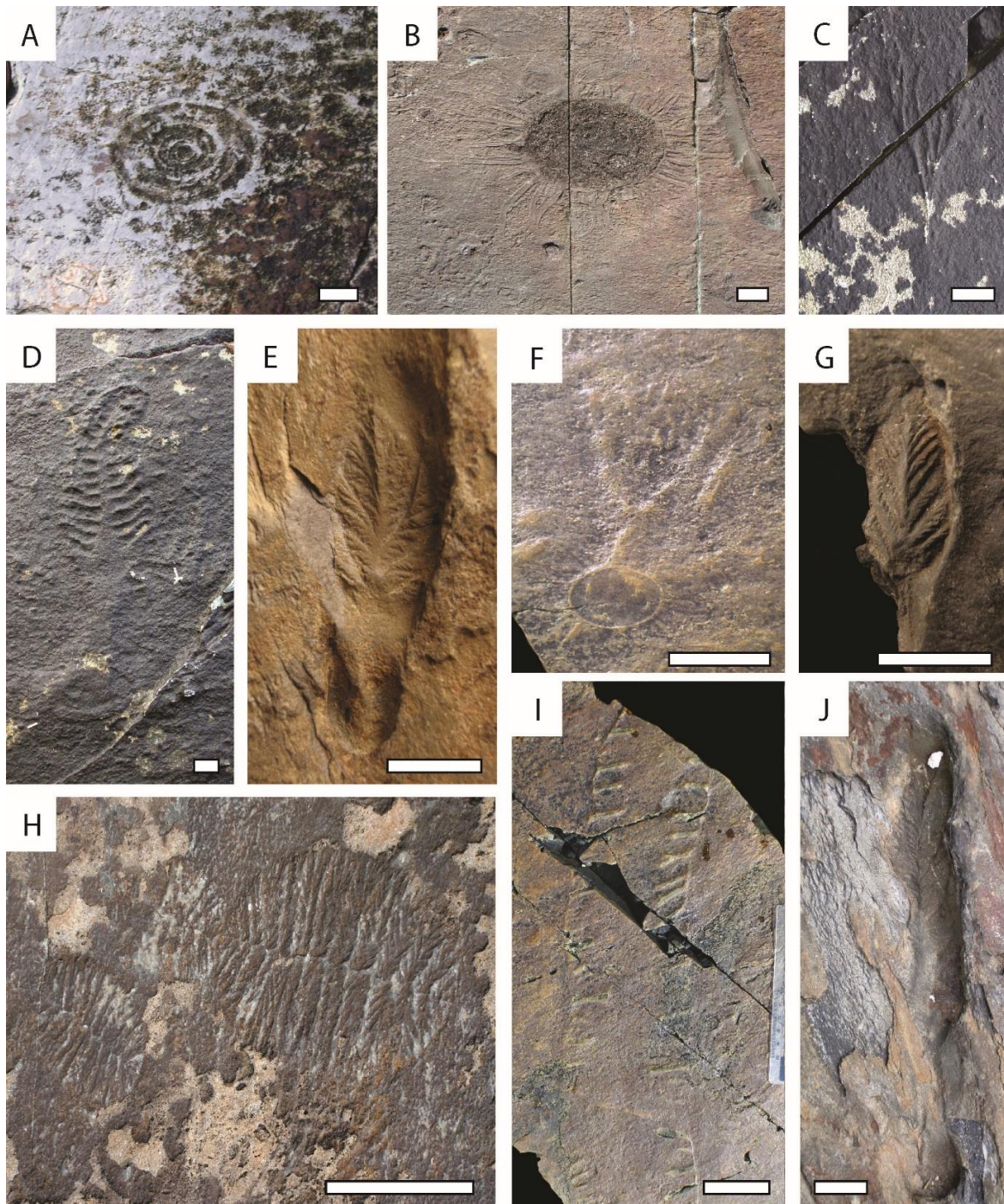


Figure 6. Representative taxa from the Ediacaran rocks of the Bonavista Peninsula (A–D, F, H–I), and the Spaniard’s Bay region (E, G, J). **A:** *Aspidella terranovica* Fermeuse Fm. **B:** *Hiemalora stellaris*, Murphy’s Cove, Mistaken Point Fm. **C:** *Parviscopa bonavistensis*, Mistaken Point Fm. **D:** *Charniodiscus* sp. Mistaken Point Fm. **E:** *Beothukis mistakensis*, Trepassey Fm. **F:** *Primocandelabrum hiemaloranum* (holotype), Mistaken Point Fm. **G:** *Avalofractus abaculus*, Trepassey Formation. **H:** *Fractofusus andersoni*, Trepassey Fm. **I:** *Hadryniscala avalonica* (holotype), Mistaken Point Fm. **J:** *Trepassia wardae*, Trepassey Formation. Scale bars = 10 mm, except F, H and I = 50 mm.

Current research into the Mistaken Point Ediacaran Fossils

Mistaken Point records the oldest fossils of large, architecturally complex multicellular organisms. 1000s of these fossils occur through hundreds of metres of stratigraphic section. Efforts to protect this site and provide global recognition for its paleontological riches have led to the province of Newfoundland and Labrador submitting a bid for UNESCO World Heritage Site status; a decision on this application is due in 2016. Since the initial discovery of macrofossils at Mistaken Point, research has focused on a variety of different topics, and some of the most active fields are discussed below.

Biological affinities and paleoecology

Much debate has surrounded the biological affinities of the Mistaken Point macrofossils, and indeed the nature of the Ediacaran soft-bodied macrobiota in general. Following Glaessner (1959), most early work on the Mistaken Point organisms considered them to be cnidarians (*e.g.*, Misra, 1969; Anderson, 1978), while similar forms from elsewhere in the Avalon region were discussed as possible algae (Ford, 1958). A turning point came with the suggestion that the Mistaken Point fossils, and the wider Ediacaran macrobiota in general, may belong to an entirely extinct Kingdom or Phylum, the ‘Vendobionta’ (Seilacher, 1992, 1999, 2007). This provocative hypothesis encouraged critical thinking about the biota, and led to many different biological groups being suggested to be represented within the Mistaken Point fossil assemblages (*e.g.*, Narbonne, 2005 *and references therein*). The general current consensus is that the biota likely includes members of several diverse Phyla and Kingdoms, and the biology of each taxon should be assessed on a case-by-case basis (Laflamme *et al.*, 2013; Liu *et al.*, 2015).

Rangeomorphs, composed of multiple fern-like self-similar branches (Narbonne, 2004) have variously been considered to represent early/stem group animals (*e.g.*, Narbonne, 2005, 2010), or a “failed experiment” towards the base of animal evolution (Narbonne, 2004, 2005, 2007), though other alternatives have been suggested (*e.g.*, Seilacher, 1992; Retallack, 1994). In terms of higher taxonomic classification systems for the Ediacaran macrobiota as a whole, terms such as Petalonamae (Pflug, 1972) and Vendobionta (Seilacher, 1992), have previously been proposed (*see also the review in Fedonkin et al.*, 2007a, p. 240–242), but these are yet to be widely accepted. Erwin *et al.* (2011) proposed a novel method of classifying the Ediacaran biota, based on morphological architecture and symmetry (*see also*

Laflamme *et al.*, 2013, and Grazhdankin, 2014). In addition to the Rangeomorpha, three other higher order groups recognised by those authors are represented within the MPER. The Arboreomorpha (a proposed clade of fronds possessing a central stalk and an outer margin but lacking rangeomorph branching) includes all members of the genus *Charniodiscus* (Erwin *et al.*, 2011). Porifera are considered to be represented by the triangular form *Thectardis avalonensis* (Erwin *et al.*, 2011; following Sperling *et al.*, 2011). Finally, *Triforillonia costellae* from the Fermeuse Formation (Stop 3.2) is assigned to the Triradialomorpha.

The deep-marine depositional environments postulated for the Avalonian successions discount the possibility that the Mistaken Point Ediacaran macro-organisms (preserved *in situ* on the seafloor) were originally photosynthetic. Apparent analogies between rangeomorph fronds and the leaves of modern plants thus appear to indicate a convergent functional role rather than a biological ancestry (Laflamme & Narbonne, 2008). Previous discussion of rangeomorphs as sessile filter feeders (*e.g.*, Narbonne, 2005), has been superseded by the suggestion that they may have been osmotrophs, absorbing nutrients directly from the water column (Laflamme *et al.*, 2009); a finding supported by recent modelling studies investigating canopy flow in rangeomorph communities (Ghisalberti *et al.*, 2014). It remains to be seen whether frondose taxa considered by some to be non-rangeomorph fronds (*e.g.*, *Charniodiscus*) could also have been osmotrophs, but it should be noted that in a recent paper, Sperling *et al.* (2011), by considering *Thectardis* to be a sponge, imply that it at least may have obtained nutrients via filter feeding.

The diverse and abundant fossil assemblages on the Mistaken Point bedding planes lend themselves well to paleoecological study. Clapham and Narbonne (2002) documented apparent tiering within the rangeomorph-dominated communities, inferring that the various species were competing for nutrient resources in the water column. By assuming that the surfaces record census populations of the ecosystems at the time of ash burial, modern ecological methods have been applied to the Mistaken Point assemblages (Clapham *et al.*, 2003; Darroch *et al.*, 2013). These suggest that ancient Avalonian ecosystems show community structure similar to that of Phanerozoic and modern suspension-feeding animal communities (though comparison with non-metazoan modern biotic groups was not explored), and have also provided information on reproductive strategies. However, the suggestion that the bedding planes may record time-averaged, not census, populations (*cf.* Liu

et al., 2011), may cast doubt on the validity of these inferences (Liu *et al.*, 2015). Most recently, spatial analyses have been employed to investigate reproductive strategies amongst rangeomorphs (specifically the genus *Fractofusus*; Mitchell *et al.*, 2015; Stop 2.3).

Evolution, radiation, and extinction

Waggoner (2003) proposed that three Ediacaran biotic assemblages - the Avalon, White Sea, and Nama - can be recognised within the global late Ediacaran biota (Fig. 3). There is some overlap between taxa in these various assemblages, and they are largely defined by their facies associations, paleogeography, and their relative ages. The Avalon biotic assemblage is typically found in the oldest localities (580–560 Ma), which are centred around the micro-continent of Avalonia, and deposited within deep-water depositional environments. The situation has become more complicated with the discoveries of new sites and organisms since 2003, particularly those from China (*e.g.*, the Miaohu biota; Xiao *et al.*, 2002), and it is becoming increasingly clear that facies are more likely to be responsible for governing the composition of fossil assemblages than temporal or taphonomic factors (Grazhdankin, 2004; Laflamme *et al.*, 2013; Gehling & Droser, 2014).

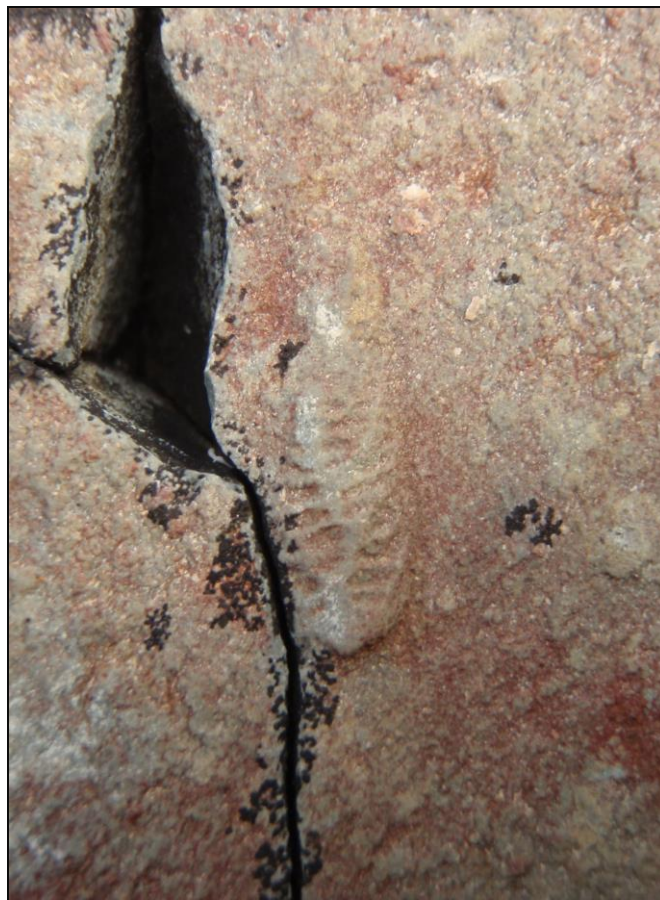
Geochronology

Despite the importance of Newfoundland's Ediacaran sites, only a handful of published geochronological dates are available for the region. These suffer from being presented only within abstracts (Benus, 1988; Bowring *et al.*, 2003), or in figures in text-books (Van Kranendonk *et al.*, 2008); the isochrons from which they are derived, and the precise stratigraphic levels from which they were obtained, have rarely been published.

The Gaskiers glacial is considered to have ended 582.4 ± 0.4 Ma (Bowring *in* Van Kranendonk *et al.*, 2008). Ashes adjacent to the ivesheadiomorph bed at Pigeon Cove (Stop 2.1) have been dated by U-Pb to 578.8 ± 0.5 Ma (Van Kranendonk *et al.*, 2008), demonstrating that some of the first fossils in the region were present as little as three million years after the end of the Gaskiers glacial (Narbonne and Gehling, 2003). The only other widely cited date for the successions comes from the Mistaken Point E Surface (Stop 2.3), which is dated at 565 ± 3 Ma (Benus, 1988). Geochronological studies are underway to obtain further dates from the Avalonian sections.

PART 2: FIELD TRIP ITINERARY

The field trip itinerary is broken into three full days. Day One represents a free-standing single-day fieldtrip, and focuses on rocks of the Spaniard’s Bay area. Days Two and Three focus on the Ediacaran fossils of the southeastern Avalon Peninsula, including the first appearance of the classic soft-bodied “Ediacaran biota” anywhere in the world, via the spectacular fossil assemblages of the Mistaken Point Ecological Reserve, and outcrops of the Fermeuse Formation in the vicinity of Ferryland. Field trip stops are indicated in Figure 4. It is possible that the order of these excursions will need to be adjusted in the light of weather conditions. It is also possible that the order of stops on a given day may require some adjustment, or that some stops will need to be omitted due to time constraints.



Small frondose fossil from Pigeon Cove, Mistaken Point Ecological Reserve.

DAY ONE FIELD TRIP STOPS

Harbour Main and Spaniard's Bay

Stop 1.1: Harbour Main

*Leave St. John's along the TCH and take exit 36 to Holyrood. In Holyrood take a left on Route 60 towards Harbour Main. In the town of Harbour Main turn right onto Harbour Drive and follow the shore for 0.7km, parking opposite the St. Peter and Paul Church. Two localities will be visited. **Take care when descending to the outcrops.***

Harbour Main contains one of the best exposures of the Gaskiers Formation and its associated carbonate horizon in Newfoundland. The Neoproterozoic interval contains at least three large-scale glacial events, which have been interpreted to record climatic perturbations of enormous spatial and temporal extent (Hoffman, 1998; Halverson *et al.*, 2005). The two largest events, the Sturtian (717–660 Ma) and the Marinoan (ending ~635 Ma; Rooney *et al.*, 2015), document glacial activity at equatorial paleolatitudes, and coincide with significant shifts in marine carbon isotope values (Halverson *et al.*, 2005). Although several authors have suggested that these glaciations may have been ‘bottleneck’ events for evolution, in recent years increasing evidence suggests that multiple eukaryotic groups survived through this interval (e.g. Bosak *et al.*, 2011, 2012; Ye *et al.*, 2015).

The ~583–582 Ma Gaskiers Formation of Newfoundland is a glacial diamictite, and can reach thicknesses of ~280m (Myrow & Kaufman, 1999). However, it has a limited temporal range (maybe as little as 1 million years; Van Kranendonk *et al.*, 2008), and does not appear to have been globally extensive. Correlation with other glacial deposits of the latest Ediacaran (e.g. the Moelv tillite of Norway, or the Squantum tillite of the Boston Basin) are as yet unconfirmed (Trindade & Macouin, 2007). However, unlike most mid- to late Ediacaran glacial deposits, the Gaskiers does appear to have a ‘cap carbonate’ at its top, and this can be clearly seen at Harbour Main. The Harbour Main carbonate is a ~40cm thick, discontinuous, very-fine-grained, unfossiliferous recrystallized white-pink limestone. It was deposited on a slope, as evidenced by slumps within the diamictite beneath. This slumping

may be responsible for the presence of what appear to be identical clasts of carbonate *within* the diamictite (Myrow & Kaufman, 1999).



Figure 7. The transition from red diamictite to red mudstone, and then green-beige weathering (originally white) carbonates at the Harbour Main locality.

The diamictite itself contains 5–6cm diameter clasts within a silt- to grit-sized matrix. Evidence for dropstones is rare, and although exotic clasts of quartzite and foliated granite exist, the majority of clasts are from Avalonian igneous sources (Eyles & Eyles, 1989). Towards the top of the diamictite, weathering becomes red in colour, and the unit exhibits several laminations as well as multiple small faults. The upper ~50cm of the diamictite contains few clasts, and is essentially a red mudstone, with thin green siltstone interbeds, before the main limestone bed. The base of the mudstone has been interpreted as a flooding surface (Myrow & Kaufman, 1999). The mudstone then conformably grades into the limestone, which contains nodular concretions in places.

Differences in the thickness and continuity of the carbonate at the two sites we will visit raise questions about the validity of this unit as a true ‘cap carbonate’ (as discussed in Narbonne *et al.*, 2005). The diamictites at both sites are considered to represent a similar level offset by faulting, but those at the point next to the church contain clasts and rafts of mudstone and limestone, as opposed to a continuous cap. These observations most parsimoniously suggest that the strata were deposited upslope, and have been transported to their current position by slumping, with those at the church point being more disturbed and losing their original stratigraphic relationships to a greater extent to those at the first site (Narbonne *et al.*, 2005). However, the possibility that carbonate clasts within the diamictite suggest carbonate deposition before the end of the glaciation has also been raised (Myrow & Kaufman, 1999).

Today’s remaining localities have been designated provincial “Significant Paleontological Sites”, and are protected under the Newfoundland and Labrador Regulation 67/11, under the Historic Resources Act. The collection, marking, or damaging of fossils is strictly prohibited, and scientific research may only be carried out under permit.

<http://www.assembly.nl.ca/legislation/sr/annualregs/2011/nr110067.htm>

The fossil localities near the town of Spaniard’s Bay were brought to global attention in a *Science* paper documenting exceptional preservation of rangeomorph branching (Narbonne, 2004). Morphological features <150 µm in size are preserved in some specimens, and the site has revealed much information about both the ontogeny and architecture of rangeomorph taxa (*e.g.*, Flude & Narbonne, 2008; Narbonne *et al.*, 2009; Brasier *et al.*, 2012). Late Ediacaran strata spanning the Drook to Fermeuse Formations are found in the Spaniard’s Bay area, although the Briscal Formation is not present (*for a detailed account of the sedimentology of this region, see* Ichaso *et al.*, 2007).

Stop 1.2: The ‘Allison’ Surface

We will continue north along Route 60 to the community of Spaniard’s Bay. North of Spaniards Cove we will take a left along Bishops Cove Shore Road, heading north along the coastline to the famous ‘Allison’ Surface, home of spectacularly-preserved ‘three-dimensional’ rangeomorph fossils.

The key fossil-bearing bedding plane described by Narbonne (2004) is named after Allison Daley, who originally discovered the fossils at this site (Allison is now a renowned Cambrian palaeontologist, holding a lectureship at the University of Oxford, U.K.). The section is horizontally-bedded, and records thin-bedded T_{de} turbidites of the Trepassey Formation, with occasional slumps further up the succession (Narbonne *et al.*, 2005). Deposition is thus inferred to have taken place in a deep-marine slope environment (Ichaso *et al.*, 2007). Unlike many Ediacaran fossil-bearing surfaces in Newfoundland, the ‘Allison’ Surface is not smothered by a volcanic tuff, but by sandy volcanoclastic sediments.

Around 100 complete rangeomorph specimens are present on the surface, typically being <10cm in length. However, hundreds of other holdfasts and scours on the surface suggest original fossil densities are likely to have been extremely high. Overall taxonomic diversity on the surface is relatively low, but the rangeomorphs include *Trepassia* (Fig. 4J), *Beothukis* (Fig. 4E), *Charnia* sp., and the only occurrence of the genus *Avalofractus* anywhere in the world (Fig. 4G; Narbonne *et al.*, 2009). Uniquely, some specimens at this site appear to preserve internal morphological detail (Narbonne, 2004). Rangeomorphs are preserved almost three-dimensionally on the bedding plane, an observation that has attracted considerable discussion. Most recently it has been suggested that this unusual topographic relief results from burial of the original community by a high velocity flow. The flow scoured hollows in the seafloor on the leeward side of the organisms, and they were impressed into this soft, fine-grained sediment, where they were buried and preserved (Brasier *et al.*, 2013). Abundant sedimentological evidence, including scours, levees, tool marks, and flat-topped ripples, supports this hypothesis (Fig. 8). Impression of the organisms into the muddy substrate is partly responsible for the exceptionally fine morphological detail recorded here (Narbonne *et al.*, 2005).

Burial within a high velocity flow regime may also explain other enigmatic structures preserved on the surface. These include ‘bubble trains’, which are elongate groups of hollows

preserved between flat-topped ripples. Originally described as potential evidence for microbial roll-up structures (Laflamme *et al.*, 2011b), they have alternatively been suggested to reflect load structures formed by the current that smothered the ecosystem (Brasier *et al.*, 2013). Other unique features on this bed are the smooth regions that seem to envelop some of the fronds (labelled (b) in Fig. 8c) previously interpreted as biological ‘sheaths’ (Narbonne *et al.* (2009). An alternative explanation is that these structures represent the edges of the scours into which the fronds have fallen (Brasier *et al.*, 2013). Efforts to resolve this debate are ongoing, but it is likely that many more key insights into rangeomorph biology and ecology will be gleaned from this unique site in the coming years.

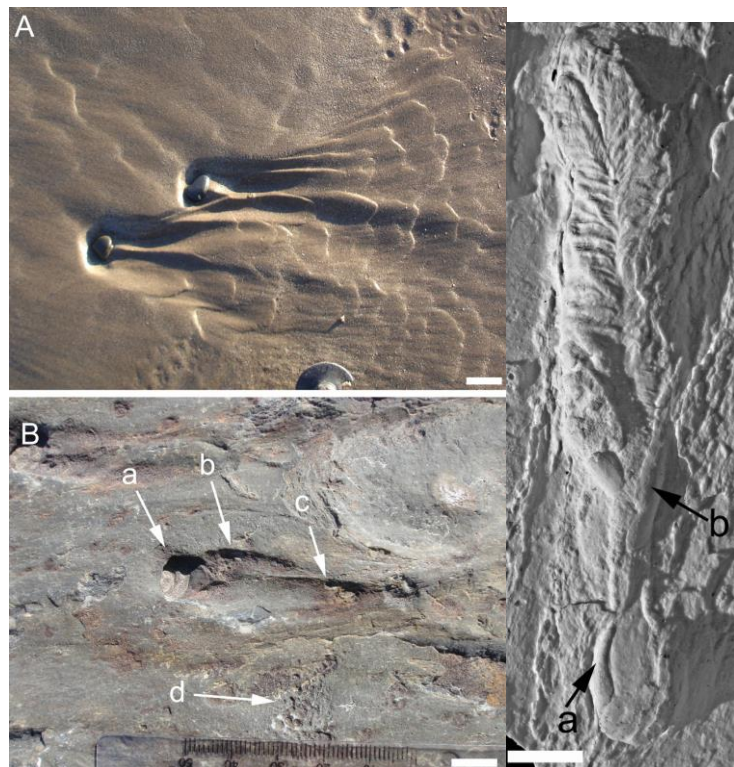


Figure 8. Evidence for a sedimentary current-scour explanation for the ‘three-dimensional’ preservation of Ediacaran macrofossils on the ‘Allison’ Surface. (A) Longitudinal obstruction scour forming on a modern beach in the lee of two small obstacles; current flow towards the right. (B) A longitudinal obstruction scour on the fossiliferous surface at Spaniard’s Bay, with paleocurrent flow to the right. (C) Cast of a specimen of *Trepassia wardae* (OUM ÁT.440/p), viewed laterally, showing the sediment overhang above the basal disc, the depth of the scour trough in which the specimen sits, and the inferred current direction. Scale bar for A = 20 mm; B, C = 10 mm. From Brasier *et al.*, 2013, figs 7 and 10.

Stop 1.3: Green Head

*After returning to Spaniard's Bay, we will take a small secondary road leading to Green Head. We will park the vehicles at the end of the road and walk a short distance along a coastal path to the headland. **Take care when descending to the beach.***

The bedding plane at Green Head possesses a diverse assemblage of Ediacaran macrofossils on shallow-dipping surfaces along the tide-line. Cleavage planes through the section provide excellent exposures through the thin to medium bedded turbidite sequence (T_{cde} and T_{de}) of the Mistaken Point Formation in this region. Beds are generally tabular, with sharp bases and normal grading, and no evidence of shallow-water conditions (Narbonne *et al.*, 2005). Cross bedding within individual turbidites is often picked out by dark brown carbonate-rich sands, with paleocurrent inferred to be in the east/southeast. However, frond alignments on the fossil beds indicate alignment to the southwest, suggesting that they have been oriented by contour currents (Narbonne *et al.*, 2005). The thin volcanoclastic layer smothering this surface appears to have a patchy, discontinuous distribution.

The fossil assemblage is identical in taxonomic composition and taphonomic style to those found over 100km away at Mistaken Point, and include *Pectinifrons*, *Charniodiscus spinosus*, *Bradgatia* and *Fractofusus*, alongside multiple concentric discs that represent the impressions of holdfast structures for frondose organisms. Most specimens are mature individuals, and the succession has been interpreted as a mid-succession community on the basis of its paleoecological attributes (Clapham *et al.*, 2003). We will see the same taxa in greater abundances within the Mistaken Point Ecological Reserve.

This is the final stop on today's field trip. We will now head back to the vehicles and return to St. John's.

DAY TWO FIELD TRIP STOPS

Mistaken Point Ecological Reserve

Upon leaving St. John's, we will travel south on Route 10 (the 'Irish Loop Drive') to the settlement of Portugal Cove South, and the Edge of Avalon Interpretation Centre. The centre houses a display on the fossils of Mistaken Point, and includes part of the cast of the 'E' Surface made in 2009 in a collaborative project between interested museums, universities, and the Government of Newfoundland and Labrador (see Stop 2.3 for further information). It also hosts exhibits on local culture and history, natural history, and the nearby Cape Race lighthouse. The visitor centre marks your last opportunity to make use of public conveniences until we return from the field – there are no facilities, and very little natural cover, within the reserve itself.

From Portugal Cove South, we follow the coastal road for 1.9 km, and then join the gravel track of the Cape Race road. All of today's sites lie within the Mistaken Point Ecological Reserve (Figure 1).

Stop 2.1: Pigeon Cove

This stop will introduce participants to the sedimentology and taphonomy of the Ediacaran units within the Mistaken Point Ecological Reserve, and to their stratigraphic context. The diverse Pigeon Cove bedding plane possesses one of the oldest fossil assemblages in the Reserve, and contains an interesting mixture of large, effaced ivesheadiomorphs, and well-preserved juvenile rangeomorphs.

THIS SITE HAS ONE OF THE HIGHEST RATES OF COASTAL EROSION WITHIN THE RESERVE. PLEASE DO NOT WALK ON THE PIGEON COVE FOSSIL SURFACE. PLEASE ALSO BEWARE OF LARGE WAVES.

Pigeon Cove lies within the upper Drook Formation, which preserves the oldest assemblages of Ediacaran macrofossils in Newfoundland (Narbonne & Gehling, 2003). The main fossil-bearing surface lies immediately beneath a 35-cm-thick volcanic ash deposit, radiometrically dated to 578.8 ± 0.5 Ma (Van Kranendonk *et al.*, 2008). The bed and its

fossils were therefore deposited around 3 million years after the end of the Gaskiers glacial event (Narbonne & Gehling, 2003; Van Kranendonk *et al.*, 2008).

Fossils here lie on a fine siltstone that is interspersed by several wispy red-weathering levels. These often record horizons with very thin tuffs, and the red colouration is a result of oxidation of pyrite that formed via microbial activity at the interface between ash and seafloor sediment (*cf.* Gehling, 1999; Darroch *et al.*, 2012). The overlying yellow-green tuff is responsible for preserving the fossils, having smothered the organisms *in situ* on the seafloor. The Drook assemblage contains large specimens of *Trepassia wardae*, *Vinlandia antecedens*, *Thectardis avalonensis*, and numerous ivesheadiomorphs (*e.g.*, Narbonne *et al.*, 2005), but multiple juvenile rangeomorphs of < 30 mm length (including *Charnia masoni* and potentially *Charniodiscus* sp.), along with filamentous fossils, have recently increased this diversity (Liu *et al.*, 2012).

Ivesheadiomorphs

The most obvious impressions on the Pigeon Cove surface are rounded collections of high relief, irregularly positioned lobes and troughs, which range from 5–40 cm in diameter and have informally been termed ‘pizza discs’ (*e.g.* Fig. 9G). They were originally ascribed to the taxon *Ivesheadia lobata* Boynton and Ford, 1995, but that form, along with *Blackbrookia oaksii* and *Shepshedia palmata* (the latter occurring only in Charnwood, Leicestershire), were reinterpreted as taphomorphs, and synonymised within the ivesheadiomorphs (Liu *et al.*, 2011). All such forms are characterised by high-relief preservation of sub-angular to rounded lobes, within an often sharply defined boundary. No two ivesheadiomorph fossils are identical, and there appears to be a preservational continuum from typical ivesheadiomorphs through specimens showing small regions of rangeomorph branching, to well-preserved rangeomorphs (Fig. 9). Preservation of well-preserved rangeomorphs adjacent to, and sometimes even superimposed upon, poorly preserved ivesheadiomorphs indicates that the observed morphologies are primary features. It was therefore suggested that ivesheadiomorphs may be the degraded remains of rangeomorphs and other taxa that had died and rotted on the seafloor (in the absence of evidence for scavenging, predation or bioturbation; Liu *et al.*, 2011), a view that contrasts with previous medusoid (Boynton & Ford, 1995), localised microbial mat (Hofmann *et al.*, 2008; Laflamme *et al.*, 2011b) and even poriferan (Narbonne, 2007) explanations.

Depressions between the lobes of ivesheadiomorphs at this locality are commonly partially filled with pale yellow un-weathered volcanic ash. The high-relief lobes of the discs are inferred to have filled from beneath after burial, with sediment pushed up to fill the void left by the decaying organism (*see* Fig. 5). Alternative suggestions as to the origin of ivesheadiomorph impressions include entrapment of a frond within the tuff/sediment above a fossil surface, followed by its decay and subsequent loading from above (Wilby *et al.*, 2011), and discrete microbial colonies living beneath the sediment-water interface (Laflamme *et al.* 2011b). These hypotheses differ in their detail, but agree that ivesheadiomorphs are not valid body-fossil taxa, and that microbial activity is likely to have been responsible for their unusual appearance. There will be further opportunities to observe a wider range of ivesheadiomorph morphologies at the Mistaken Point ‘E’ Surface (Stop 2.3).

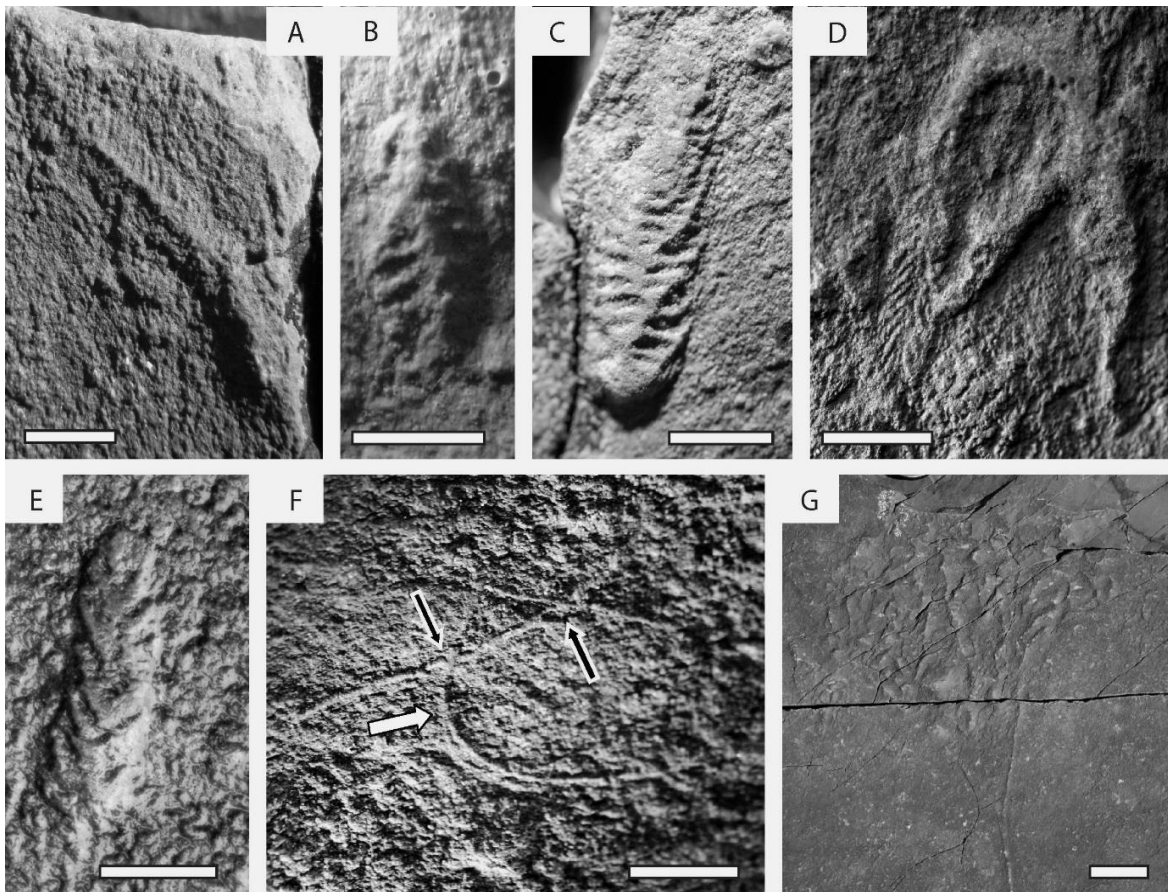


Figure 9. Fossils of the Pigeon Cove surface, Drook Formation. **A:** aff. *Trepassia wardae*. **B:** *Charniodiscus* sp. **C:** *Charnia* aff. *masoni*. **D:** A possible new form, or a poorly preserved aff. *Trepassia*. **E:** *Charnia masoni*. **F:** Fine filamentous fossils, showing branching (white arrow), and superposition (black arrows). **G:** The ‘tethered’ ivesheadiomorph, now missing from the surface (curated in The Rooms Provincial Museum, St. John’s). Scale bars = 5 mm, except F = 10 mm, and G = 50 mm. Images compiled from Liu *et al.*, 2012.

Juvenile Rangeomorphs and Secondary Community Succession

Over 100 small (6–30 mm length) rangeomorph specimens, representing at least four different taxa, also occur at Pigeon Cove (Fig. 9; Liu *et al.*, 2012). These are preserved amongst and occasionally on top of ivesheadiomorphs, but show much finer resolution of morphological detail. *Trepassia wardae*, *Charnia masoni*, ?*Charniodiscus* sp. and potentially another *Charnia* species (Fig. 9 A–E) are broadly aligned in a northeasterly direction. The rangeomorph/ivesheadiomorph assemblage has been interpreted to represent an example of secondary community succession (*cf.* Horn, 1974), with an initial population of large, perhaps senescent, Ediacaran organisms dying on the seafloor and decaying to form ivesheadiomorphs, with a founder population of immature rangeomorphs colonising the surface around them, prior to burial of the whole community by an ash (Liu *et al.*, 2012).

Filamentous fossils

Pigeon Cove also reveals the preservation potential (as siliciclastic casts) of fine filamentous structures on the Ediacaran seafloor. Two bedding surfaces here show filaments. The main surface contains over 140 individual strands, 0.5–1 mm in width and up to 130 mm long, occasionally showing evidence of simple Y-shaped branching along their lengths (Fig. 9F; Liu *et al.*, 2012). A surface about 40 mm beneath the main bed (stained red by iron oxides) preserves abundant filamentous structures of similar dimensions, which are very strongly aligned, and exhibit clear superposition (Callow & Brasier, 2009a).

The filamentous fossils show similarities to structures interpreted as sabelliditids from the Ediacaran of Spain (Jensen *et al.*, 2007); tubular fossils from the Nama assemblage (Cohen *et al.*, 2009); siliciclastic casts/moulds of filaments from the U.K. (Peat, 1984; Callow & Brasier, 2009b); and algal fossils from China (Yuan *et al.*, 2005). With so many possible interpretations, and a lack of preserved organic material or detailed morphological structure, it is currently difficult to assign the Drook Formation filaments to a specific phylogenetic group (*see* extended discussion in Liu *et al.*, 2012). However, those on the stratigraphically lower surface have been compared with bacteria, fungi, and vendotaenids (Callow & Brasier, 2009a).

Stop 2.2: Watern Cove

After continuing east along the Cape Race Road, we will disembark at the trailhead for Mistaken Point (NOTE: self-guided visits to the fossil sites within Mistaken Point Ecological Reserve are illegal). Fog permitting, Mistaken Point will be visible during our ~3 km walk across the Barrens. At the Watern Cove river crossing, the river follows the axis of a fault, offsetting outcrops of the Mistaken Point 'D' and 'E' Surfaces on either side of it. To the east, the surfaces are small, almost vertically dipping, and mostly covered in volcanic ash. However to the west, they have much greater areal extent, and the fossils on them are mostly exposed. Protection from the waves from the overlying beds means that this is one of the best outcrops at which to see Ediacaran fossils within the reserve.

The Watern Cove surfaces sit within turbiditic sequences of the upper Mistaken Point Formation. Sedimentology and fossil assemblage composition change very little over the ~1km that separates the fossil surfaces here from those at Mistaken Point itself, demonstrating the lateral continuity of the paleocommunities, and the planar nature of the sedimentation regime (*see also* Narbonne *et al.*, 2005). Paleocological cluster analysis (Clapham *et al.*, 2003) further demonstrated that there is little variation in the spatial distribution of taxa on the seafloor between Watern Cove and Mistaken Point. This stop will briefly introduce the key taxa from the Mistaken Point Formation assemblages, and most of these are described later in this guide. The morphology of one taxon that is quite rare at Mistaken Point, *Hapsidophyllas*, is seen very clearly at Watern Cove.

***Hapsidophyllas flexibilis* (Bamforth and Narbonne, 2009)**

Hapsidophyllas is a bipolar organism that can grow to impressive sizes of >50 cm in diameter (Fig. 10B). The pattern of branching within *Hapsidophyllas* (and in the large unipolar frond *Fronidophyllas* from elsewhere within the MPER), contrasts with that seen in typical rangeomorph taxa (Bamforth & Narbonne, 2009). These two taxa have therefore been deemed to possess hapsidophyllid branching (Bamforth & Narbonne, 2009), and their relationship to other frondose organisms within the assemblage requires further study.

Stop 2.3: Mistaken Point

Continue along the coastal trail for around 1km to Mistaken Point itself. Mistaken Point obtained its name from the fact that it was commonly mistaken by mariners for Cape Race, which lies farther to the east. There are several documented cases of ships having turned north towards St. John's too soon at this point, and becoming wrecked on the rugged coastline.

AT THE EDGE OF THE FOSSIL SURFACES, PLEASE REMOVE YOUR FOOTWEAR AND PUT ON THE 'BAMA BOOTIES' PROVIDED. WALKING ON THE FOSSIL SURFACE WITHOUT 'BAMA BOOTIES' IS PROHIBITED.

Monitoring of the site has revealed that prolonged exposure to human erosion has contributed to a marked loss of preservational fidelity on these surfaces. Wearing 'Bama Booties' helps to protect the fossils from long-term erosion.

Mistaken Point Overview

The bedding planes of Mistaken Point are world-renowned for the abundant and diverse Ediacaran fossil communities they preserve. We will examine the 'D' and 'E' Surfaces, which lie within the medium-bedded turbidites of the mid- to upper Mistaken Point Formation. The depositional environment here is interpreted as a deep-marine slope (Wood *et al.*, 2003), with fossils being preserved beneath coarse-grained volcanic ashes. The ashes smothered the seafloor, covering the organisms *in situ*, but the lower resistance of the ash (with respect to the surrounding siltstones) means that it is preferentially weathered, exposing the large bedding planes we see before us. Diagenetic carbonate nodules are visible in the cliff faces. Ripple-like features seen on many of the surfaces here are considered to be tectonic in origin (Thomas, 2012).

Much of the Avalon region in Newfoundland has undergone considerable post-depositional tectonic deformation, leading to many of the bedding planes, and their fossil impressions, being either stretched or compressed on the surfaces. To determine the original shape of the organisms, the effects of this tectonic deformation must be removed. A

technique called retro-deformation has generally been employed to quantify and correct for the tectonic strain (Seilacher, 1999; Wood *et al.*, 2003).

The ‘D’ and ‘E’ Surfaces take their names from labels assigned to fossil surfaces in a series of sedimentary logs published in the conference field guide of Landing *et al.* (1988). Zircons from the tuff immediately overlying the ‘E’ Surface have been dated to 565 ± 3 Ma (Benus, 1988), but it is hoped that more precise dates will become available in the near future. The 565 Ma date suggests that the fossil assemblages at Mistaken Point are several million years older than other iconic Ediacaran fossils from the White Sea of Russia (555 Ma; Martin *et al.*, 2000), and Namibia (~549 to 543 Ma; Grotzinger *et al.*, 1995).

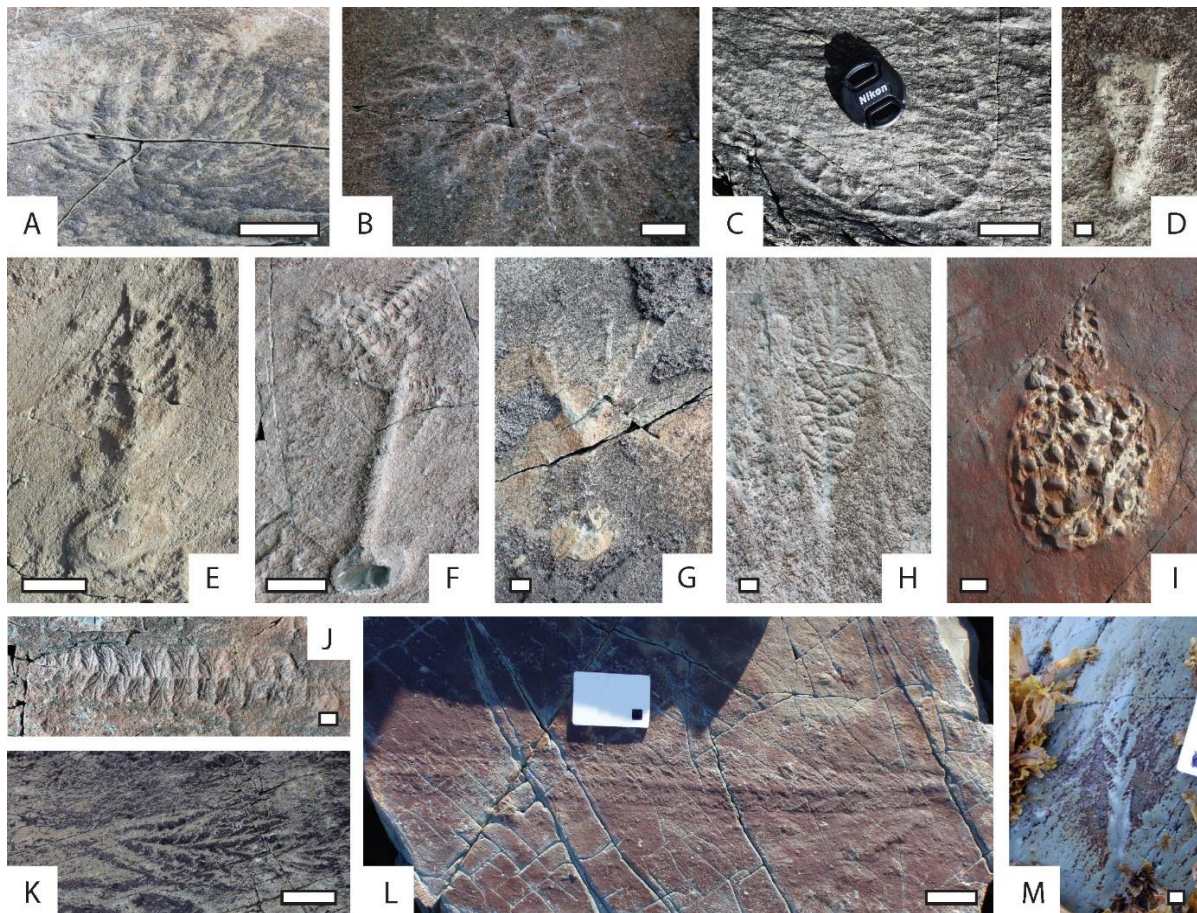


Figure 10. A selection of the fossils commonly found within the Mistaken Point Ecological Reserve. **A:** *Bradgatia* sp. **B:** *Hapsidophyllas flexibilis*. **C:** *Pectinifrons abyssalis*. **D:** *Thectardis avalonensis*. **E:** *Charniodiscus spinosus*. **F:** *Charniodiscus procerus*. **G:** *Primocandelabrum* sp. **H:** *Beothukis mistakensis* (paratype). **I:** Ivesheadiomorph. **J:** *Fractofusus misrai*. **K:** *Culmofrons plumosa* (holotype). **L:** *Trepassia wardae*. **M:** *Charnia* aff. *masoni*. Scale bars in A–C, E–F, I, K–L = 50 mm, in D, G–H, J and M = 10 mm. All specimens occur on the upper surface of beds.

Fossils of the ‘D’ Surface

The ‘D’ Surface possesses a remarkable assemblage of >1450 Ediacaran macro-organisms belonging to at least eight taxa (Clapham, 2011). Preservation is good, but small individuals, particularly frondose forms, are not seen (compare this with the ‘E’ Surface). The tiered nature of the assemblages, with different organisms constructed such that their fronds are held at different heights above the surface (presumably to obtain nutrients from the water column; Clapham & Narbonne, 2002), is particularly clear here. For example, *Fractofusus* specimens comprise the lowest tier, reclining on the seafloor, with *Bradgatia* and *Pectinifrons* slightly higher, and frondose forms such as *Charniodiscus* occupying the highest tiers (*cf.* Clapham & Narbonne, 2002). Comparisons between different bedding plane assemblages in the Mistaken Point region permitted those authors to construct a model for ecological succession, interpreting differences in fossil assemblages as early (high dominance of low-level tier organisms), middle, and late (diverse assemblages with complex tiering) stage communities (Clapham & Narbonne, 2002). Under this model, the ‘D’ Surface is recognised as a fairly early stage community, while ‘E’ preserves a middle stage community.

***Bradgatia* (Boynton and Ford, 1995)**

Bradgatia is one of the most recognisable rangeomorph taxa within the Conception Group. This organism has the gross morphology of a lettuce, seemingly comprising multiple fronds that radiate away from a central point (Fig. 10A). Both disc and stem are seemingly absent in this form. Although ‘D’ Surface specimens reach a reasonable size of up to ~20 cm in diameter, they do not reach the ~50 cm diameters found in Leicestershire, U.K. (*Bradgatia linfordensis*; Boynton and Ford, 1995).

***Pectinifrons* (Bamforth *et al.*, 2008)**

Pectinifrons is a comb-shaped rangeomorph, consisting of a central rod with multiple rangeomorph branches coming off it in two rows (Bamforth *et al.*, 2008; Fig. 10C). The rod is almost always curved, with all rangeomorph branches preserved on the inside edge of this curve. Curvature was originally discussed as a primary feature of living individuals (Bamforth *et al.*, 2008), but it could alternatively be a taphonomic feature, formed as the tissues within the organism contracted after death. *Pectinifrons* is considered to have been

sessile and epifaunal, with its rangeomorph branches elevated into the water column to obtain nutrients (Bamforth *et al.*, 2008).

***Fractofusus* (Gehling and Narbonne 2007)**

Fractofusus occurs in huge numbers on the Mistaken Point ‘D’ and ‘E’ Surfaces, and provides a good example to demonstrate the concept of self-similar rangeomorph branching (Figs. 10J and 11). It is composed of a series of bundles of fern-like rangeomorph sub-units, arranged in two rows. There appear to be two growth poles to the organism (*i.e.*, it adds new branches at both ends of the growth axis), and the high fidelity preservation of the lower surfaces of these organisms suggests that *Fractofusus* was a benthic recliner, lying in contact with the seafloor at the time of burial by the volcanic tuff (Gehling & Narbonne, 2007).

Two species of *Fractofusus* are known from Mistaken Point, with *F. misrai* being far more common than *F. andersoni* on these surfaces. The abundance of *Fractofusus misrai* on the ‘D’ and ‘E’ surfaces is in stark contrast to the scenario on the majority of MPER beds, where it is comparatively rare. Recent paleoecological studies of the spatial distribution of *Fractofusus* specimens in Newfoundland suggest that its communities were clustered on bedding planes in a manner that implies a reproductive strategy involving both stolon-like connections (Mitchell *et al.*, 2015), and distribution of waterbourne propagules. At present, physical evidence for such stolons is absent, but this suggestion has significant implications for our understanding of rangeomorph biology.

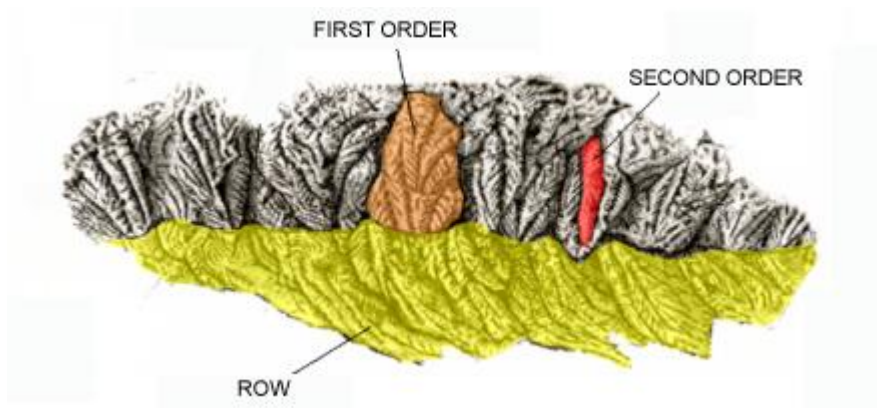


Figure 11. A sketch of a *Fractofusus misrai* specimen, showing how the terminology of Brasier *et al.* (2012) can be applied to this organism. Image courtesy of Prof. M. Brasier, adapted from Brasier & Antcliffe 2009, fig. 9a.

Fossils of the ‘E’ Surface

The ‘E’ Surface possesses the most abundant and diverse assemblage of Ediacaran macro-organisms currently described in Newfoundland (>4000 specimens; Clapham, 2011). *Fractofusus* is by far the most numerically abundant taxon (comprising ~30% of the assemblage; Clapham *et al.*, 2003), but it is interesting to note that *Pectinifrons*, so abundant on the ‘D’ Surface, does not appear on ‘E’. Frondose taxa such as *Charniodiscus* comprise >50% of the assemblage (Clapham, 2011), and are largely aligned towards the southeast, consistent with the inferred downslope direction (Seilacher, 1999; Wood *et al.*, 2003).

***Primocandelabrum* (Hofmann *et al.*, 2008)**

A disc (which possesses radial root-like structures at its margin in some specimens from the Bonavista Peninsula; Hofmann *et al.*, 2008), tethers *Primocandelabrum* to the seafloor. Its stem leads to a series of branches that diverge in a ‘candelabrum’ structure (Fig. 10G). The complete organism is rare in the MPER (the ‘E’ Surface contains multiple possible juveniles, but few mature specimens), but the discoidal fossil *Hiemalora*, observed on a number of bedding planes, may represent the isolated discoidal holdfast of certain *Primocandelabrum* specimens (*cf.* Serezhnikova, 2007; Hofmann *et al.*, 2008).

***Charniodiscus* (see Laflamme *et al.*, 2004)**

The genus *Charniodiscus* is represented by at least three species in MPER: *Charniodiscus arboreus*, *Charniodiscus procerus*, and *Charniodiscus spinosus* (Fig. 10E, F). These species are distinguished on the basis of morphometric characteristics (Laflamme *et al.*, 2004), but are united by their general structure of a discoidal tethering holdfast, a cylindrical stem, and a single frond elevated into the water column. Rare specimens do occasionally reveal fine branching structure, but their construction is yet to be decoded in the same detail as that of the rangeomorphs. Much work needs to be done to resolve the taxonomy of this taxon – even the relationship of the Newfoundland forms to their U.K. counterpart *Charniodiscus concentricus* (the type species of the genus) is still to be adequately addressed.

***Beothukis* (Brasier & Antcliffe, 2009)**

Named after the native Beothuk tribe of Newfoundland, this taxon was key to decoding rangeomorph architecture. The second order rangeomorph units of *Beothukis* are clearly displayed (*see* for example the paratype, Fig. 10H), but first order branches are rotated out of the plane of preservation. This observation ultimately led to the development of the nomenclature proposed for the description of rangeomorphs (Brasier & Antcliffe 2009; Brasier *et al.*, 2012; *see also* Narbonne *et al.*, 2009).

***Ivesheadiomorph* variants**

Three variants of *Ivesheadia* Boynton and Ford, 1995 (all now encompassed within the ivesheadiomorphs) were previously recognised from the Avalon successions of Newfoundland; lobate discs, pizza discs, and bubble mats (Narbonne *et al.*, 2001). The ‘E’ Surface possesses good examples of lobate discs and bubble mats. Lobate discs are rounded, high relief impressions, with typically five to ten deep grooves running from their edges to the centres. They are commonly 10–15 cm in diameter, and do not appear to be associated with any other organisms on the surfaces. In contrast, bubble mats are sharp-ridged reticulate patterns, far more variable in overall shape and size, with a lower surface profile. They can reach around 40cm in width.

***Thectardis avalonensis* (Clapham *et al.*, 2004)**

Thectardis is one of the most enigmatic and controversial forms within the Ediacaran macrobiota, most recently being interpreted, largely on the basis of its length to width ratio, as a possible sponge (Sperling *et al.*, 2011). It is a triangular, positive epirelief impression, but possesses limited additional morphological detail beyond that (Fig. 10D). Until more informative specimens are found, this taxon will likely remain of uncertain biological affinity.

Casting Project

In the summer of 2009, collaboration between the Government of Newfoundland and Labrador, the Royal Ontario Museum, the Johnson Geo Centre, the University of Oxford, Memorial University of Newfoundland, and Queen’s University, resulted in the casting of

900 square feet of the Mistaken Point 'E' Surface bedding plane. Research Casting International, of Trenton, Ontario, were hired to produce the cast, and they spent several weeks preparing the surface, laying the latex, peeling the cast, cleaning up, and (with the aid of helicopter assistance), transporting it from the site. The finished replicas are spectacular, and enable the fossil assemblages to be lit and studied in controlled conditions by both scientists and museum visitors. Partial casts now reside in the ROM, Queens, Oxford, Bristol, the Johnson Geo Centre, and at the Edge of Avalon Interpretive Centre. Ultimately the casts will not only bring these spectacular organisms to a wider public; their existence also reduces erosion of the fossil surface itself, by reducing footfall on the site.

Stop 2.4: The Trace Fossil Bed, Mistaken Point

After removing the 'Bama Booties' and retrieving your footwear, we will embark upon a short walk ~50 m stratigraphically up-section. This bedding surface lies within turbidites of the uppermost Mistaken Point Formation. It is capped by a 1 mm-thick, coarse and pyritic tuff, which is responsible for preserving the impressions.

The Trace Fossils

Despite the proven preservation of fine morphological features in body fossils in Ediacaran rocks at MPER, evidence for contemporaneous locomotion or bioturbation is scarce. This has long been taken to suggest that the Mistaken Point biota was sessile (*cf.* Narbonne, 2005), an interpretation supported by a lack of evidence for movement in many other Ediacaran sites worldwide; a 2006 review of proposed Ediacaran trace fossils determined that the majority of them were either abiogenic sedimentary structures, tubular body fossils, or structures of questionable origin (Jensen *et al.*, 2006). Although around ten ichnogenera were recognised as genuine, none of these had been observed from Avalonian localities (Jensen *et al.*, 2006).

In recent years, multiple ichnofossils have been discovered in latest Ediacaran successions worldwide. These include horizontal shallow burrowing by 'under-mat miners' in Australia, Russia, and NW Canada (*e.g.*, Seilacher, 1999; Carbonne & Narbonne, 2014),

bilobed traces in China (Chen *et al.*, 2013), and possible evidence for vertical movement to escape small sedimentary influxes (Menon *et al.*, 2013). The best evidence that members of the Ediacaran macrobiota were motile comes from impressions interpreted as grazing or rasping traces in association with the body fossil *Kimberella* in the White Sea (discussed in detail in Ivantsov, 2010; Gehling *et al.*, 2014), and ‘ghost traces’ of *Yorgia* and *Dickinsonia* (e.g., Ivantsov & Malakhovskaya, 2002), now named *Epibaion* (Ivantsov, 2011; *though see* McIlroy *et al.*, 2009). Potential evidence for abundant vertical burrowing with meniscate backfill, from the Khatyspyt Formation of Siberia (~557 Ma; Rogov *et al.*, 2012), is currently undergoing reassessment. These examples indicate that a surprising array of diverse locomotory behaviours were present in the global oceans by 555 Ma.

In Avalonia, putative worm burrows from Charnwood Forest (Boynton and Ford, 1995), and a handful of possible trails from Carmarthenshire (Cope and Bevins, 1993), comprised the only suggestions of movement prior to 2010. In that year, evidence for locomotion was described in the form of horizontal surface traces at Mistaken Point, found 53 m stratigraphically above the ~565 Ma ‘E’ Surface (Liu *et al.*, 2010a). These Mistaken Point structures therefore represent some of the oldest evidence for metazoan locomotion in the geological record.

The Mistaken Point Trace Fossils

The Mistaken Point traces occur on a thin ledge, quite unlike the expansive bedding planes that characterise the body fossil assemblages. Eighty four traces run across the surface in all directions, often with curving paths. Traces are from 15–172 mm in length, and 1–13 mm in width (Liu *et al.*, 2010a; 2014b). They form slight depressions in the surface, but are bounded on either side by positive epirelief ridges/levees of sediment, inferred to have been displaced by the trace-maker as it moved across the seafloor. Twenty nine of the traces exhibit a series of evenly spaced concave ridges within their length, which face towards a simple circular pit that forms the termination point (Liu *et al.*, 2010a; Fig. 12). Several examples also cross paths, with later specimens truncating previous ones (Fig. 12D). Where visible, it is evident that the morphology of the traces does not continue down into the substrate. Since MPER is a protected site, and a candidate World Heritage Site, it has not been possible to sample and thin section any examples to test this assertion.

After refuting multiple abiogenic mechanisms of formation, the original authors proposed, based partly on observations of modern metazoan trace-makers, that the Mistaken Point forms were created by the activities of an organism that possessed muscular tissue, and moved in a similar way to modern sea anemones (Liu *et al.*, 2010a). Alternative explanations for them as possible protistan traces (*cf.* Matz *et al.*, 2008) can be rejected on the basis of the complexity of the internal structure observed within the Mistaken Point specimens, as opposed to the smooth internal impressions of modern gromiid trails (Liu *et al.*, 2014b). Further impressions recording possible evidence of locomotion will be viewed later in the trip within the younger Fermeuse Formation of Ferryland (Stop 3.2; Menon *et al.*, 2013; Liu & McIlroy, 2015).

Following discussion at this locality, we shall head back to the vehicles. If the weather is good, participants may wish to take the opportunity to enjoy the views, and look out for Humpback and Minke whales, seals, and otters just offshore. Also keep an eye out for birds (including whimbrels, shearwaters, and loons), and the occasional carnivorous pitcher plant as we head inland.

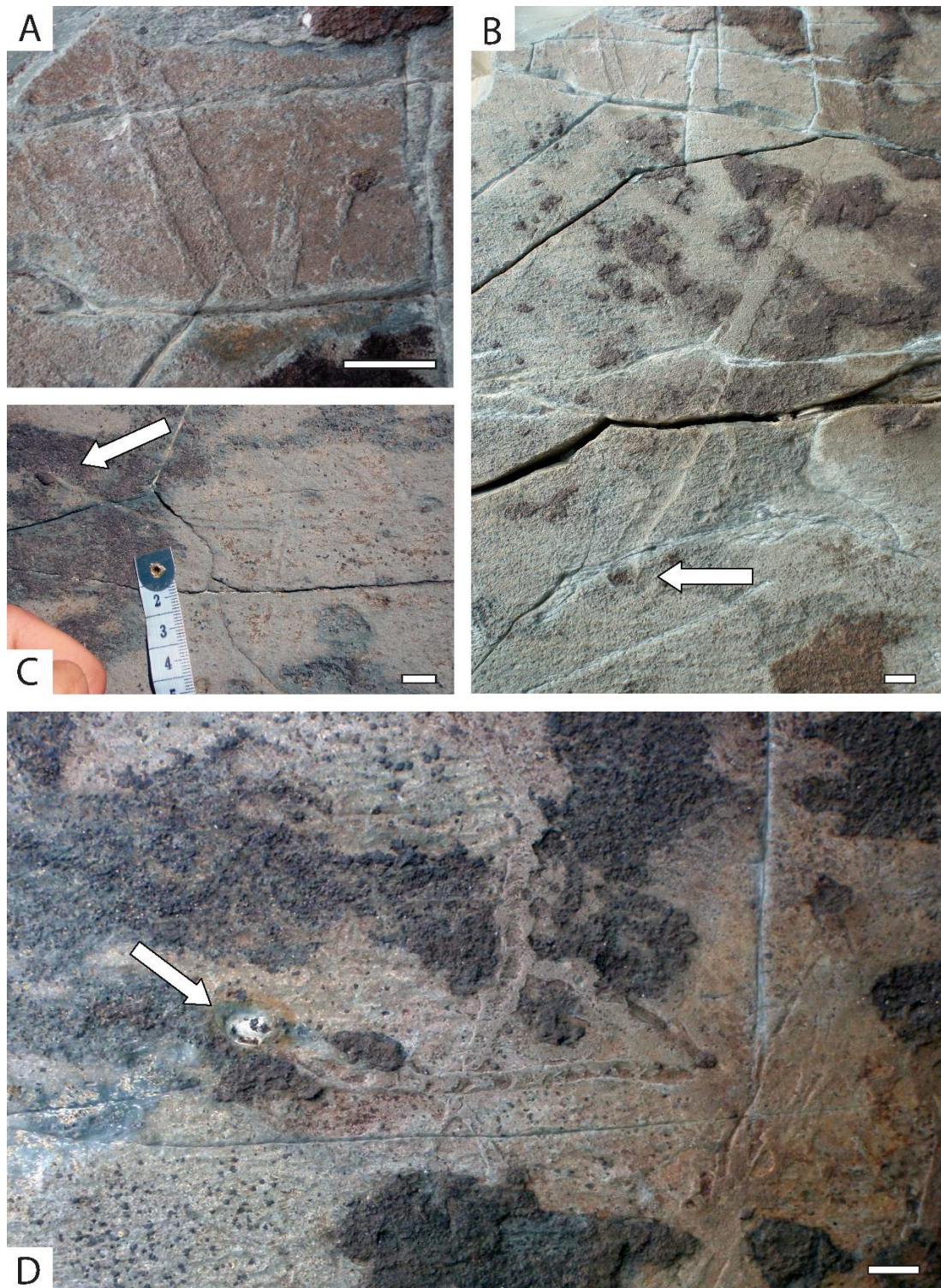


Figure 12. A selection of trace fossils from the upper Mistaken Point Fm., Mistaken Point, Newfoundland. **A:** Two traces lacking internal structure. **B:** The longest trace on the surface, showing transverse hemispheric ridges running down its length, and ending in a terminal negative-relief disc (arrowed). Specimens in A and B can be found on Oxford University Museum cast OUM ÁT 418/p. **C:** Two simple traces exhibiting cross-cutting relationships, the horizontal one ending in a terminal disc (arrowed). Cast OUM ÁT 421/p. **D:** A series of at least four traces, clearly showing several directions of movement, and cross-cutting relationships. Cast OUM ÁT 421/p. One trail ends in a prominent pit (arrowed). All scale bars = 10 mm. From Liu, 2011b (unpublished D.Phil. thesis, University of Oxford, fig. 6.5).

DAY THREE FIELD TRIP STOPS

Mistaken Point Ecological Reserve, and Ferryland

The Briscal Formation

Today we will investigate the sedimentology and paleontology of the Briscal Formation, which sits immediately beneath the Mistaken Point Formation. For a long time the Briscal has been considered to be largely unfossiliferous, but in recent years several fossil-bearing bedding planes have been found within this unit. The Briscal Formation is only locally present in Newfoundland, outcropping in the south of the Avalon Peninsula and thinning to the north and west. It does not appear in the Spaniard's Bay or Bonavista regions. It is a largely sandy unit, with multiple thick-bedded coarse, sandy turbidites, grits, and sporadic but locally very thick (1–2 m) tuffaceous beds. Its maximum stratigraphic thickness of ~1200m is realised on the St. Shott's Peninsula to the west (Williams & King, 1979).

Stop 3.1: Bed BR5

We will drive from Trepassey back down the Cape Race road, but will take an earlier trail out to Bristy Cove (a hike of around 30 minutes). Following a brief orientation stop, we will continue for another kilometre to a newly discovered fossil site in the lower Briscal Formation, which is yielding spectacular fossil material.

THIS SURFACE IS NEWLY DISCOVERED, AND IS CURRENTLY UNDER STUDY BY RESEARCHERS AT THE UNIVERSITY OF BRISTOL. WHILE YOU ARE FREE TO TAKE PHOTOGRAPHS, WE ASK THAT YOU RESPECT THE FACT THAT THIS MATERIAL IS CURRENTLY UNPUBLISHED, AND IS BEING ACTIVELY WORKED UP. PLEASE TAKE CARE WHEN DESCENDING THE HILLSIDE TO THIS OUTCROP – THE SLOPE IS STEEP, AND ROCKS ARE LOOSE, SO TAKE CARE NOT TO DISLODGE THEM ABOVE OTHER TRIP PARTICIPANTS.



Figure 13. *Fractofusus* from the BR5 surface, Briscal Formation, MPER. Scale bar increments at bottom right are millimetres.

Until recently, the only notable fossil surface documented from the Briscal Formation was the so-called ‘x-ray’ bed at Bristy Cove (*see* Clapham *et al.*, 2003), which is only a couple of square metres in area, but possesses over 100 low-relief impressions of small *Fractofusus*. A regional survey by myself and Jack Matthews (University of Oxford) led to the discovery of bed BR5, which sits roughly 60 m stratigraphically above the base of the Briscal Formation. BR5 contains 10 distinct taxa, hundreds of specimens, and some of the best preservation of Ediacaran fossils yet seen anywhere in the world. The bedding plane is characterised by red iron oxide veneer across the entire surface, and although it is mostly exposed in two large trapezoid platforms of ~60m² each, the surface continues as a ledge along the cliff for a distance of ~170 m.

The BR5 assemblage is dominated by *Fractofusus* (Fig. 13), the vast majority of which are 1–3 cm in length. *Charniodiscus* sp., *Trepassia*, and *Primocandelabrum* are also present, and the common alignment of these tethered forms indicates a current flow to the northwest. Although the fossils appear to be preserved in the typical ‘Conception-style’ of

preservation seen elsewhere in Newfoundland, the resolution of morphological detail is remarkable, with many specimens exhibiting morphological features of < 0.1 mm. Despite this, no additional morphological characters can be distinguished; rangeomorph self-similar branching seemingly just continues at finer and finer scales. This surface is currently under study, and the major findings it reveals will be published in the near future.

Stop 3.2: Ferryland

We will return to the vehicles and drive back, via Portugal Cove South, towards St. John's. After around an hour of travelling north on Route 10, we will stop in the town of Ferryland to view the Fermeuse Formation, and the fossils it contains.

The town of Ferryland is built around a sheltered natural harbour on the east coast of the Avalon Peninsula, and is protected by the ~2 km-long Ferryland Head Peninsula. Ferryland has been occupied since 1621, when Lord Baltimore set up a colony here, and it is now the site of ongoing archaeological excavations (which have recently unearthed Beothuk arrowheads of possible greater antiquity). At the dig site, next to the harbour, you may see Ediacaran *Aspidella* specimens in the flagstones used to construct the walls and fireplaces of some of the 16th century houses.

We will be examining a continuous section through the upper Fermeuse Formation, accessed from the car park of the Colony of Avalon, by walking north along the beach. Strata here dip steeply to the southeast, and the sequence consists of thin, interbedded sandstones and dark grey mudstones, interpreted to have formed in a marine slope/delta front depositional environment (Williams & King, 1979). Although not seen at this locality, 5–6 metre thick slump deposits can be seen in the upper Fermeuse Formation at sites ~1 km to the south, in the vicinity of Silos' Cove. Fossils are preserved in abundance on the mudstone and siltstone bedding planes, with *Aspidella terranovica* being the dominant taxon (sometimes occurring in densities of 1000s of specimens per square metre; Gehling *et al.*, 2000).

The Fermeuse Assemblage

Fossils of the Fermeuse Formation initially show many differences to those of the Conception Group seen at Mistaken Point. Differences in facies mean that the preservation of fossils varies substantially from that seen at Mistaken Point, with no ash involved in the casting process of the organisms in the Fermeuse (*cf.* Narbonne, 2005). The Fermeuse assemblages are also relatively depauperate in terms of taxonomic diversity, being primarily dominated by discoidal fossils. It seems, however, that at least some of this variation in species richness can be explained taphonomically; on the Bonavista Peninsula, ~200 km to the NW, the Fermeuse Formation (there containing frequent tuffs) does record significant taxonomic diversity, including frondose forms (Hofmann *et al.*, 2008). ESEM studies on Fermeuse Fm. sediments have also hinted at a key role for microbes in the taphonomic process, with Laflamme *et al.* (2011a) identifying enrichments in Al, Mg, Fe and K, consistent with biofilm formation, in the sediment immediately surrounding discoidal fossils.

Aspidella terranovica (Billings, 1872)

The most common fossil found in Ferryland is the simple discoidal form *Aspidella terranovica*. *Aspidella* range from a few millimetres to 12 cm in diameter at this locality, and exhibit a wide range of morphologies, all of which have previously been considered to reflect taphonomic variants of the same organism (Gehling *et al.*, 2000). Over the years, there has been considerable debate as to whether *Aspidella* really represents a biological organism (*see summary in* Gehling *et al.*, 2000), but it is now accepted that it is truly biogenic. Gehling *et al.* (2000), suggested that as many as 24 different discoidal species around the world could be synonymised within *Aspidella*, and they described three ‘morphotypes’ (flat, convex, and type), that were considered to reflect end-members of a morphological continuum (Figs. 14, 15). Furthermore, *Aspidella* was interpreted, based on the possible presence of a stem in rare specimens, to represent the holdfast of a frondose organism (Gehling *et al.*, 2000). It seems to the current authors, however, that the abundant variety in *Aspidella* morphology within Fermeuse Formation bedding planes, and their extremely high densities on some surfaces, suggests there may be more than one taxon present within the present *Aspidella* grouping. Recent work examining the composition of sediments associated with *Aspidella* from the Fermeuse Formation of Newfoundland suggests that the organisms may have incorporated sediment within their bodies during life, in a similar way to modern deep marine

xenophyophores (Laflamme *et al.*, 2011a; *though see also* Seilacher, 1992; Seilacher *et al.*, 2003).

***Triforillonia costellae* (Gehling *et al.*, 2000)**

The discoidal *Triforillonia costellae* (Fig. 15F), is a small (average 20–26 mm) tri-lobed impression, broadly resembling a shamrock/clover leaf. It is extremely rare, and is interpreted by its original authors to have been a ‘soft, sack-like body’, though lack of material and obvious taphonomic variability has precluded phylogenetic interpretation of this species (Gehling *et al.*, 2000). *Triforillonia* has not been observed outside of the Fermeuse Formation in Ferryland.



Figure 14. The morphological variability within *Aspidella terranovica*, from Gehling *et al.*, 2000, text-fig. 6.

***Palaeopascichnus delicatus* (Palij, 1976)**

Palaeopascichnus (Fig. 15B) is a chain of curved, sausage-shaped chambers, often inflating in one direction, and capable of branching. It is one of the rarest taxa within the Ediacaran successions of Avalonia. *Palaeopascichnus* was initially described as an ichnofossil (Palij *et al.*, 1979), an interpretation that has since been refuted (Gehling *et al.*, 2000; Jensen, 2003). *Palaeopascichnus* has alternatively been described as a potential protist, more specifically belonging to the xenophyophores (Seilacher *et al.*, 2003). However, Antcliffe *et al.* (2011) ruled out a xenophyophoran affinity on the basis of developmental analysis, and concluded that *Palaeopascichnus* likely represents the body fossil of an unknown protozoan organism.

Simple horizontal traces

Recent finds suggest the presence of small horizontal curved and looping surface traces, up to 3 mm in width and several centimetres in length, on a small number of Fermeuse Formation bedding planes at this locality (Liu & McIlroy, 2015). Although they are extremely rare amongst the assemblage, traces are reasonably abundant on the bedding planes they occur on. Possible evidence for potential internal meniscae can be found within some of the specimens, but the recent nature of their discovery means that their biogenicity is yet to be tested.

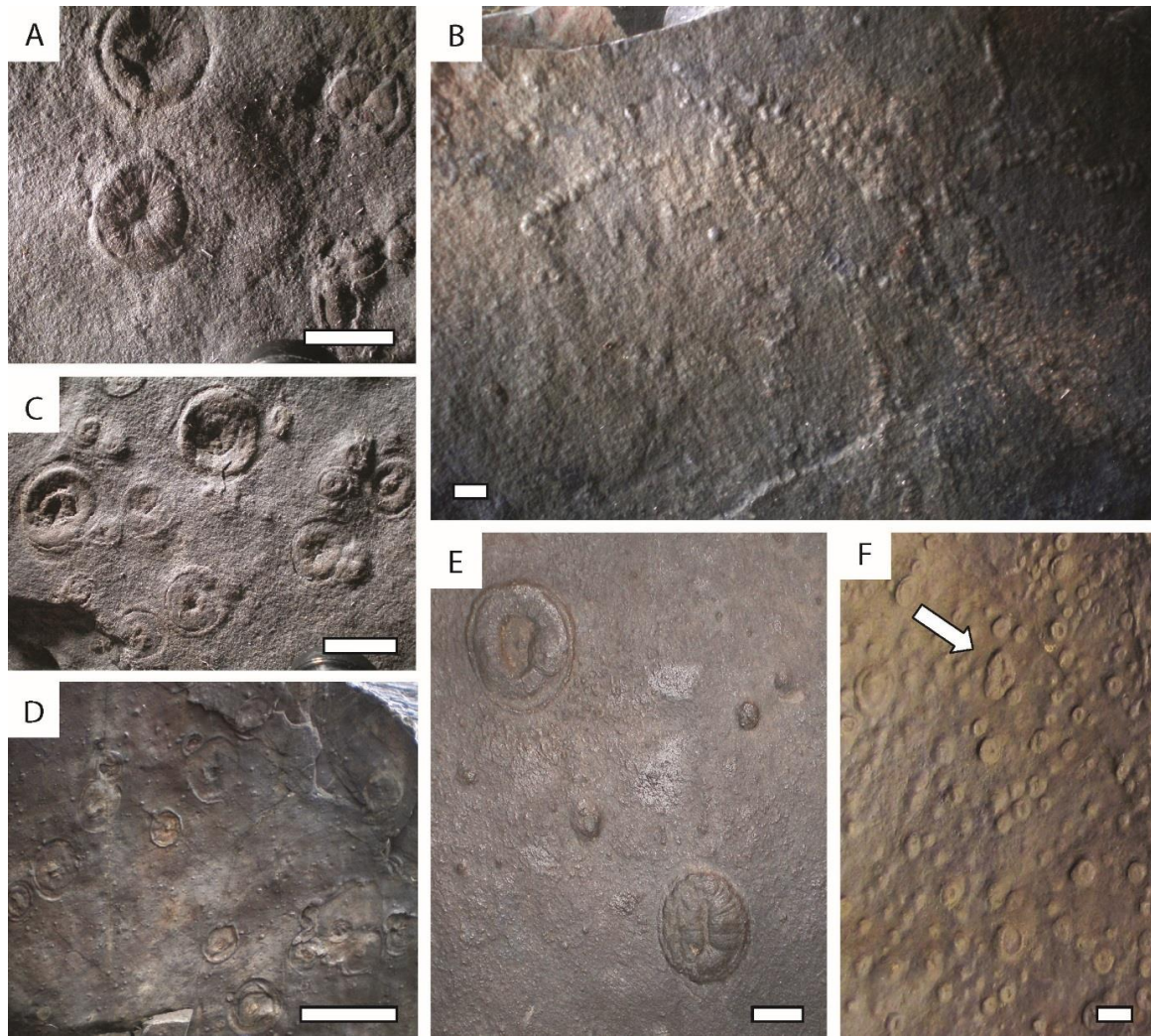


Figure 15. A representative selection of fossils from the Fermeuse Formation, Newfoundland. **A:** *Aspidella terranovica* (flat/type morph), St John's, NL. **B:** aff. *Palaeopascichnus delicatus*, Ferryland, NL. **C:** *Aspidella terranovica* (convex morph), Ferryland, NL. **D:** *Aspidella terranovica* (flat morph), Ferryland, NL. **E:** *Aspidella terranovica* (type morph), Ferryland, NL. **F:** *Triforillonia costellae* (arrowed) amongst multiple *Aspidella* specimens, Ferryland, NL. Morph terminology follows (Gehling *et al.*, 2000). Scale bars = 10 mm except D, where scale = 50 mm.

Inventory of taxa known to be present within the Mistaken Point Ecological Reserve

Taxon	Original reference	Additional references
<i>Charnia masoni</i>	Ford, 1958	
<i>Vinlandia antecedens</i>	Laflamme <i>et al.</i> , 2007	Brasier <i>et al.</i> , 2012
<i>Trepassia wardae</i>	Narbonne and Gehling, 2003	Narbonne <i>et al.</i> , 2009
<i>Beothukis mistakensis</i>	Brasier and Antcliffe, 2009	
<i>Culmofrons plumosa</i>	Laflamme <i>et al.</i> , 2012	
<i>Fronidophyllas grandis</i>	Bamforth and Narbonne, 2009	
<i>Charniodiscus spinosus</i>	Laflamme <i>et al.</i> , 2004	
<i>Charniodiscus procerus</i>	Laflamme <i>et al.</i> , 2004	
<i>Charniodiscus arboreus</i>	Glaessner and Daily, 1959	Laflamme <i>et al.</i> , 2004
<i>Hapsidophyllas flexibilis</i>	Bamforth and Narbonne, 2009	
<i>Bradgatia</i> sp.	Boynton and Ford, 1995	Flude and Narbonne 2008
<i>Fractofusus misrai</i>	Gehling and Narbonne, 2007	
<i>Fractofusus andersoni</i>	Gehling and Narbonne, 2007	
<i>Pectinifrons abyssalis</i>	Bamforth <i>et al.</i> , 2008	
<i>Primocandelabrum</i> sp.	Hofmann <i>et al.</i> , 2008	
<i>Parviscopa bonavistensis</i>	Hofmann <i>et al.</i> , 2008	
<i>Aspidella terranovica</i>	Billings, 1872	Gehling <i>et al.</i> , 2000
<i>Hiemalora stellaris</i>	Clapham <i>et al.</i> , 2003	Fedonkin, 1982
<i>Thectardis avalonensis</i>	Clapham <i>et al.</i> , 2004	Sperling <i>et al.</i> , 2011
<i>Ivesheadiomorphs</i>	Boynton and Ford, 1995	Liu <i>et al.</i> , 2011
Trace fossils	Liu <i>et al.</i> , 2010a	
Filamentous microfossils	Callow and Brasier, 2009a	Liu <i>et al.</i> , 2012

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