Taphonomy, taxonomy and geoconservation of the 'Upper Island Cove' Ediacaran fossil assemblage

by © Christopher McKean

A thesis submitted to the School of
Graduate Studies in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy

Department of Earth Sciences
Memorial University of Newfoundland

June 2024

St. John's, Newfoundland

ABSTRACT

Exquisite three-dimensional, high relief Ediacaran fossils on the Allison Surface, Upper Island Cove, were discovered 20 years ago. This project has implemented novel methods and modern understandings of the Ediacaran biota to improve our understanding of this under-studied site. Through the collection and assessment of taphonomic and sedimentological data it can be seen that the unique preservation of the assemblage was the result of erect and reclined fronds being encased in the top centimetre of a partly lithified T_d silt, prior to subsequent exhumation by obstruction scours in the lee of a later community of erect organisms. After exhumation both the upper and lower surfaces of the fronds were cast by an overlying pyritic, fine-grained T_c sandstone which led to the high relief preservation. This improved understanding of site taphonomy, alongside the addition of over 150 newly discovered specimens, led to a taxonomic reassessment of the surface and the description of three new taxa: 1) *Avalofractus dosomitus* sp. nov., 2) *Kannabuchia artkingii* gen. et sp. nov. and 3) *Corellia washageuis* gen. et sp. nov. New morphotypes of *Arborea*, *Bradgatia* and *Charnia* have also been described from the surface, including for the first-time documentation of a differentiated upper surface in *Bradgatia*. The presence of unique taphonomic processes and endemic species on the Allison Surface highlight the importance of protecting the site. As such a novel approach to site observation was implemented at the surface, which shows that the fossils are at risk to both anthropic and environmental factors. The mitigation techniques that have been suggested to protect the site from irreparable damage can also be applied to other at-risk localities worldwide.

GENERAL SUMMARY

The Allison Surface, Upper Island Cove, was discovered 20 years ago yet has largely remained under-studied in that time. This project has focused on improving our understanding of the unique three-dimensional, highly detailed Ediacaran fossils found at the site. By collecting evidence from the fossils and surrounding rocks it can be seen that the fossils were once a combination of upright and reclined organisms that were encased in the top centimetre of a layer of silt on the ocean floor, which were later exposed in scours within the silt by a strong current eroding the sediment around a later group of organisms. After being exposed, these fossils were buried beneath a finely grained sandstone which was rich in the mineral pyrite and greatly aided in preserving the detail seen in the fossils. During the project over 150 new fossils were discovered which led to the description of three new species: 1) *Avalofractus dosomitus* sp. nov., 2) *Kannabuchia artkingii* gen. et sp. nov. and 3) *Corellia washageuis* gen. et sp. nov. Alongside the new species, both the upper and lower surfaces of many of the fossils were discovered, not only is this a rarity in fossils of this age but it has allowed us to better understand many previously studied species. The unique preservation, as well as species only known from the Allison Surface, highlights the importance of protecting the site. As such a new technique for site observation was implemented which showed that the fossils are currently at risk to both human and environmental threats. Techniques have been suggested and developed to protect the site from irreparable damage, with these techniques having the potential to be implemented in the protection of other at-risk fossil sites in Newfoundland and worldwide.

CO-AUTHORSHIP AND COPYRIGHT STATEMENT

This thesis is substantially my own, original work, being presented in the 'Manuscript Style' and composed of five chapters, with my supervisors and colleagues having contributed to its development. Chapters 1 and 5, the Introduction and Conclusions respectively, have been solely devised and wrote by Christopher McKean, with editorial input from Duncan McIlroy and Suzanne Dufour. Chapters 2, 3 and 4 are presented as stand-alone manuscripts for individual journal submission, Christopher McKean is the lead author for each of these chapters with additional contributions made by the co-authors. The contributions made by each co-author are as follows, this information can also be found in the preface at the start of each chapter:

Chapter 2 was devised by Christopher McKean, Rod S. Taylor and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from Rod S. Taylor and Duncan McIlroy. Collection of taphonomic and sedimentological data was conducted by Christopher McKean and Duncan McIlroy, with data analysis conducted by Christopher McKean, Rod S. Taylor and Duncan McIlroy. The taphonomic model presented within this chapter was developed by Christopher McKean and Duncan McIlroy, and further refined by Christopher McKean. All figures were constructed by Christopher McKean.

Chapter 3 was devised by Christopher McKean and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from Duncan McIlroy. Collection and analysis of data was conducted by Christopher McKean. The systematic palaeontology(s) presented in this chapter were developed by Christopher McKean, with input from Duncan McIlroy. All figures were constructed by Christopher McKean.

Chapter 4 was devised by Christopher McKean, Jack J. Matthews and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from Jack J. Matthews, Rod S. Taylor and Duncan McIlroy. Collection and analysis of data was conducted by Christopher McKean, based off of a method originally developed by Jack J. Matthews. Interpretation of results and discussion of mitigation techniques was conducted by Christopher McKean and refined through feedback from Jack J. Matthews and Duncan McIlroy. Casting of the Allison Surface as outlined in this chapter was led by Christopher McKean. All figures were constructed by Christopher McKean. The data used for Fig. 4.11 was collected by Benjamin W.T. Rideout who provided support in discovering the accessory sites in Conception Bay North, for which he has been acknowledged as an author in this chapter and the published paper.

At the time of submission *Chapters 2* and *4* have been published with the international journals *Lethaia* and *Geoheritage* respectively. Some changes have been made from the published format; however, the content and structure of the chapters is preserved. The copyright for *Chapter 2* is retained by the authors as stated by *Lethaia*: “As an author for this journal, you retain copyright and publishing rights to your own article without restrictions, and you grant any third party the right to read, download, copy, distribute, print, search or link to the full text of your article in accordance with the Creative Commons Attribution 4.0 International (CC BY 4.0) license". The copyright for *Chapter 4* is retained by the authors as stated by *Geoheritage*/*Springer Nature* "Ownership of copyright in the Article will be vested in the name of the Author. When reproducing the Article or extracts from it, the Author will acknowledge and reference first publication in the Journal".

ACKNOWLEDGEMENTS

I would like to thank my supervisors Duncan McIlroy and Rod Taylor for giving me the opportunity to move to Newfoundland and have the adventure of a lifetime. Duncan, I cannot imagine having had such a great and successful time doing a PhD with anyone else. Your advice, encouragement and humour have helped get me through so many hurdles, and thanks to you I *shall* never use certain words *whilst* writing again. Rod, as the first person I met when being fresh off the plane in strange new land, I thank you for your advice on everything from how to conduct myself as a scientific communicator to where best to get a decent cup of coffee. A special thank you also goes to Suzanne Dufour and Jack Matthews of my supervisory committee for their support and confidence in my work.

It is safe to say this experience would not have been the same if it were not for the other members of the MUNPaleobiology Research Group. Jess, Gio, Dani, Jenna, Pascal, Nagi, Hayley and Mike I could not have asked for a better set of people to work with, I'll fondly remember all the laughter and lively debates both in the office and out in the field. None of this work would have been possible if it hadn't been for the financial support from Duncan McIlroy's NSERC Discovery Grant and Memorial University of Newfoundland.

Finally, I want to thank my family and friends for being with me every step of the way. In particular Mum, Dad and Lizzie – I cannot thank the three of you enough, you've continued to encourage and support me every single day and none of what I have achieved across my PhD and beyond would have been possible without you.

TABLE OF CONTENTS

CHAPTER 3 – A palaeobiological and taxonomic reconsideration of the Ediacaran biota of Upper Island Cove, Conception Bay North, Newfoundland: New taxa and the tops and bottoms of Ediacaran fronds 102

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF TABLES

CHAPTER 4

LIST OF APPENDICES

APPENDIX A

APPENDIX B

APPENDIX C

CHAPTER 1

Introduction

"*Consequently, if the theory be true, it is indisputable that before the lowest Cambrian stratum was deposited long periods elapsed, as long as, or probably far longer than, the whole interval from the Cambrian age to the present day; and that during these vast periods the world swarmed with living creatures.*"

Charles Darwin, On the Origin of Species (1859)

1.1 OVERVIEW

The Ediacaran period was a critical time in the development of life on Earth, occurring at the end of the Neoproterozoic it saw the advent of the first complex, multicellular organisms; the Ediacaran biota (Narbonne 2005; Knoll *et al*. 2006; Liu *et al*. 2015; Fig. 1.1). At the start of the Ediacaran period the planet was covered in a widespread global glaciation known as the Marinoan (Prave *et al*. 2016), which was followed by the shorter and less extensive Gaskiers glaciation (Pu *et al*. 2016). The end of both glaciation events led to an increase in the oxygenation of the world's oceans, with the end of the Gaskiers glaciation coinciding with the first appearance of the Ediacaran biota in the fossil record (Narbonne and Gehling 2003; Canfield *et al*. 2007; Sahoo *et al*. 2012).

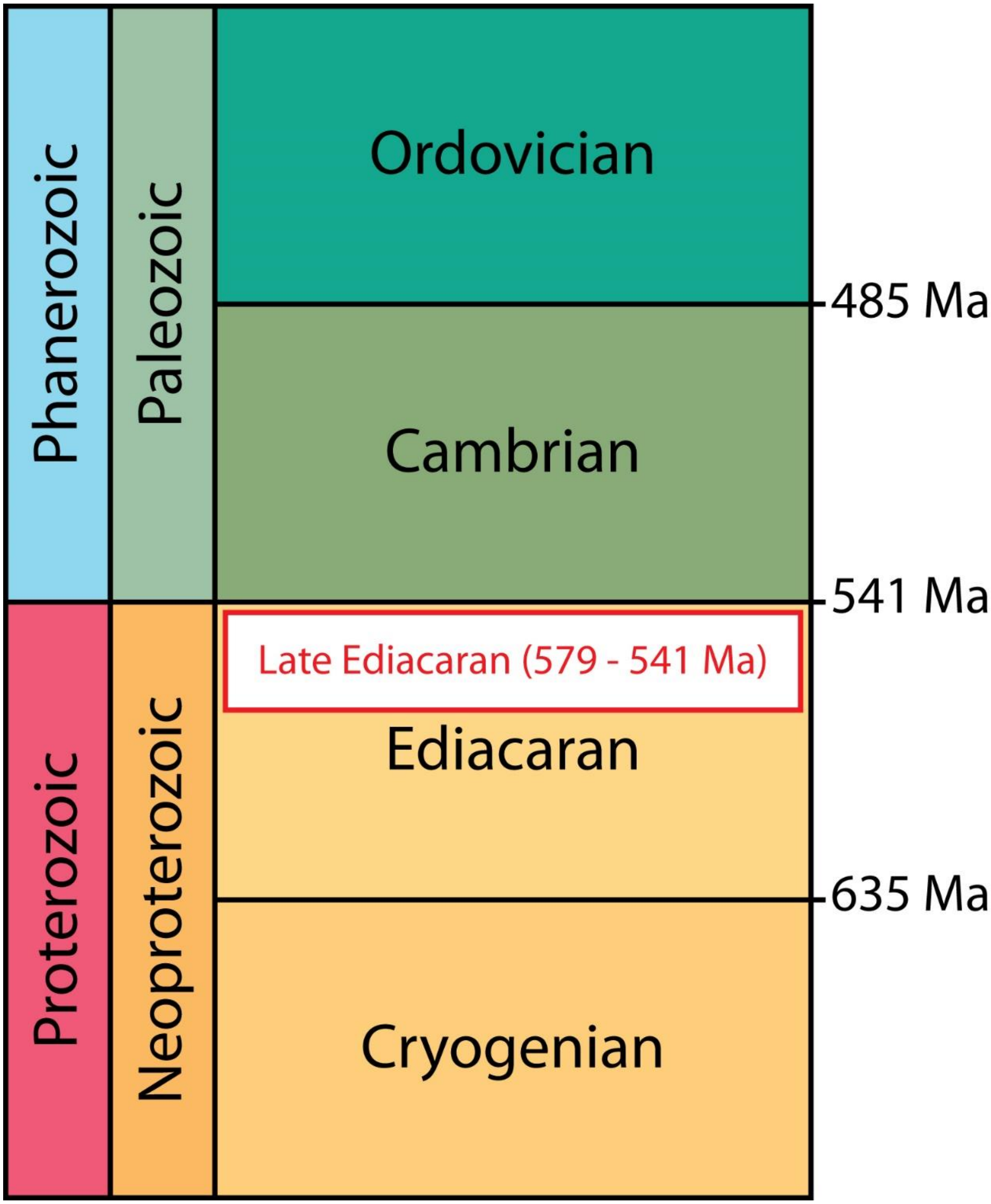


Fig. 1.1 – Geological time scale of Proterozoic to Phanerozoic transition highlighting the late Ediacaran which saw the advent of the Ediacaran biota, the first complex macroscopic organisms on the planet (dates rounded to the nearest integer; modified from Walker and Geissman 2022).

The first recognised Neoproterozoic fossils were discovered in the mid-20th century in Charnwood Forest, Leicestershire, United Kingdom (Ford 1958). Prior to this similar fossils had been discovered elsewhere in Australia and Africa (Gürich 1930, 1933; Sprigg 1947), however, it was not until the discovery of the Charnwood fossils that these discoveries were retroactively recognised as being Neoproterozoic in age (Glaessner 1959). Since the 1950s fossils belonging to the Ediacaran biota have been found on every continent, apart from the Antarctic, and cover a time span of over 38 myr (Liu *et al*. 2013; Pu *et al*. 2016; Dececchi *et al*. 2017). The first Ediacaran fossils found in Newfoundland were discovered in the late-19th century belonging to the discoidal fossil *Aspidella terranovica* (Billings 1872; Gehling *et al*. 2000), however, in the early- to mid-20th century these were reinterpreted as gas escape structures of a non-biological origin (Clarke 1923; Gehling *et al*. 2000; Boyce and Reynolds 2008). At the start of the 21st century *Aspidella* was reinterpreted as a body fossil and, as such, was once again recognised as being biological in origin (Gehling *et al*. 2000). The debate surrounding *Aspidella*, however, meant that it wasn't until the 1960s that the first undisputed Neoproterozoic fossils from Newfoundland were discovered, at Mistaken Point (Anderson and Misra 1968).

The fossils discovered at Mistaken Point were that of frondose organisms, now known as the Rangeomorpha and the Arboreomorpha (Pflüg 1972; Erwin *et al*. 2011; Liu *et al*. 2015). Since the discovery of the Mistaken Point fossils their abundance and quality of preservation has been integral in furthering our understanding of the Ediacaran biota (e.g. Clapham *et al*. 2003; Bamforth *et al*. 2008; Darroch *et al*. 2013; Mitchell and Kenchington 2018; McIlroy *et al*. 2022b). Over the course of the following decades smaller Ediacaran fossil sites were discovered across southeastern Newfoundland (King 1988; Narbonne 2004). However, it was not until the discovery of abundant and diverse Ediacaran fossil sites on the Bonavista Peninsula that a significant second location was known from Newfoundland (O'Brien and King 2004; Hofmann *et al*. 2008). The importance of the Newfoundland biota was further highlighted through radiometric dating, showing the Ediacaran fossils of southeastern Newfoundland to be the oldest Ediacaran fossils discovered anywhere on the planet (Noble *et al*. 2015; Matthews *et al*. 2020; Fig. 1,2), making them inherently important in our understanding of early evolution.

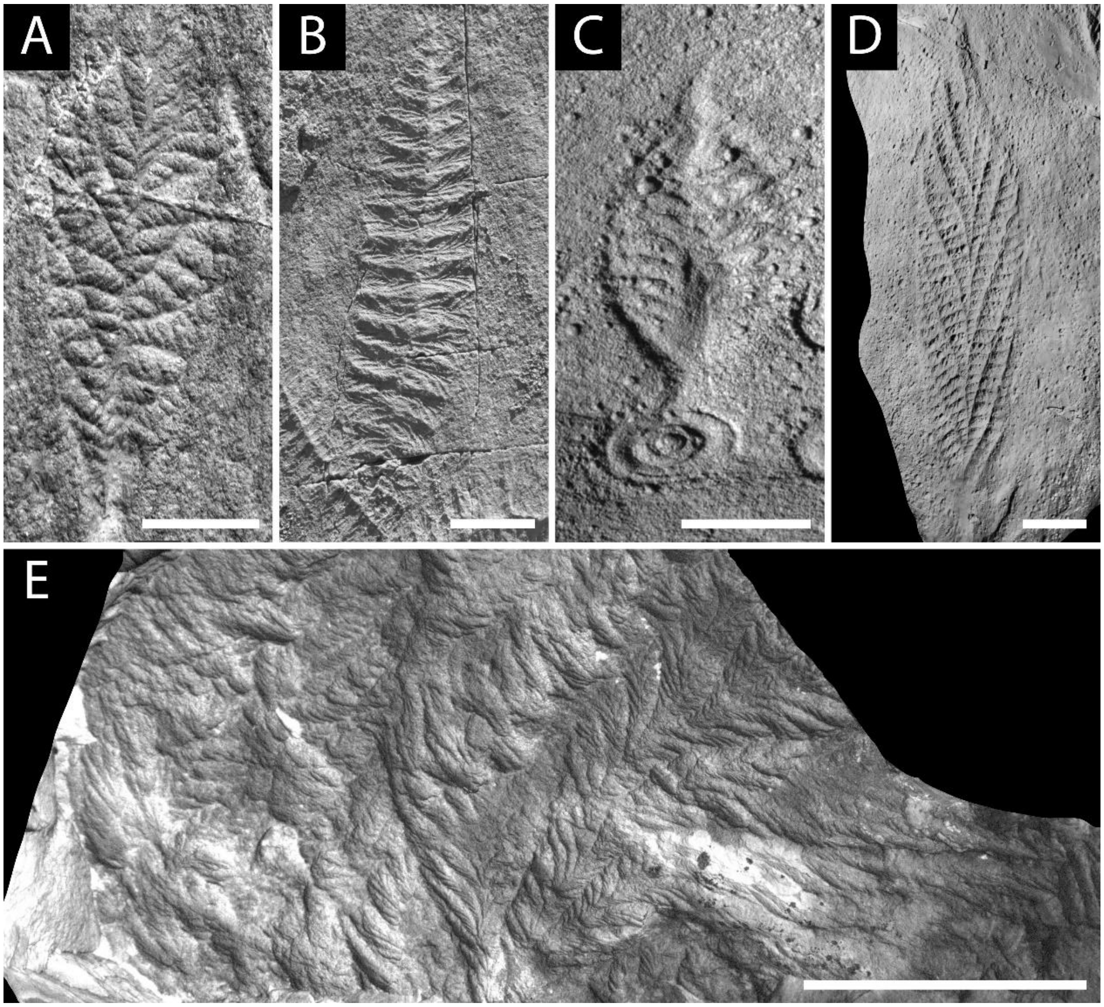


Fig. 1.2 – Selection of Ediacaran fossils from across southeastern Newfoundland. A, holotype of *Beothukis mistakensis* from the Mistaken Point Ecological Reserve (field photo). B, *Fractofusus misrai* from the Mistaken Point Ecological Reserve (field photo). C, *Arborea spinosus* from the recently discovered EM Coombes Surface in Conception Bay North (cast). D, *Charnia* cf. *gracilis* from the recently discovered EM Coombes Surface in Conception Bay North (cast). E, *Bradgatia* sp. from the MUN Surface located in the Discovery UNESCO Global Geopark, Bonavista Peninsula (NFM F-877). (scale bars – 3 cm)

One site of particular importance to the Newfoundland material found outside of the Mistaken Point Ecological Reserve and the Discovery UNESCO Global Geopark, on the

Bonavista Peninsula, is the Allison Surface, a ~130 m^2 fossiliferous surface located 100 km from the city of St. John's in the town of Upper Island Cove, Conception Bay North (Brasier *et al*. 2013; Fig. 1.3). Originally misidentified as being located in the neighbouring town of Spaniard's Bay, the Allison Surface was first described in the literature 20 years ago; this site was noted for its preservation of exquisite high relief, three-dimensional Ediacaran fossils, which preserve sub-mm detail (Narbonne 2004; Fig. 1.3). Initially the Ediacaran fossils located in Upper Island Cove were thought to be 'individual frondlets' of larger rangeomorph organisms (Narbonne 2004), but were later reinterpreted as juvenile forms known from elsewhere in Newfoundland, such as *Beothukis*, *Charnia* and *Bradgatia* (Flude and Narbonne 2008; Narbonne *et al*. 2009; Fig. 1.2A, D-E). Alongside the exquisite preservation, the site also became known for the endemic species *Avalofractus abaculus* (Narbonne *et al*. 2009; Fig. 1.3A) and for being the only Ediacaran fossil locality in Newfoundland where fossils were not preserved underneath an associated layer of ash (Chapter 2), which has been invoked in aiding preservation in the Newfoundland material (Narbonne 2005).

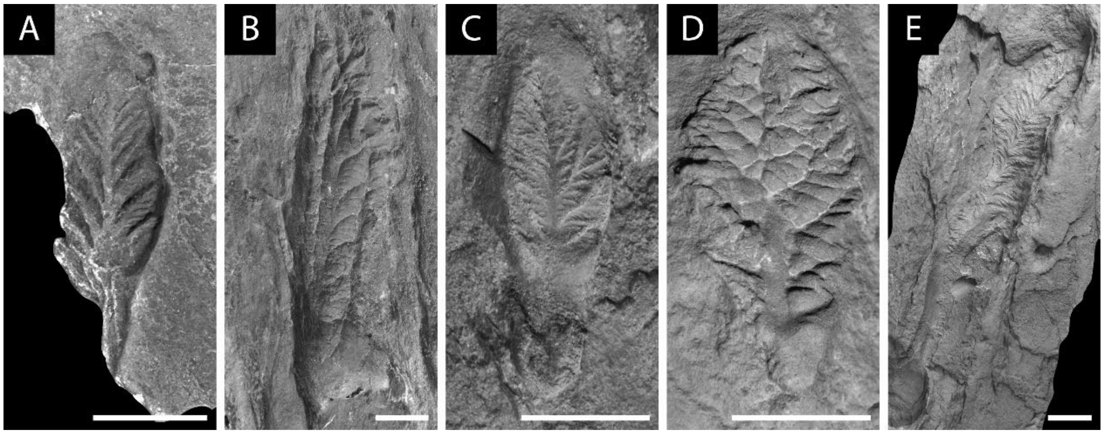


Fig. 1.3 – Previously identified rangeomorph taxa from Upper Island Cove with their originally assigned names (following Flude and Narbonne 2008; Narbonne *et al.* 2009), some of which are challenged herein. A, *Avalofractus abaculus* (NFM F-754). B, *Bradgatia linfordensis* (NFM F-755). C, *Beothukis mistakensis* (NFM F-758). D, *Charnia* cf. *C. masoni* (cast SB-2020-019(b)iii-a). E, *Trepassia wardae* (cast SB-2021-055iv). (scale bars – 1 cm)

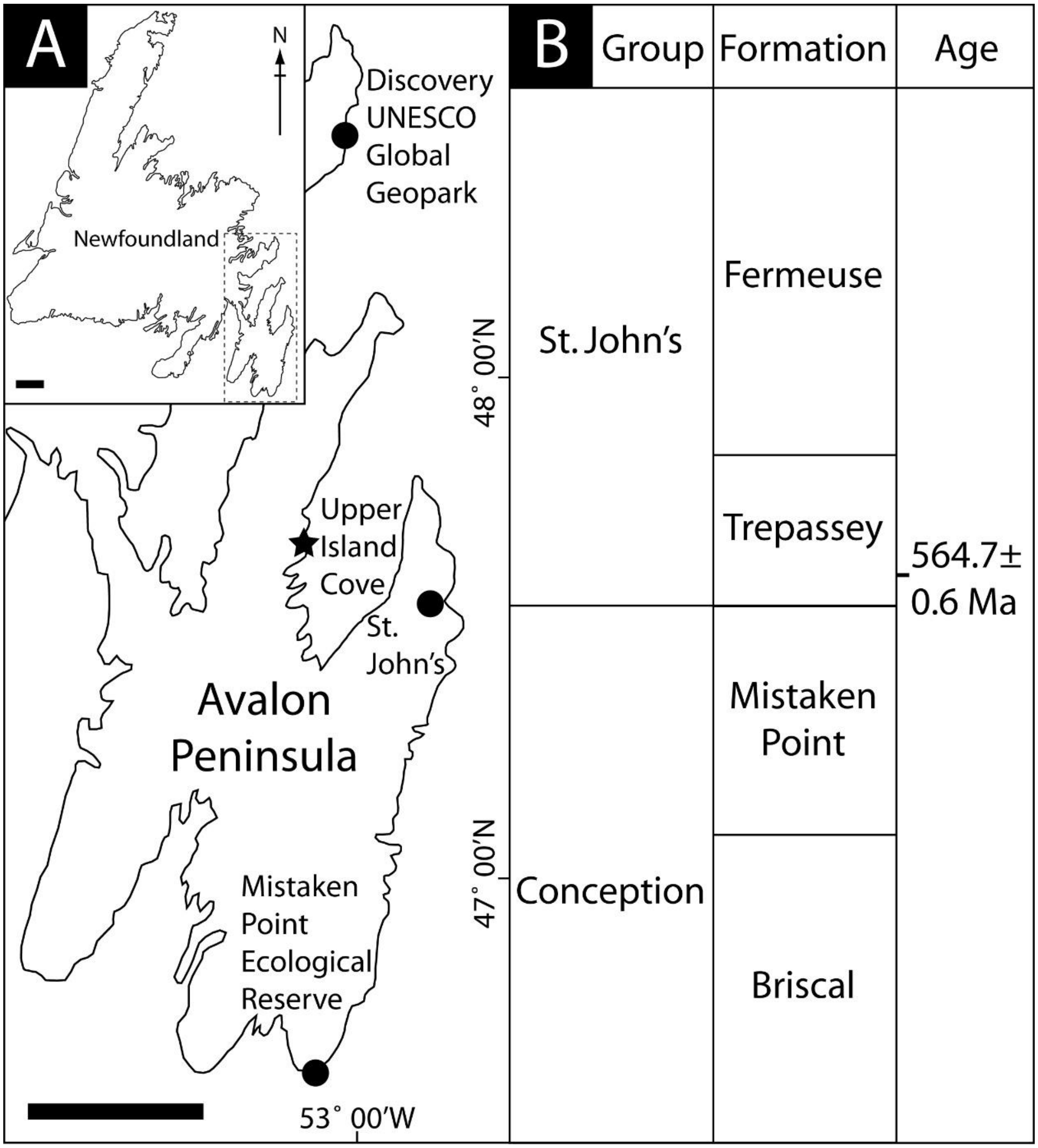
Despite the exceptional preservation of the fossils found on the Allison Surface only a handful of studies have looked into the location in significant detail since its initial discovery (Narbonne 2004; Narbonne *et al.* 2009; Brasier *et al.* 2012). Fossil data from the site has been used for sedimentological, morphological and palaeoecological studies (e.g. Ichaso *et al.* 2007; Flude and Narbonne 2008; Mitchell *et al.* 2019), however, for the locality to be of further use in future Ediacaran research a comprehensive understanding of the taphonomy and taxonomy of the Allison Surface is required.

To that end this PhD project, as presented in this thesis, aims to further our understanding of the Allison Surface at Upper Island Cove. Through reviewing the previous studies conducted at the site using new sedimentological and taphonomic data and improved approaches to the systematics of Ediacaran taxonomy, a better understanding of this unique site will be obtained. Finally, as the Allison Surface is located in a developed area the site's integrity is at risk from both anthropic (human) and environmental factors. As such this thesis also deals with developing a new approach to site observation and risk identification which can be used as a framework for Ediacaran sites located across Newfoundland and the world.

1.2 GEOLOGICAL SETTING

1.2.1 Avalonia

The Ediacaran fossils of southeastern Newfoundland are located on the Avalon and Bonavista Peninsulas (Anderson and Misra 1968; Hofmann *et al*. 2008; Liu *et al*. 2015; Fig. 1.4). Alongside contemporaneous parts of central England, southeastern Newfoundland formed during the late Neoproterozoic as part of the microcontinent Avalonia (Murphy and Nance 1989; Cocks *et al*. 1997). Avalonia has traditionally been reconstructed as an island-arc chain off of the coast of northwestern Gondwana at high palaeolatitudes in the southern hemisphere during the Neoproterozoic (van Stall *et al*. 1998, fig. 7; Pisarevsky *et al*. 2008, fig. 3). More recently, however, studies have used palaeomagnetic data to show that Avalonia was located at low palaeolatitudes in the southern hemisphere between 20–32°S of the equator (Pisarevsky *et al*. 2012; Keppie and Keppie 2014; Fig. 1.5). While palaeomagnetic data is less reliable for the positioning of Gondwana in the late Neoproterozoic (Tohver *et al*. 2006), carbonates deposited at this time suggest that the supercontinent was also positioned at low southern latitudes in close proximity to Avalonia (Geyer and Landing 1995, 2006; Murphy *et al*. 2004; Pollock *et al*. 2009; Pisarevsky *et al*. 2012).



Group	Formation	Age
St. John's	Fermeuse	
	Trepassey	564.7± 0.6 Ma
Conception	Mistaken Point	
	Briscal	

Fig. 1.4 – Map indicating the location of key fossil sites in southeastern Newfoundland. A, close-up map of the Avalon Peninsula highlighting the location of Upper Island Cove in relation to other important Ediacaran fossil sites and the city of St. John's. B, stratigraphic column indicating the

position of the fossil surface in the Trepassey Formation and the age of the assemblage (following Matthews *et al*. 2020). (scale bars – 50 km)

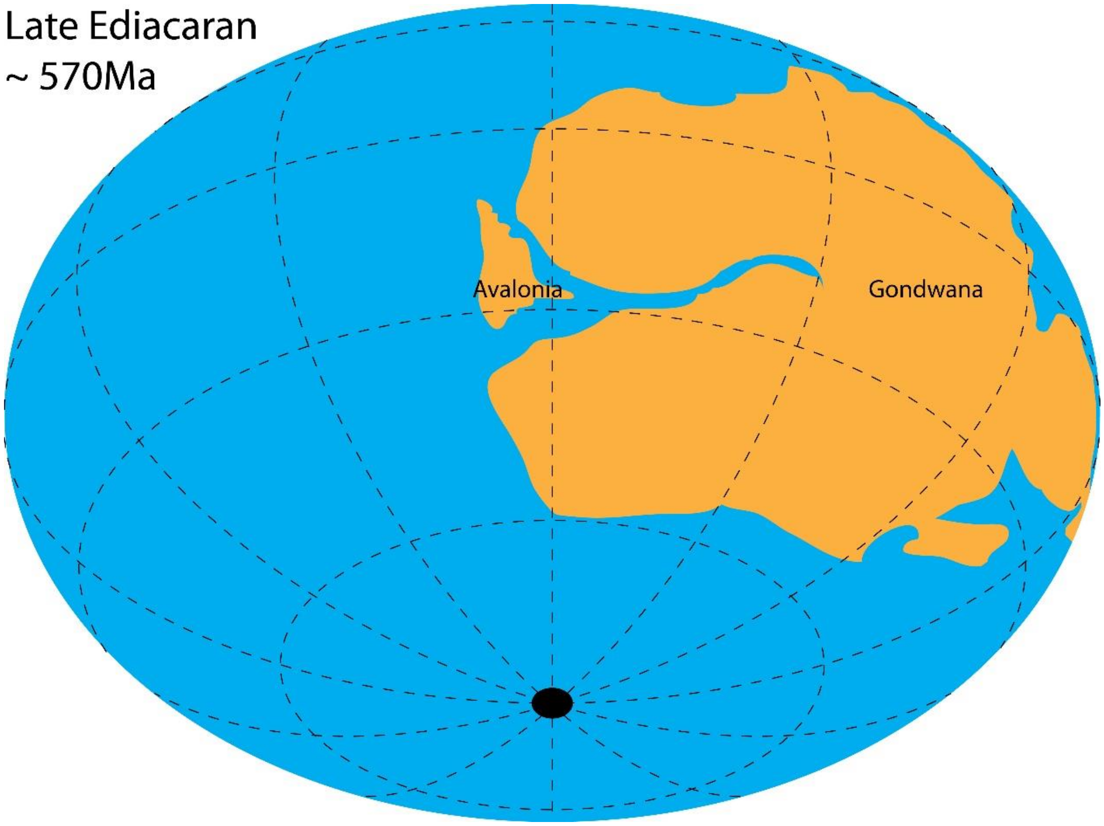


Fig. 1.5 – Palaeomap showing the geographical location of Avalonia off the coast of northwestern Gondwana during the late Ediacaran (modified from Pisarevsky *et al*. 2012).

As an island-arc chain Avalonia was subject to arc-related magmatism during the Ediacaran period, which was driven by subduction on the northwestern margin of Gondwana (Murphy and Nance 2002; McIlroy and Horák 2006). By the time the first Ediacaran organisms appear in the fossil record after the Gaskiers glaciation, ~579 Ma (van Kranendonk *et al*. 2008; Liu *et al*. 2013; Boag *et al*. 2016), Avalonia had transitioned from arc-magmatism to extensional-magmatism (McIlroy and Horák 2006). This would have led to an increase in tectonic and volcanic activity, which in turn played a key role in the formation of the Ediacaran fossils found across much of Newfoundland and central England (Narbonne 2005). The majority of Avalonian Ediacaran fossil localities are preserved beneath a fine layer of ash, which aided in preserving the impression of the soft tissue in Conception-Style preservation (Narbonne 1998; Narbonne 2005; Bobrovskiy *et al*. 2019).

1.2.2 Upper Island Cove

The fossil-bearing rocks of southeastern Newfoundland, which include the Mistaken Point Ecological Reserve (Anderson and Mista 1968; Wood *et al*. 2003), the Discovery UNESCO Global Geopark on the Bonavista Peninsula (Hofmann *et al*. 2008) and the Allison Surface at Upper Island Cove (Narbonne 2004; Narbonne *et al*. 2009), make up part of western Avalonia (Murphy and Nance 2002; Murphy *et al*. 2004, fig. 1). Most of Ediacaran fossil sites found in Newfoundland, including Upper Island Cove, were deposited beneath the storm-wave base, as can be seen by the lack of any shallow-water sedimentological features (Ichaso *et al*. 2007; but also see Pérez-Pinedo *et al*. 2023). Instead of being preserved underneath a layer of volcanic ash, the Ediacaran fossils at Upper Island Cove are buried within the top of a T_d turbidite, beneath a layer of fine-grained T_c sandstone (Ichaso *et al*. 2007; Narbonne *et al*. 2009; Brasier *et al*. 2013, fig. 2b). It is likely that the turbidity currents generated off of the coast of Avalonia during the late Ediacaran that led to the deposition of these T_c and T_d layers were instigated by tectonic activity associated with the extensional-magmatism of the time (Wood *et al*. 2003).

The fossils at Upper Island Cove are located within the Trepassey Formation of the St. John's Group (Narbonne *et al*. 2009; Matthews *et al*. 2020; Fig. 1.4B). Dates for the Trepassey Formation range between 565–563.6 Ma, based off of U-Pb dating, with the same lithostratigraphical unit of the Allison Surface located in the Mistaken Point Ecological Reserve dated at 564.71 ±0.88 Ma (Canfield *et al*. 2020; Matthews *et al*. 2020). This makes the fossils preserved at Upper Island Cove younger than their counterparts in the Mistaken Point Ecological Reserved and the Discovery UNESCO Global Geopark (Hofmann *et al*. 2008; Narbonne *et al*. 2009; Matthews *et al*. 2020).

The lithology preserved at Upper Island Cove is composed of volcaniclastics, pelagic mudstones and turbidite deposits of siltstone, mudstone and fine-grained sandstone (T_{c-e}) (Ichaso *et al*. 2007; Narbonne *et al*. 2009; Brasier *et al*. 2013). It has been inferred that the turbidite units were deposited by weak to moderate turbidity currents (Brasier *et al*. 2013), with slumping located both above and below the fossil bed indicating that deposition occurred on a slope (Ichaso *et al*. 2007). The fine-grain T_c sandstone that overlays the fossiliferous surface is known to have abundant pyrite (Brasier *et al*. 2013, fig. 3), and prior to this project the most up to date taphonomic model for preservation at the site invoked early diagenetic pyrite as aiding in the three-dimensional preservation of the fossils seen on the Allison Surface (Brasier *et al*. 2013).

1.3 AVALONIAN ASSEMBLAGE

The Ediacaran localities of southeastern Newfoundland and central England make up the Avalonian Assemblage (Waggoner 2003; Xiao and Laflamme 2009; Liu *et al*. 2015). The

Ediacaran biota can be split into three distinct assemblages, based off of their spatial, temporal and, to an extent, species composition across the globe (Bottjer and Clapham 2006; Xiao and Laflamme 2009; Grazhdankin 2014). In order of oldest to youngest the three assemblages are: the Avalonian Assemblage, the White Sea Assemblage of Russia and Australia and the Nama Assemblage which is best preserved in Namibia (Waggoner 2003; Bottjer and Clapham 2006; Xiao and Laflamme 2009).

The Avalonian Assemblage is not only the oldest assemblage, but it is also the only one to contain fossils from deep-water environments (Narbonne and Gehling 2003; Xiao and Laflamme 2009; but also see Grazhdankin 2014; Pérez-Pinedo *et al*. 2023). Although, it should be noted that similarly aged Ediacaran fossils, also from a deep-water environment, have recently been reported from NW Canada (Boag *et al*. 2024). With this coinciding with the end of the Gaskiers glaciation it shows that the deep-water became ventilated on the eve of the appearance of the earliest macroscopic organisms (Canfield *et al*. 2007; Xiao and Laflamme 2009; Sahoo *et al*. 2012). As the oldest Ediacaran organisms are preserved within this deep-water environment (Liu *et al*. 2011), it has been suggested that complex life originated within this setting (Xiao and Laflamme 2009). The assemblage is dominated by frondose Ediacaran organisms such as *Charnia*, *Arborea*, *Charniodiscus*, *Culmofrons* and *Fractofusus* (Ford 1958; Laflamme *et al*. 2004; Gehling and Narbonne 2007; Laflamme *et al*. 2012; Pérez-Pinedo *et al*. 2022; Pasinetti and McIlroy 2023), alongside discoidal fossils (Gehling *et al*. 2000; Hofmann *et al*. 2008), putative metazoans such as *Haootia* (Liu *et al*. 2014) and the earliest trace fossils (Liu *et al*. 2010; Menon *et al*. 2013; Liu and McIlroy 2015).

Many recent palaeoecological studies have focused on the Avalonian Assemblage, as the fossils preserved are crucial in furthering our understanding of how the earliest macroorganisms on the planet lived. These studies into the late Neoproterozoic ecosystem have investigated modes of life (McIlroy *et al*. 2022b; Pérez-Pinedo *et al*. 2023), feeding methods (Laflamme *et al*. 2009; McIlroy *et al*. 2021; Butterfield 2022), community succession (Clapham *et al*. 2003; Eden *et al*. 2022), environmental interaction (Dufour and McIlroy 2017; Mitchell *et al*. 2020), ecological tiering (Wilby *et al*. 2015; Mitchell and Kenchington 2018) and reproduction strategies (Mitchell *et al*. 2015; Pasinetti and McIlroy 2023). For effective research into the palaeoecology of a group of organisms the taphonomy and taxonomy must first be understood, as such the results and findings from this project will be fundamental in incorporating the Allison Surface into future palaeoecological studies of the Avalonian Assemblage.

1.4 THE EDIACARAN BIOTA

The Ediacaran biota are a disparate group of enigmatic organisms that are grouped together due to their shared appearance in the Ediacaran period, not a biological affinity to one another (Laflamme *et al*. 2013; Dunn *et al*. 2018). Until the presence of the cloudinids in the Nama Assemblage all Ediacaran taxa were soft-bodied organisms (Germs 1972; Hahn and Pflüg 1985; Tarhan *et al*. 2016). As such all that is preserved of much of the Ediacaran biota is impressions left in the substrate (Bobrovskiy *et al*. 2019), which has made accurate phylogenetic work challenging (Droser and Gehling 2015; Evans *et al*. 2021). Despite this, cladistic analysis has been able to highlight distinct clades and groups within the biota (Erwin *et al*. 2011; Dececchi *et al*. 2017).

The phylogenetic affinity of the Ediacaran biota as a whole is widely debated. Previously suggested phylogenetic affinities suggested for the Ediacaran biota include algae (Ford 1958), a now extinct taxonomic Kingdom: Vendobionta (Seilacher 1989, 1992), fungi (Peterson *et al*. 2003), stem-group metazoans (Droser and Gehling 2015; Dunn *et al*. 2018) and eumetazoans (Jenkins 1985; Dunn *et al*. 2021, 2022). It is now largely accepted that the Ediacaran biota likely consisted of stem-group metazoans and eumetazoans (Grazhdankin 2016; Budd and Jensen 2017; Dunn *et al*. 2018; Evans *et al*. 2021), with the relative percentage of candidate eumetazoans increasing towards the base of the Phanerozoic and the Cambrian Explosion (Laflamme *et al*. 2013; Cribb *et al*. 2019).

In the Avalonian Assemblage and at Upper Island Cove the most common component of the Ediacaran biota are the frondose organisms belonging to the clades Rangeomorpha and Arboreomorpha (Pflüg 1972; Narbonne *et al*. 2009; Erwin *et al*. 2011; Brasier *et al*. 2013; Liu *et al*. 2015; Figs 1.2, 1.3). These clades are found across all three Ediacaran assemblages with a diverse geographical and temporal range (Glaessner and Wade 1966; Nedin and Jenkins 1988; Fedonkin *et al*. 2007; Xiao and Laflamme 2009; Liu *et al*. 2015; Darroch *et al*. 2021; Wood *et al*. 2023). Their preservation means that typically only a single side of the organism is preserved, leading to the traditional interpretation that these organisms had identical morphology on both surfaces (Gehling and Narbonne 2007). However, recent studies into both the rangeomorphs and arboreomorphs have shown that both clades contain taxa with differentiated surfaces (Dunn *et al*. 2019a, 2019b; Butterfield 2022; Taylor *et al*. 2023), challenging many previously held assumptions on the morphology of these enigmatic organisms.

1.4.1 Rangeomorpha

The Rangeomorpha are the most abundant group in the Avalonian Assemblage (Liu *et al*. 2015; Fig. 1.2A-B, D-E), and make up the majority of recognised taxa from the Allison Surface at Upper Island Cove (Narbonne *et al*. 2009; Brasier *et al*. 2013; Fig. 1.3). Rangeomorphs are characterised by the fractal, or self-similar, branching that composes the frondose portion of the organism (Narbonne *et al*. 2009; Kenchington and Wilby 2017; Fig. 1.6). The self-similar nature of rangeomorph branching means that the architecture of the branches repeats at smaller divisions, known as orders (Narbonne *et al*. 2009; Brasier *et al*. 2012; Hoyal Cuthill and Conway Morris 2014). Up to four orders of self-similar branching has been observed in the Rangeomorpha, with fourth-order branching first being identified in the fossils from Upper Island Cove (Narbonne *et al*. 2009).

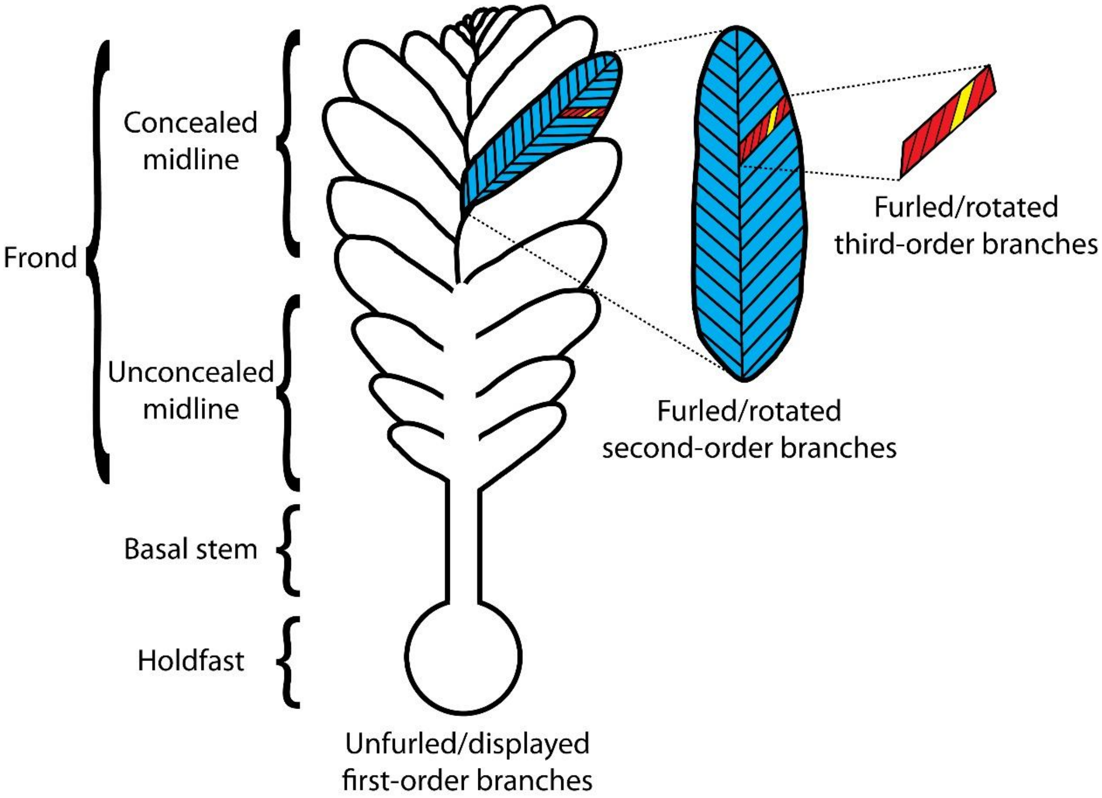


Fig. 1.6 – Schematic diagram of a rangeomorph showing the self-similar branching architecture. Key, first-order branch = blue, second-order branch = red, third-order branch = yellow (modified from Kenchington and Wilby 2017).

The self-similar branching in rangeomorphs is arranged in rows either side of a midline, creating the frondose body plan (Brasier *et al*. 2012; Liu *et al*. 2015). The majority of rangeomorphs are composed of two rows of self-similar branching (Brasier *et al*. 2012), however the taxon *Bradgatia*, known from Upper Island Cove and many other Ediacaran localities, is composed of multiple rows of branches (Boynton and Ford 1995; Flude and Narbonne 2008; Brasier *et al*. 2012). Alongside the frond, many rangeomorphs are composed of a basal stem which terminates in a holdfast which was likely anchored into the sediment (Seilacher 1992; Narbonne *et al*. 2009; Brasier *et al*. 2012; Dufour and McIlroy 2017; Fig. 1.6). The length of the stem varies across rangeomorph taxa but is often used to invoke an erect mode of life in the organisms when present (Clapham *et al*. 2003; Narbonne *et al*. 2009; Brasier *et al*. 2013; Mitchell and Kenchington 2018; McIlroy *et al*. 2022b; but also see Pasinetti and McIlroy *et al*. 2023). Most rangeomorph fronds are unipolar (Brasier *et al*. 2012), growing by the insertion of first-order branches at the terminal end of the frond, followed by their inflation (Gehling and Narbonne 2007; Antcliffe and Brasier 2008; Dunn *et al*. 2018). Bipolar rangeomorphs with two growth tips, e.g. *Fractofusus* and *Pectinifrons*, and multipolar fronds with multiple growth tips, e.g. *Bradgatia*, are also found in the Avalonian Assemblage (Gehling and Narbonne 2007; Bamforth *et al*. 2008; Brasier *et al*. 2012).

The architecture of rangeomorph branches can be split into two categories; furled or unfurled and rotated or displayed (Brasier *et al*. 2012, fig. 3). This gives a combination of four separate possible branch architectures within the rangeomorph (furled/rotated, furled/displayed, unfurled/rotated and unfurled/displayed), which can vary in a single taxon at different branch orders (e.g. McIlroy *et al*. 2022b). Branch architecture is used within the rangeomorpha to differentiate between different genera as outlined by Brasier *et al*. (2012). Species level differences are based on both discrete and continuous characteristics such as morphological distinction in shape, size and the presence of a stem and/or holdfast (Brasier *et al*. 2012; Liu *et al*. 2015; Hawco *et al*. 2020).

Traditionally rangeomorphs were interpreted as erect fronds in the water column tethered to the substrate by their holdfast (e.g. Narbonne 1998, fig. 9a; Brasier *et al*. 2013, fig. 13; Liu *et al*. 2015, fig. 7; but also see McIlroy *et al*. 2022a, 2022b), similar to modern Pennatulacea (i.e. sea-pens Glaessner 1959, 1984; but also see Antcliffe and Brasier 2007). This led to the suggestion that rangeomorphs fed by either filter feeding or osmotrophy, similar to many benthic organisms in the present day (Jenkins 1985; Laflamme *et al*. 2009; Butterfield 2022). Despite this common interpretation, little fossil evidence to support filter feeding or osmotrophy had been found until, recently, potential pore structures were discovered in a three-dimensional *Charnia* in the White Sea Assemblage (Butterfield 2022), highlighting the importance of uniquely preserved, three-dimensional fossils in developing our understanding of the Ediacaran biota.

In the past 20 years, rangeomorph fossils in the Avalonian Assemblage have been found that lack an associated basal stem attached to a holdfast and as such have been interpreted as epifaunal recliners on the seafloor (Gehling and Narbonne 2007; Taylor *et al*. 2021). This in turn led to the revision of some classically interpreted erect rangeomorph fronds as epifaunal recliners, due to the organism lacking a structure that would allow them to be erect in the water column (McIlroy *et al*. 2022b; Pérez-Pinedo *et al*. 2023). It has been noted that reclined rangeomorphs had a large surface area in direct contact with the sea-floor, however, as they were soft-bodied organisms this would have led to an increased risk of hydrogen sulphide poisoning from prolonged contact with the anoxic seafloor (Dufour and McIlroy 2017, fig. 2). It has therefore been suggested that reclined rangeomorphs were capable of chemosymbiosis with sulphur reducing bacteria to remove harmful build-up of hydrogen sulphide, and that reclined rangeomorphs may have utilised phagocytosis as a means of digesting the bacteria as a feeding strategy (Dufour and McIlroy 2017; McIlroy *et al*. 2021).

1.4.2 Arboreomorpha

The Arboreomorpha are another frondose Ediacaran clade found in the Avalonian Assemblage and at Upper Island Cove (Laflamme *et al*. 2004; Brasier *et al*. 2013; Liu *et al*. 2015; Fig. 1.2C), alongside other localities in the White Sea Assemblage and China (Glaessner and Daily 1959; Borchvardt and Nessov 1999; Wang *et al*. 2020; Grimes *et al*. 2023). Arboreomorphs do not possess the fractal/self-similar branching architecture seen in rangeomorphs (Pérez-Pinedo *et al*. 2022). Instead, these frondose organisms are composed of parallel branches emanating from a central stalk that terminate in a basal stem and holdfast (Laflamme *et al*. 2018; Dunn *et al*. 2019a; Fig. 1.7).

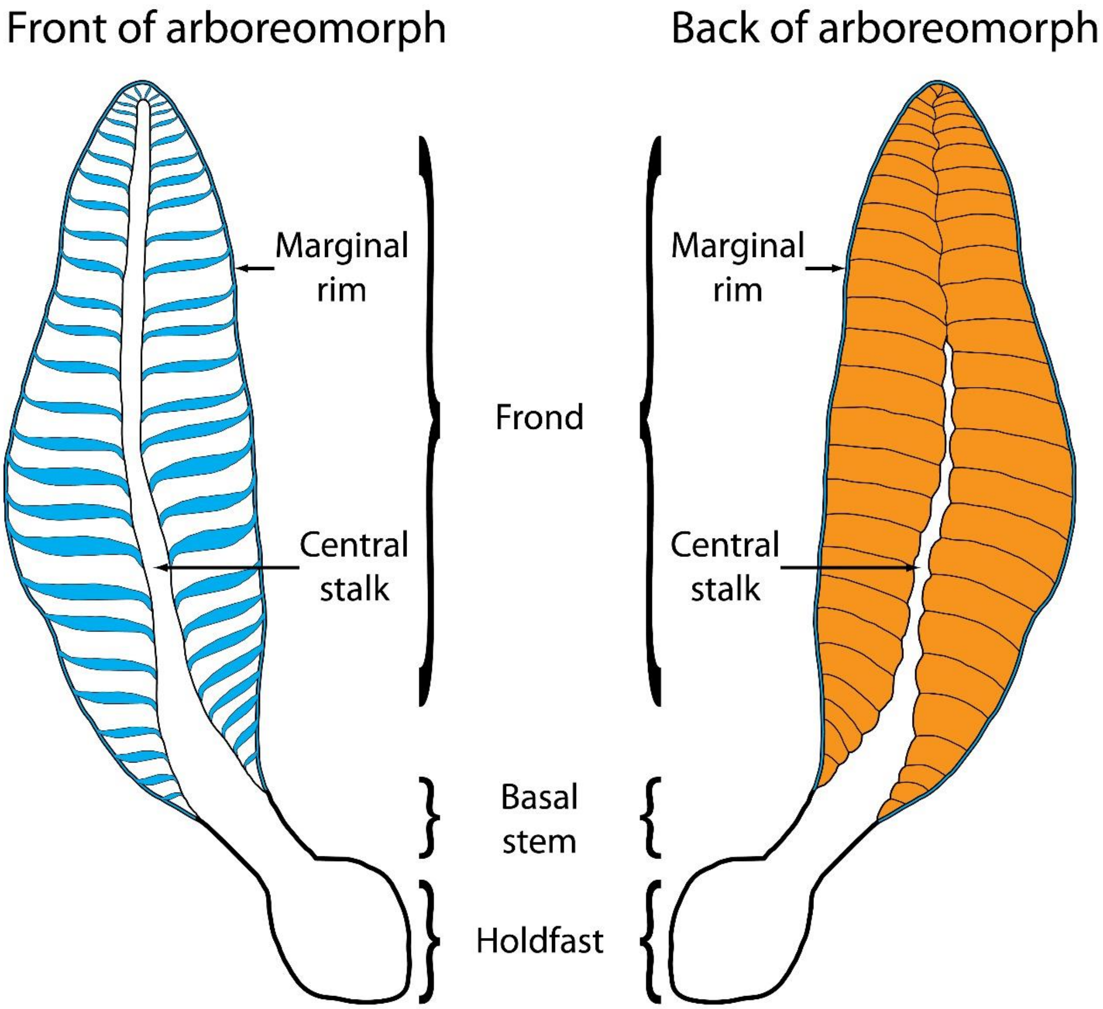


Fig. 1.7 – Schematic diagram of an arboreomorph showing the differentiated front and back sides of the organism. Key, 'pea pod' primary units = blue, backing sheet = orange (modified from Dunn *et al.* 2019a).

The two most common and widespread genera in the Arboreomorpha are *Arborea* (Glaessner and Wade 1966; Laflamme *et al*. 2018; Dunn *et al*. 2019a) and *Charniodiscus* (Ford 1958; Pérez-Pinedo *et al*. 2022). While both taxa are composed of bifoliate, unipolar fronds with parallel branching (Laflamme *et al*. 2018; Pérez-Pinedo *et al*. 2022), they differ in their gross morphology. *Arborea* are planar leaf-like organisms, which have a distinctive differentiation between their front and back sides (Laflamme *et al*. 2018; Dunn *et al*. 2019a; Pérez-Pinedo *et al*. 2022). The front side of *Arborea* is composed of primary branches that are in the shape of 'pea pods' which are attached to the central stalk, with a marginal rim located at the distal tip of the branches (Laflamme *et al*. 2018; Dunn *et al*. 2019a; Fig. 1.7). The back side of *Arborea* shows no evidence for the *Arborea*-type branching, instead these fossils preserve the impression of a backing-sheet that covers the frondose portion of the organism (Dunn *et al*. 2019a; Fig. 1.7).

Charniodiscus differs from *Arborea* in that it lacks both the planar leaf-like structure and backing sheet. Instead, *Charniodiscus* is sub-conical to conical in shape, with primary branches folding across the centre of the organism (Pérez-Pinedo *et al*. 2022). Typically, *Charniodiscus* is preserved as a mixed epirelief impression on a fossiliferous surface, the branches being preserved in negative epirelief and the stem, being made of a more robust material, preserved in positive epirelief (Laflamme *et al*. 2004; Laflamme and Narbonne 2008; Brasier and Antcliffe 2009; Pérez-Pinedo *et al*. 2022, fig. 4). This has made reconstructing the taxon in three-dimensions challenging, however, the discovery of a full-relief three-dimensional *Charniodiscus* on the Allison Surface at Upper Island Cove clearly shows the sub-conical structure preserved, with the folded primary branches (Pérez-Pinedo *et al*. 2023, fig. 8). Not only did this specimen help researchers to reconstruct this classic Ediacaran genus in three-dimensions (Pérez-Pinedo *et al*. 2023, fig. 5), it also highlighted how the unique preservation of the Ediacaran fossils at Upper Island Cove gives us an exceptional opportunity to further our understanding of these enigmatic organisms.

1.5 OBJECTIVES OF THESIS

The objective of the research presented within this thesis is to further our understanding of the unique Ediacaran fossil locality known as the Allison Surface, in Upper Island Cove, to allow it to be included in broader palaeontological studies including exceptional lagerstätte preservation, palaeoecology, palaeobiogeography and phylogenetics. Prior to this project it had been over a decade since the last focussed study was conducted at the site (Brasier *et al*. 2013). Previous studies conducted at the site have focused on addressing the taxonomy and taphonomy of the Allison Surface (e.g. Narbonne 2004; Flude and Narbonne 2008; Narbonne *et al*. 2009; Brasier *et al*. 2013). However, much of this research is now in need of revision due to updated systematics for Ediacaran taxonomy being developed since the species composition of the locality was first addressed (e.g. Brasier *et al*. 2012; Dunn *et al*. 2019a), alongside the observation of new sedimentological and fossil evidence (e.g. Hawco *et al*. 2020; McIlroy *et al*. 2022b) that contradicts the previously suggested taphonomic models used for explaining the unique high-relief, three-dimensional preservation seen on the surface. Without properly understanding the taphonomy and taxonomy of the Allison Surface its validity as a location for use in broader Ediacaran research is brought into question. To better understand the Allison Surface, the fossils present and its place in future Ediacaran research the following objectives have been addressed:

1) Develop an updated taphonomic model for the preservation of exquisite, three-dimensional, high relief Ediacaran fossils on the Allison Surface, taking into account all taphonomic and sedimentological evidence present at the site (Chapter 2).
2) Reassess and update the taxonomy of the fossils present on the Allison Surface using updated systematics for the Ediacaran biota (Chapter 3).

3) Understand the anthropic and environmental risks to the fossils at Upper Island Cove and develop mitigation techniques to aid in the long-term protection of the site (Chapter 4).

With the recent discovery of multiple new fossil sites in the Conception Bay North region (Fig. 1.2C-D) the framework for site-specific investigation outlined in this thesis can be implemented by future studies on the Ediacaran biota of southeastern Newfoundland. This study also has a much broader significance to the overall study of Ediacaran palaeontology. Through understanding the preservation and species composition of the Allison Surface, as addressed in Chapters 2 and 3, these exceptional, high-relief, three-dimensional Ediacaran organisms present us with the opportunity to refine our understanding of the anatomy of the well-known, yet poorly understood, Ediacaran clades Rangeomorpha and Arboreomorpha, alongside providing new insight into ecological successions in some of the earliest Ediacaran assemblages. Furthermore, the novel method for site observation developed and discussed in Chapter 4 has wider implications, as it can be applied to a wide and varied number of at-risk palaeontological sites across Newfoundland and the globe.

1.6 STRUCTURE OF THESIS

This thesis is structured in the ‘Manuscript Style’, with Chapters 2, 3 and 4 presented as stand-alone manuscripts for journal submission. The preface of each chapter states what stage of publication the chapter can be found in at the time of thesis submission. As stand-alone chapters each has been co-authored by separate individuals, with Christopher

McKean as the lead author for each, as such a detailed co-authorship statement can be found within the preface of each co-authored chapter.

As this PhD project has focused on furthering our understanding of the Allison Surface at Upper Island Cove, the chapters follow the order in which the studies were conducted with subsequent chapters drawing on information from previous chapters. To this end the thesis chapters follow the research objectives as follows:

Chapter 1 – Introduction
Chapter 2 – Taphonomy of the Upper Island Cove Lagerstätte
Chapter 3 – Taxonomic reassessment of the Upper Island Cove Lagerstätte
Chapter 4 – Geoconservation of the Upper Island Cove Lagerstätte
Chapter 5 – Conclusion/Summary

To understand a fossil the taphonomic processes that the organism was subject to during the fossilisation process must be understood, so as not to introduce wrongful bias. For this reason, Chapter 2 focuses on the taphonomy of the Allison Surface, critiquing previous taphonomic models and developing an improved model which incorporates all taphonomic and sedimentological evidence at the site. Once the taphonomic processes were understood it was possible to assess the taxa present and conduct a taxonomic assessment of the Upper Island Cove assemblage. This is the focus of Chapter 3 which emends the diagnosis of several of the Ediacaran taxa and describes three new species that are present at the site, including one that is endemic to the Allison Surface. Finally, in light of the unique preservation and presence of two endemic species at the Allison Surface (*Avalofractus* *abaculus* and *Kannabuchia artkingii* gen. et sp. nov.; Chapter 3) Chapter 4 uses a novel approach to identify and highlight the anthropic and environmental risks to the Allison Surface, suggesting mitigation techniques for the site's long-term protection that can be utilised at other at-risk Ediacaran sites worldwide.

REFERENCES

Anderson, M.M. and Misra, S.B. 1968. Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland. *Nature*, **220**, 680–681, https://doi.org/10.1038/220680a0

Antcliffe, J.B. and Brasier, M.D. 2007. *Charnia* and sea pens are poles apart. *Journal of the Geological Society*, **164**, 49–51, https://doi.org/10.1144/0016-76492006-080

Antcliffe, J.B. and Brasier, M.D. 2008. *Charnia* at 50: Developmental models for Ediacaran fronds. *Palaeontology*, **51**, 11–26, https://doi.org/10.1111/j.1475-4983.2007.00738.x

Bamforth, E.L., Narbonne, G.M. and Anderson, M.M. 2008. Growth and ecology of a multi-branched Ediacaran rangeomorph from the Mistaken Point assemblage, Newfoundland. *Journal of Paleontology*, **82**, 763–777, https://doi.org/10.1666/07-112.1

Billings, E. 1872. On some fossils from the primordial rocks of Newfoundland. *Canadian Naturalist and Quarterly Journal of Science*, **6**, 465–479.

Boag, T.H., Darroch, S.A.F. and Laflamme, M. 2016. Ediacaran distributions in space and time: testing assemblage concepts of earliest macroscopic body fossils. *Paleobiology*, **42**, 574–594, https://doi.org/10.1017/pab.2016.20

Boag, T.H., Busch, J.F., Gooley, J.T., Strauss, J.V. and Sperling, E.A. 2024. Deep-water first occurrences of Ediacara biota prior to the Shuram carbon isotope excursion in the Wernecke Mountains, Yukon, Canada. *Geobiology*, **22**, e12597, https://doi.org/10.1111/gbi.12597

Bobrovskiy, I., Krasnova, A., Ivantsov, A., Luzhnaya (Serezhnikova), E. and Brocks, J.J. 2019. Simple sediment rheology explains the Ediacara biota preservation. *Nature Ecology & Evolution*, **3**, 582–589, https://doi.org/10.1038/s41559-019-0820-7

Borchvardt, D.V. and Nessov, L.A. 1999. New records of metaphytes from the Vendian (Precambrian) of Zimnii Bereg of the White Sea. *Trudy Zoologicheskogo Instituta Rossiĭskoĭ Akademii Nauk*, **277**, 50–57.

Bottjer, D.J. and Clapham, M.E. 2006. Evolutionary palaeoecology of Ediacaran benthic marine animals. *In*: Xiao, S. and Kaufman, A.J. (eds) *Neoproterozoic Geobiology and Paleobiology*. Topics in Geobiology, **27**, 91–114, https://doi.org/10.1007/1-4020-5202-2_4

Boyce, W.D. and Reynolds, K. 2008. The Ediacaran fossil *Aspidella terranovica* Billings, 1872 from St. John's Convention Centre test pit CjAe-33. *Current Research, Newfoundland and Labrador Department of Natural Resources—Geological Survey*, **08-1**, 55–61.

Boynton, H.E. and Ford, T.D. 1995. Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, **13**, 165–182.

Brasier, M.D. and Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: New insights from laser analysis. *Journal of the Geological Society*, **166**, 363–384, https://doi.org/10.1144/0016-76492008-011

Brasier, M.D., Antcliffe, J.B. and Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124, https://doi.org/10.1111/j.1475-4983.2012.01164.x

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Budd, G.E. and Jensen, S. 2017. The origin of the animals and a 'Savannah' hypothesis for early bilaterian evolution. *Biological Reviews*, **92**, 446–473, https://doi.org/10.1111/brv.12239

Butterfield, N.J. 2022. Constructional and functional anatomy of Ediacaran rangeomorphs. *Geological Magazine*, **159**, 1148–1159, https://doi.org/10.1017/S0016756820000734

Canfield, D.E., Poulton, S.W. and Narbonne, G.M. 2007. Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life. *Science*, **315**, 92–95, https://doi.org/10.1126/science.1135013

Canfield, D.E., Knoll, A.H., Poulton, S.W., Narbonne, G.M. and Dunning, G.R. 2020. Carbon isotopes in clastic rocks and the Neoproterozoic carbon cycle. *American Journal of Science*, **320**, 97–124, https://doi.org/10.2475/02.2020.01

Clapham, M.E., Narbonne, G.M. and Gehling, J.G. 2003. Paleoecology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland.

Paleobiology, **29**, 527–544, https://doi.org/10.1666/0094-8373(2003)029%3C0527:POTOKA%3E2.0.CO;2

Clark, T.H. 1923. New fossils from the vicinity of Boston. *Proceedings of the Boston Society of Natural History*, **36**, 473–485.

Cocks, L.R.M., McKerrow, W.S. and van Staal, C.R. 1997. The margins of Avalonia. *Geological Magazine*, **134**, 627–636, https://doi.org/10.1017/S0016756897007425

Cribb, A.T., Kenchington, C.G., Koester, B., Gibson, B.M., Boag, T.H., Racicot, R.A., Mocke, H., Laflamme, M. and Darroch, S.A.F. 2019. Increase in metazoan ecosystem engineering prior to the Ediacaran-Cambrian boundary in the Nama Group, Namibia. *Royal Society Open Science*, **6**, 190548, https://doi.org/10.1098/rsos.190548

Darroch, S.A.F., Laflamme, M. and Clapham, M.E. 2013. Population structure of the oldest known macroscopic communities from Mistaken Point, Newfoundland. *Paleobiology*, **39**, 591–608, https://doi.org/10.1666/12051

Darroch, S.A.F., Cribb, A.T., Buatois, L.A., Germs, G.J.B., Kenchington, C.G., Smith, E.F., Mocke, H., O'Neil, G.R., Schiffbauer, J.D., Maloney, K.M., Racicot, R.A., Turk, K.A., Gibson, B.M., Almond, J., Koestar, B., Boag, T.H., Tweedt, S.M. and Laflamme, M. 2021. The trace fossil record of the Nama Group, Namibia: Exploring the terminal Ediacaran roots of the Cambrian Explosion. *Earth-Science Reviews*, **212**, 103435, https://doi.org/10.1016/j.earscirev.2020.103435

Darwin, C. 1859. *The Origin of Species (Collins Classics)*. HarperCollins.

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2017. Relating Ediacaran fronds. *Paleobiology*, **43**, 171–180, https://doi.org/10.1017/pab.2016.54

Droser, M.L. and Gehling, J.G. 2015. The advent of animals: The view from the Ediacaran. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 4865–4870, https://doi.org/10.1073/pnas.1403669112

Dufour, S.C. and McIlroy, D. 2017. Ediacaran pre-placozoan diploblasts in the Avalonian biota: The role of chemosynthesis in the evolution of early animal life. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 211–219, https://doi.org/10.1144/SP448.5

Dunn, F.S., Liu, A.G. and Donoghue, P.C.J. 2018. Ediacaran developmental biology. *Biological Reviews*, **93**, 914–932, https://doi.org/10.1111/brv.12379

Dunn, F.S., Liu, A.G. and Gehling, J.G. 2019a. Anatomical and ontogenetic reassessment of the Ediacaran frond *Arborea arborea* and its placement within total group Eumetazoa. *Palaeontology*, **62**, 851–865, https://doi.org/10.1111/pala.12431

Dunn, F.S., Wilby, P.R., Kenchington, C.G., Grazhdankin, D.V., Donoghue, P.C.J. and Liu, A.G. 2019b. Anatomy of the Ediacaran rangeomorph *Charnia masoni*. *Papers in Palaeontology*, **5**, 157–176, https://doi.org/10.5061/dryad.fg14s2r

Dunn, F.S., Liu, A.G., Grazhdankin, D.V., Vixseboxse, P., Flannery-Sutherland, J., Green, E., Harris, S., Wilby, P.R. and Donoghue, P.C.J. 2021. The developmental biology of *Charnia* and the eumetazoan affinity of the Ediacaran rangeomorphs. *Science Advances*, **7**, eabe0291, https://doi.org/10.1126/sciadv.abe0291

Dunn, F.S., Kenchington, C.G., Parry, L.A., Clark, J.W., Kendall, R.S. and Wilby, P.R. 2022. A crown-group cnidarian from the Ediacaran of Charnwood Forest, UK. *Nature Ecology & Evolution*, **6**, 1095–1104, https://doi.org/10.1038/s41559-022-01807-x

Eden, R., Manica, A. and Mitchell, E.G. 2022. Metacommunity analyses show an increase in ecological specialisation throughout the Ediacaran period. *PLoS Biology*, **20**, e3001289, https://doi.org/10.1371/journal.pbio.3001289

Erwin, D.H., Laflamme, M., Tweedt, S.M., Sperling, E.A., Pisani, D. and Peterson, K.J. 2011. The Cambrian conundrum: Early divergence and later ecological success in the early history of animals. *Science*, **334**, 1091–1097, https://doi.org/10.1126/science.1206375

Evans, S.D., Droser, M.L. and Erwin, D.H. 2021. Developmental processes in Ediacara macrofossils. *Proceedings of the Royal Society B*, **288**, 20203055, https://doi.org/10.1098/rspb.2020.3055

Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. and Vickers-Rich, P. 2007. *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press.

Flude, L.I. and Narbonne, G.M. 2008. Taphonomy and ontogeny of a multibranched Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland. *Canadian Journal of Earth Sciences*, **45**, 1095–1109, https://doi.org/10.1139/E08-057

Ford, T.D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 211–217, https://doi.org/10.1144/pygs.31.3.211

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Gehling, J.G., Narbonne, G.M. and Anderson, M.M. 2000. The first named Ediacaran body fossil, *Aspidella Terranovica*. *Palaeontology*, **43**, 427–456, https://doi.org/10.1111/j.0031-0239.2000.00134.x

Germs, G.J.B. 1972. New shelly fossils from the Nama Group, South West Africa. *American Journal of Science*, **272**, 752–761, https://doi.org/10.2475/ajs.272.8.752

Geyer, G. and Landing, E. 1995. The Cambrian of the Moroccan Atlas regions. *In*: Geyer, G. and Landing, E. (eds) *Morocco '95—the Lower-Middle Cambrian standard of western Gondwana*. Beringeria, Special Issue, **2**, 7–46.

Geyer, G. and Landing, E. 2006. Morocco field excursion 2006. Ediacaran-Cambrian depositional environments and stratigraphy of the western Atlas regions. *In*: Geyer, G. and Landing, E. (eds) *Morocco 2006. Ediacaran-Cambrian depositional environments and stratigraphy of the western Atlas regions. Explanatory description and field excursion guide*. Beringeria, Special Issue, **6**, 47–112.

Glaessner, M.F. 1959. Precambrian Coelenterata from Australia, Africa and England. *Nature*, **183**, 1472–1473, https://doi.org/10.1038/1831472b0

Glaessner, M.F. 1984. *The Dawn of Animal Life: A biohistorical Study*. Cambridge University Press.

Glaessner, M.F. and Daily, B. 1959. The geology and late Precambrian fauna of the Ediacara fossil reserve. *Records of the South Australia Museum*, **13**, 369–401.

Glaessner, M.F. and Wade, M. 1966. The Late Precambrian fossils from Ediacara, South Australia. *Palaeontology*, **9**, 599–628.

Grazhdankin, D. 2014. Patterns of evolution of the Ediacaran soft-bodied biota. *Journal of Paleontology*, **88**, 269–283, https://doi.org/10.1666/13-072

Grazhdankin, D. 2016. Forbidden fruits in the Garden of Ediacara. *Paläontologische Zeitschrift*, **90**, 649–657, https://doi.org/10.1007/s12542-016-0327-3

Grimes, K.F., Narbonne, G.M., Gehling, J.G., Trusler, P.W. and Dececchi, T.A. 2023. Elongate Ediacaran fronds from the Flinders Ranges, South Australia. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2023.45

Gürich, G. 1930. Die bislang ältesten Spuren von Organismen in Südafrika. *International Geological Congress (XV), Pretoria, Union of South Africa, Die altesten Fossilien Sud-Afrikas*, **2**, 670–680.

Gürich, G. 1933. Die Kuibis-Fossilien der Nama-Formation von Südwestafrika. *Paläontologische Zeitschrift*, **15**, 137–154, https://doi.org/10.1007/BF03041648

Hahn, G. and Pflüg, H.D. 1985. Die Cloudinidae n. fam., Kalk-Röhren aus dem Vendium and Unter-Kambrium. *Senckenbergiana Lethaea*, **65**, 413–431.

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Hofmann, H.J., O'Brien, S.J. and King, A.F. 2008. Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36, https://doi.org/10.1666/06-087.1

Hoyal Cuthill, J.F. and Conway Morris, S. 2014. Fractal branching organizations of Ediacaran rangeomorph fronds reveal a lost Proterozoic body plan. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 13122–13126, https://doi.org/10.1073/pnas.1408542111

Ichaso, A.A., Dalrymple, R.W. and Narbonne, G.M. 2007. Paleoenvironmental and basin analysis of the late Neoproterozoic (Ediacaran) upper Conception and St. John's groups, west Conception Bay, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 25–41, https://doi.org/10.1139/e06-098

Jenkins, R.J.F. 1985. The enigmatic Ediacaran (late Precambrian) genus *Rangea* and related forms. *Paleobiology*, **11**, 336–355, https://doi.org/10.1017/S0094837300011635

Kenchington, C.G. and Wilby, P.R. 2017. Rangeomorph classification schemes and intra-specific variation: Are all characters created equal? *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 221–250, https://doi.org/10.1144/SP448.19

Keppie, J.D. and Keppie, D.F. 2014. Ediacaran-Middle Paleozoic oceanic voyage of Avalonia from Baltica via Gondwana to Laurentia: Paleomagnetic, faunal and geological constraints. *Geoscience Canada*, **41**, 5–18, https://doi.org/10.12789/geocanj.2014.41.039

King, A.F. 1988. *Geology of the Avalon Peninsula, Newfoundland (parts of 1K, 1L, 1M, 1N and 2C)*. Newfoundland Department of Mines and Energy Map **88-01**.

Knoll, A.H., Javaux, E.J., Hewitt, D. and Cohen, P. 2006. Eukaryotic organisms in Proterozoic oceans. *Philosophical Transactions of the Royal Society B*, **361**, 1023–1038, https://doi.org/10.1098/rstb.2006.1843

Laflamme, M. and Narbonne, G.M. 2008. Ediacaran fronds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 162–179, https://doi.org/10.1016/j.palaeo.2007.05.020

Laflamme, M., Narbonne, G.M. and Anderson, M.M. 2004. Morphometric analysis of the Ediacaran frond *Charniodiscus* from the Mistaken Point Formation, Newfoundland. *Journal of Paleontology*, **78**, 827–837, https://doi.org/10.1666/0022-3360(2004)078%3C0827:MAOTEF%3E2.0.CO;2

Laflamme, M., Xiao, S. and Kowaleski, M. 2009. Osmotrophy in modular Ediacara organisms. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 14438–14443, https://doi.org/10.1073/pnas.0904836106

Laflamme, M., Flude, L.I. and Narbonne, G.M. 2012. Ecological tiering and the evolution of a stem: The oldest stemmed frond from the Ediacaran of Newfoundland, Canada. *Journal of Paleontology*, **86**, 193–200, https://doi.org/10.1666/11-044.1

Laflamme, M., Darroch, S.A.F., Tweedt, S.M., Peterson, K.J. and Erwin, D.H. 2013. The end of the Ediacara biota: Extinction, biotic replacement, or Cheshire Cat? *Gondwana Research*, **23**, 558–573, https://doi.org/10.1016/j.gr.2012.11.004

Laflamme, M., Gehling, J.G. and Droser, M.L. 2018. Deconstructing an Ediacaran frond: Three-dimensional preservation of *Arborea* from Ediacara, South Australia. *Journal of Paleontology*, **92**, 323–335, https://doi.org/10.1017/jpa.2017.128

Liu, A.G. and McIlroy, D. 2015. Horizontal surface traces from the Fermeuse Formation, Ferryland (Newfoundland, Canada), and their place within the late Ediacaran ichnological revolution. *In*: McIlroy, D. (ed.) *Ichnology: Publications arising from*

ICHNIA III. Geological Association of Canada, Miscellaneous Publication, **9**, 141–156.

Liu, A.G., McIlroy, D. and Brasier, M.D. 2010. First evidence for locomotion in the Ediacara biota from the 565 Ma Mistaken Point Formation, Newfoundland. *Geology*, **38**, 123–126, https://doi.org/10.1130/G30368.1

Liu, A.G., McIlroy, D., Antcliffe, J.B. and Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630, https://doi.org/10.1111/j.1475-4983.2010.01024.x

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2013. Exploring an Ediacaran 'nursery': Growth, ecology and evolution in a rangeomorph palaeocommunity. *Geology Today*, **29**, 23–26, https://doi.org/10.1111/j.1365-2451.2013.00860.x

Liu, A.G., Matthews, J.J., Menon, L.R., McIlroy, D. and Brasier, M.D. 2014. *Haootia quadriformis* n. gen., n. sp., interpreted as a muscular cnidarian impression from the Late Ediacaran period (approx. 560 Ma). *Proceedings of the Royal Society B*, **281**, 20141202, https://doi.org/10.1098/rspb.2014.1202

Liu, A.G., Kenchington, C.G. and Mitchell, E.G. 2015. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380, https://doi.org/10.1016/j.gr.2014.11.002

Matthews, J.J., Liu, A.G., Yang, C., McIlroy, D., Levell, B. and Condon, D.J. 2020. A chronostratigraphic framework for the rise of the Ediacaran macrobiota: New constraints from Mistaken Point Ecological Reserve, Newfoundland. *GSA Bulletin*, **133**, 612–624, https://doi.org/10.1130/B35646.1

McIlroy, D. and Horák, J.M. 2006. Neoproterozoic: The late Precambrian terranes that formed Eastern Avalonia. *In*: Brenchley, P.J. and Rawson, P.F. (eds) *The Geology of England and Wales*, *Second Edition*. Geological Society, London, 9–23, https://doi.org/10.1144/GOEWP

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Pérez-Pinedo, D., Pasinetti, G., McKean, C., Taylor, R.S. and Hiscott, R.N. 2022a. Rheotropic epifaunal growth, not felling by density currents is responsible for many Ediacaran fossil orientations at Mistaken Point. *Frontiers in Earth Science*, **10**, 849194, https://doi.org/10.3389/feart.2022.849194

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022b. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

Menon, L.R., McIlroy, D. and Brasier, M.D. 2013. Evidence for Cnidaria-like behavior in ca. 560 Ma Ediacaran *Aspidella*. *Geology*, **41**, 895–898, https://doi.org/10.1130/G34424.1

Mitchell, E.G. and Kenchington, C.G. 2018. The utility of height for the Ediacaran organisms of Mistaken Point. *Nature Ecology & Evolution*, **2**, 1218–1222, https://doi.org/10.1038/s41559-018-0591-6

Mitchell, E.G., Kenchington, C.G., Liu, A.G., Matthews, J.J. and Butterfield, N.J. 2015. Reconstructing the reproductive mode of an Ediacaran macro-organism. *Nature*, **524**, 343–346, https://doi.org/10.1038/nature14646

Mitchell, E.G., Harris, S., Kenchington, C.G., Vixseboxse, P., Roberts, L., Clark, C., Dennis, A., Liu, A.G. and Wilby, P.R. 2019. The importance of neutral over niche processes in structuring Ediacaran early animal communities. *Ecology Letters*, **22**, 2028–2038, https://doi.org/10.1111/ele.13383

Mitchell, E.G., Bobkov, N., Bykova, N., Dhungana, A., Kolesnikov, A.V., Hogarth, I.R.P., Liu, A.G., Mustill, T.M.R., Sozonov, N., Rogov, V.I., Xiao, S. and Grazhdankin, D.V. 2020. The influence of environmental setting on the community ecology of Ediacaran organisms. *Interface Focus*, **10**, 20190109, http://doi.org/10.1098/rsfs.2019.0109

Murphy, J.B. and Nance, R.D. 1989. Model for the evolution of the Avalonian-Cadomian belt. *Geology*, **17**, 735–738, https://doi.org/10.1130/0091-7613(1989)017%3C0735:MFTEOT%3E2.3.CO;2

Murphy, J.B. and Nance, R.D. 2002. Sm–Nd isotopic systematics as tectonic tracers: An example from West Avalonia in the Canadian Appalachians. *Earth-Science Reviews*, **59**, 77–100, https://doi.org/10.1016/S0012-8252(02)00070-3

Murphy, J.B., Pisarevsky, S.A., Nance, R.D. and Keppie, J.D. 2004. Neoproterozoic–Early Paleozoic evolution of peri-Gondwanan terranes: Implications for Laurentia-Gondwana connections. *International Journal of Earth Sciences*, **93**, 659–682, https://doi.org/10.1007/s00531-004-0412-9

Narbonne, G.M. 1998. The Ediacara biota: A terminal Neoproterozoic experiment in the evolution of life. *GSA Today*, **8**, 1–6.

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M. 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442, https://doi.org/10.1146/annurev.earth.33.092203.122519

Narbonne, G.M. and Gehling, J.G. 2003. Life after snowball: The oldest complex Ediacaran fossils. *Geobiology*, **31**, 27–30, https://doi.org/10.1130/0091-7613(2003)031%3C0027:LASTOC%3E2.0.CO;2

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 503–523, https://doi.org/10.1666/08-072R1.1

Nedin, C. and Jenkins, R.J.F. 1998. First occurrence of the Ediacaran fossil *Charnia* from the southern hemisphere. *Alcheringa: An Australasian Journal of Palaeontology*, **22**, 315–316, https://doi.org/10.1080/03115519808619329

Noble, S.R., Condon, D.J., Carney., J.N., Wilby, P.R., Pharaoh, T.C. and Ford, T.D. 2015. U-Pb geochronology and global context of the Charnian Supergroup, UK: Constraints on the age of key Ediacaran fossil assemblages. *Geological Society of America Bulletin*, **127**, 250–265, https://doi.org/10.1130/B31013.1

O'Brien, S.J. and King, A.F. 2004. Ediacaran fossils from the Bonavista Peninsula (Avalon Zone), Newfoundland: Preliminary descriptions and implications for regional correlation. *Newfoundland Department of Mines and Energy—Geological Survey,* **04-1**, 203–212.

Pasinetti, G. and McIlroy, D. 2023. Paleobiology and taphonomy of the rangeomorph *Culmofrons plumosa*. *Palaeontology*, **66**, e12671, https://doi.org/10.1111/pala.12671

Pérez-Pinedo, D., McKean, C., Taylor, R.S. and McIlroy, D. 2022. *Charniodiscus* and *Arborea* are separate genera within the Arboreomorpha: Using the holotype of *C. concentricus* to resolve a taxonomic tangle. *Frontiers in Earth Science*, **9**, 785929, https://doi.org/10.3389/feart.2021.785929

Pérez-Pinedo, D., Neville, J.M., Pasinetti, G., McKean, C., Taylor, R. and McIlroy, D. 2023. Frond orientations with independent current indicators demonstrate the reclining rheotropic mode of life of several Ediacaran rangeomorph taxa. *Paleobiology*, **49**, 471–492, https://doi.org/10.1017/pab.2023.2

Peterson, K.J., Waggoner, B. and Hagadorn, J.W. 2003. A fungal analog for Newfoundland Ediacaran fossils? *Integrative and Comparative Biology*, **43**, 127–136, https://doi.org/10.1093/icb/43.1.127

Pflüg, H.D. 1972. Systematik der jung-präkambrischen Petalonamae. *Paläontologische Zeitschrift*, **46**, 56–67, https://doi.org/10.1007/BF02989552

Pisarevsky, S.A., Murphy, J.B., Cawood, P.A. and Collins, A.S. 2008. Late Neoproterozoic and Early Cambrian palaeogeography: Models and problems. *In*: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B. and Se Wit, M.J. (eds) *West Gondwana: Pre-Cenozoic correlations across the South Atlantic region*. Geological Society, London, Special Publications, **294**, 9–31, https://doi.org/10.1144/SP294.2

Pisarevsky, S.A., McCausland, P.J.A., Hodych, J.P., O'Brien, S.J., Tait, J.A. and Murphy, J.B. 2012. Paleomagnetic study of the late Neoproterozoic Bull Arm and Crown Hill formations (Musgravetown Group) of eastern Newfoundland: Implications for Avalonia and West Gondwana paleogeography. *Canadian Journal of Earth Sciences*, **49**, 308–327, https://doi.org/10.1139/e11-045

Pollock, J.C., Hibbard, J.P. and Sylvester, P.J. 2009. Early Ordovician rifting of Avalonia and birth of the Rheic Ocean: U–Pb detrital zircon constraints from Newfoundland. *Journal of the Geological Society*, **166**, 501–515, https://doi.org/10.1144/0016-76492008-088

Prave, A.R., Condon, D.J., Hoffmann, K.H., Tapster, S. and Fallick, A.E. 2016. Duration and nature of the end-Cryogenian (Marinoan) glaciation. *Geology*, **44**, 631–634, https://doi.org/10.1130/G38089.1

Pu, J.P., Bowring, S.A., Ramezani, J., Myrow, P., Raub, T.D., Landing, E., Mills, A., Hodgin, E. and Macdonald, F.A. 2016. Dodging snowballs: Geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. *Geology*, **44**, 955–958, https://doi.org/10.1130/G38284.1

Sahoo, S.K., Planavsky, N.J., Kendall, B., Wang, X., Shi, X., Scott, C., Anbar, A.D., Lyons, T.W. and Jiang, G. 2012. Ocean oxygenation in the wake of the Marinoan glaciation. *Nature*, **489**, 546–549, https://doi.org/10.1038/nature11445

Seilacher, A. 1989. Vendozoa: Organismic construction in the Proterozoic biosphere. *Lethaia*, **22**, 229–239, https://doi.org/10.1111/j.1502-3931.1989.tb01332.x

Seilacher, A. 1992. Vendobionta and Psammocorallia: Lost constructions of Precambrian evolution. *Journal of the Geological Society*, **149**, 607–613, https://doi.org/10.1144/gsjgs.149.4.0607

Sprigg, R.C. 1947. Early Cambrian (?) jellyfishes from the Flinders Ranges, South Australia. *Transactions of the Royal Society of South Australia*, **71**, 212–224.

Tarhan, L.G., Hood, A.v.S., Droser, M.L., Gehling, J.G. and Briggs, D.E.G. 2016. Exceptional preservation of soft-bodied Ediacara Biota promoted by silica-rich oceans. *Geology*, **44**, 951–954, https://doi.org/10.1130/G38542.1

Taylor, R.S., Matthews, J.J., Nicholls, R. and McIlroy, D. 2021. A re-assessment of the taxonomy, palaeobiology and taphonomy of the rangeomorph organism *Hapsidophyllas flexibilis* from the Ediacaran of Newfoundland, Canada. *Paläontologische Zeitschrift*, **95**, 187–207, https://doi.org/10.1007/s12542-020-00537-4

Taylor, R.S., Nicholls, R., Neville, J.M. and McIlroy, D. 2023. Morphological variation in the rangeomorph organism *Fractofusus misrai* from the Ediacaran of Newfoundland, Canada. *Geological Magazine*, **160**, 146–166, https://doi.org/10.1017/S0016756822000723

Tohver, E., D'Agrella-Filho, M.S. and Trindade, R.I.F. 2006. Paleomagnetic record of Africa and South America for the 1200–500Ma interval, and evaluation of Rodinia and Gondwana assemblies. *Precambrian Research*, **147**, 193–222, https://doi.org/10.1016/j.precamres.2006.01.015

van Kranendonk, M.J., Gehling, J.G. and Shields, G.A. 2008. Precambrian. *In*: Ogg, J.G., Ogg, G. and Gradstein, F.M. (eds) *The Concise Geologic Time Scale*. Cambridge University Press, 23–36.

van Stall, C.R., Dewey, J.F., Niocaill, C.M. and McKerrow, W.S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *In*: Blundell, D.J. and Scott, A.C. (eds) *Lyell: The Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 197–242, https://doi.org/10.1144/GSL.SP.1998.143.01.17

Waggoner, B. 2003. The Ediacaran biotas in space and time. *Integrative and Comparative Biology*, **43**, 104–113, https://doi.org/10.1093/icb/43.1.104

Walker, J.D. and Geissman, J.W. (compilers). 2022. Geologic Time Scale v.6.0. *Geological Society of America*, https://doi.org/10.1130/2022.CTS006C

Wang, X., Pang, K., Chen, Z., Wan, B., Xiao, S., Zhou, C. and Yuan, X. 2020. The Ediacaran frondose fossil *Arborea* from the Shibantan limestone of South China. *Journal of Paleontology*, **94**, 1034–1050, https://doi.org/10.1017/jpa.2020.43

Wilby, P.R., Kenchington, C.G. and Wilby, R.L. 2015. Role of low intensity environmental disturbance in structuring the earliest (Ediacaran) microbenthic tiered communities. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **434**, 14–27, https://doi.org/10.1016/j.palaeo.2015.03.033

Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, J.G. and Clapham, M.E. 2003. Paleoenvironmental analysis of the late Neoproterozoic Mistaken Point and

Trepassey formations, southeastern Newfoundland. *Canadian Journal of Earth Sciences*, **40**, 1375–1391, https://doi.org/10.1139/e03-048

Wood, R., Bowyer, F.T., Alexander, R., Yilales, M., Uahengo, C.-I., Kaputuaza, K., Ndeunyema, J. and Curtis, A. 2023. New Ediacaran biota from the oldest Nama Group, Namibia (Tsaus Mountains), and re-definition of the Nama Assemblage. *Geological Magazine*, **160**, 1673–1686, https://doi.org/10.1017/S0016756823000638

Xiao, S. and Laflamme, M. 2009. On the eve of animal radiation: Phylogeny, ecology and evolution of the Ediacara biota. *Trends in Ecology & Evolution*, **24**, 31–40, https://doi.org/10.1016/j.tree.2008.07.015

CHAPTER 2

New taphonomic and sedimentological insights into the preservation of high relief Ediacaran fossils at Upper Island Cove, Newfoundland

CHRISTOPHER MCKEAN[1*], ROD S. TAYLOR[1,2] AND DUNCAN MCILROY[1]

[1]*Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5, Canada*

[2]*Johnson Geo Centre, Memorial University of Newfoundland, St. John's, NL, A1A 1B2, Canada*

[*]*Corresponding author (cmckean@mun.ca)*

PREFACE

This chapter has been *published* with the international journal *Lethaia* (doi: 10.18261/let.56.4.2) and has been formatted for thesis submission herein. The scientific content of this chapter is identical to the research publication, with the copyright and publishing rights for this chapter being retained by the authors without restriction (see pages iv–vi). This chapter was devised by Christopher McKean, Rod S. Taylor and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from

Rod S. Taylor and Duncan McIlroy. Collection of taphonomic and sedimentological data was conducted by Christopher McKean and Duncan McIlroy, with data analysis conducted by Christopher McKean, Rod S. Taylor and Duncan McIlroy. The taphonomic model presented within this chapter was developed by Christopher McKean and Duncan McIlroy, and further refined by Christopher McKean. All figures were constructed by Christopher McKean. Additional support from those not listed as authors can be found in the acknowledgements at the end of this chapter.

ABSTRACT

Southeastern Newfoundland, Canada, is home to the oldest Ediacaran fossils in the Avalonian Assemblage mostly being preserved beneath tuffites in association with microbial matgrounds. A unique fossiliferous surface at Upper Island Cove, known as the Allison Surface, exhibits three-dimensional preservation of Ediacaran fronds without an associated tuffite or microbial matground. Previous models have invoked entrainment of fronds within turbidity currents, or by their felling into erosive scours. Our work demonstrates that the fossils were preserved within beds before being partially exhumed and cast by a subsequent sandy turbidite.

Many of the structures previously identified as rangeomorph stems are longitudinal erosional features within obstacle scours. Additional observations of stemmed/erect organisms coinciding with reclined taxa suggest crosscutting/palimpsesting of frondose taxa with deeply emplaced holdfasts. Many of the fossil organisms are found within the top of a T_d unit, with early pyritization probably aiding in their three-dimensional preservation. Most fronds are incomplete and oblique to the axis of the surrounding scours, indicating they were partly exhumed after burial. The scours likely formed in the lee of erect stemmed rangeomorph and arboreomorph taxa, which are commonly preserved as holdfasts on the surface, and occasionally crosscut buried fronds. The crosscutting of frondose taxa by holdfasts and the presence of pyritic tubes in the overlying sedimentary units suggests the preservation of three separate communities: 1) the initial T_d entombed mainly reclined organisms; 2) a pre-turbidity current community of erect taxa with bulbous holdfasts that were the loci of obstacle scours; and 3) a later community of erect organisms preserved as holdfasts/stems.

KEYWORDS

Lagerstätte, Avalonian Assemblage, Precambrian, Ediacaran biota, rangeomorph, arboreomorph, taphonomy, palaeobiology

2.1 INTRODUCTION

The Ediacaran rocks of the Avalon Assemblage in Newfoundland (Waggoner 2003) host some of the oldest complex multicellular organisms yet discovered (Narbonne 2005; Liu *et al*. 2015). The Ediacaran biota is a polyphyletic group of macro-organisms that characterize the last approx. 30 million years of the Neoproterozoic (Matthews *et al*. 2020; Walker and Geissman 2022). The Avalon Assemblage is dominated by the Rangeomorpha (Narbonne 2004; Liu *et al*. 2015), a clade identified by a uni-, bi- or multi-polar frondose body plan and fractal-like self-similar branching architecture (Narbonne *et al*. 2009; Brasier *et al*. 2012; Kenchington and Wilby 2017). Rangeomorph preservation in Newfoundland is commonly seen as positive (stems) and negative (fronds) epirelief preservation beneath tuffites (Narbonne 2005; Matthews *et al*. 2020). The most well-known Ediacaran localities in Newfoundland are found at the Mistaken Point Ecological Reserve (Anderson and Misra 1968; Liu *et al*. 2015) and on the Bonavista Peninsula (Hofmann *et al*. 2008; Liu *et al*. 2016), with fossils also being known from the “Spaniard’s Bay” assemblage (actually located in Upper Island Cove; Fig. 2.1 and referred to as such herein) and several other localities on the east coast of the Avalon Peninsula. The fossils of Upper Island Cove are unique in that they are preserved in unusually high relief and in very fine detail (Narbonne 2004; Narbonne *et al*. 2009; Brasier *et al*. 2013; Fig. 2.2).

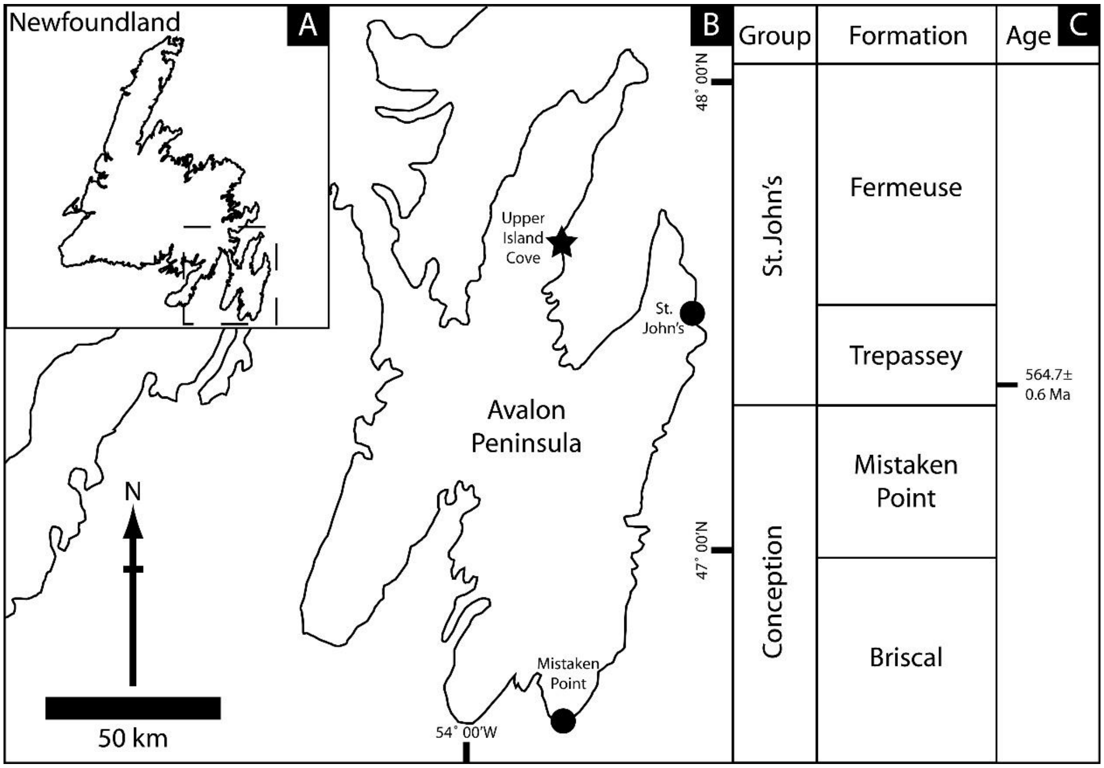


Fig. 2.1 – Map and stratigraphic column denoting the location of the Upper Island Cove assemblage. A, map of Newfoundland, Canada. B, close up of the Avalon Peninsula, Newfoundland, with the Upper Island Cove assemblage marked with a star in relation to Mistaken Point and St. John's. C, stratigraphic column indicating the formation and age of the Upper Island Cove assemblage (following Matthews *et al*. 2020).

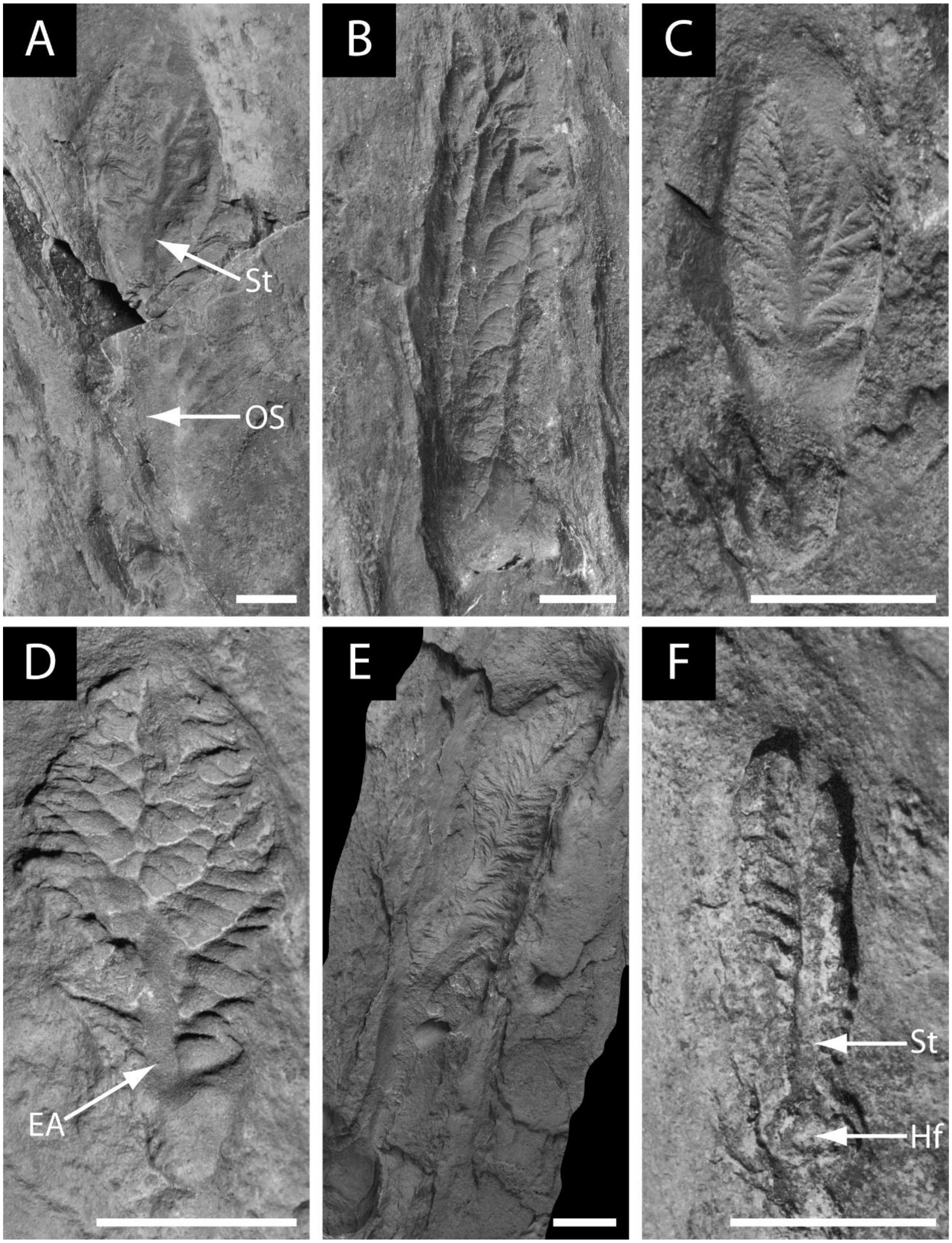


Fig. 2.2 – Previously identified Ediacaran taxa of the Upper Island Cove assemblage. A, holotype of *Avalofractus abaculus*, showing stem (St) independent of obstruction scour (OS) (NFM F-756). B, "I-shaped" *Bradgatia* sp. (NFM F-755). C, *Beothukis* sp. (NFM F-758). D, *Charnia* sp., note the eroded

axis (EA) that looks like a stem (cast SB-2020-019(b)iii-a). E, *Trepassia* sp. (cast SB-2021-055iv). F, *Charniodiscus* sp., showing stem (St) directly attached to the holdfast (Hf) (uncollected specimen). (scale bars – 1 cm)

Since the first detailed description of the Upper Island Cove assemblage two taphonomic models have been proposed:

1) The Trepassey Formation at Upper Island Cove is mainly composed of Bouma $T_{c\text{-}e}$ units interbedded with pelagic mudstones (Ichaso *et al*. 2007; Narbonne *et al*. 2009; Brasier *et al*. 2013, fig. 2b). The original model posited that the fossils were transported allochthonous organisms (or parts of organisms) entrained in a turbidity current and deposited in a Bouma T_d unit before being preserved in concretions (Narbonne 2004; Narbonne *et al*. 2009).
2) Sedimentological study of the fossils in the Upper Island Cove assemblage (Brasier *et al*. 2013; McIlroy *et al*. 2022b) noted the absence of concretions associated with the fossils and found instead that the fossils were preserved in flutes and obstruction scours that had eroded into the Bouma T_d unit. To explain this association, the rangeomorph fronds were interpreted as belonging to a community of erect fronds that post-dated turbidite deposition. Organisms from that post-turbidite community were considered to have lived anchored into the T_d deposit, before being felled into obstruction scours that formed in the lee of the frond in response to a subsequent erosional current. The high-resolution preservation of deeply impressed fronds was accounted for by the presence of soft mud in the scour which permeated between elements of the organisms.

> This moulding of the fronds was considered to have been followed by decay and casting by the overlying pyritic sand.

It has historically been accepted that most rangeomorph fronds were held erect in the water column, however an increasing amount of evidence now suggests that several common taxa, including those at Upper Island Cove, were benthic or epibenthic recliners (Hawco *et al*. 2020; McIlroy *et al*. 2021, 2022b; Taylor *et al*. 2021, 2023). Recent work has additionally demonstrated that structures interpreted as stems in the Upper Island Cove biota are part of the associated current scour (McIlroy *et al*. 2022b, fig. 2b). Since the current model (Brasier *et al*. 2013) invokes stemmed organisms falling into scour pits it is considered worthwhile to reconsider the biostratinomy/taphonomy of this deposit.

2.1.1 Geological Setting

The Upper Island Cove Ediacaran fossiliferous site, known as the Allison Surface, is situated in Conception Bay on the Avalon Peninsula of Newfoundland, over 200 km from the Ediacaran macrofossil-bearing sites at Mistaken Point and Ferryland (Anderson and Misra 1968; Narbonne 2005; Gehling and Narbonne 2007; Hawco *et al*. 2019) and 255 km southeast of the Catalina Dome on the Bonavista Peninsula (Hofmann *et al*. 2008). The Ediacaran successions of Newfoundland, along with contemporaneous deposits in the UK, formed part of the Avalonian volcanic arc (Murphy *et al*. 2004; McIlroy and Horák 2006; Ichaso *et al*. 2007), which was situated off the west coast of Gondwana (Pisarevsky *et al*. 2012). Avalonia was both tectonically and volcanically active during the late Ediacaran, having switched from arc magmatism to extensional magmatism (McIlroy and Horák

2006). This led to a predominantly volcaniclastic sedimentary provenance for the island arc basins, a key factor in much of the exceptional preservation seen in the Avalonian Assemblage (Narbonne 2005; Liu *et al*. 2011, 2013).

The Allison Surface lies within the Trepassey Formation (Narbonne 2004; Ichaso *et al*. 2007: Narbonne *et al*. 2009; Fig. 2.1C), with the same lithostratigraphic unit being dated to 564.71 ±0.88 Ma in the Mistaken Point Ecological Reserve (Matthews *et al*. 2020). The orientation of both the fronds and sedimentological current indicators for the surface are nearly perpendicular to the palaeocurrents recorded from fronds at other well-known rangeomorph-rich surfaces, such as the lower Mistaken Point Formation, from which they may have been separated by the hypothetical Harbour Main Landmass (Ichaso *et al*. 2007), and the Catalina Dome (Pérez-Pinedo *et al*. 2023). The Upper Island Cove assemblage lacks clear microbial matgrounds, which might indicate comparatively low shear strength of the sediment-water interface allowing for a degree of erosion around stems that is not seen at other Ediacaran fossil localities in the region (Figs 2.2E, 2.3A-F).

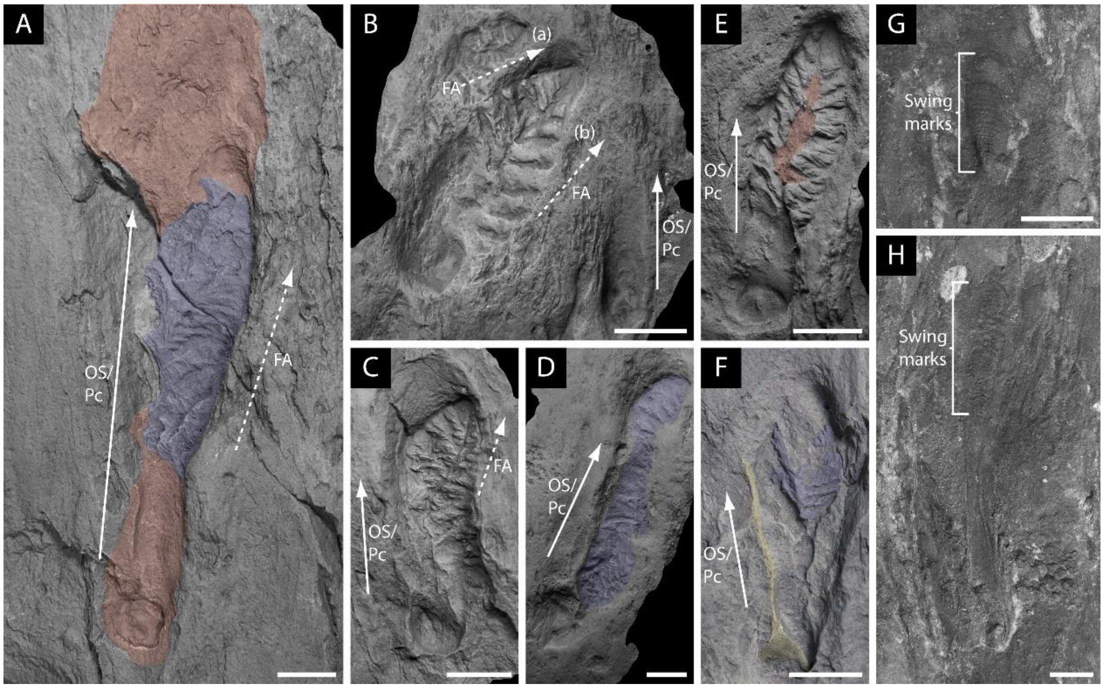


Fig. 2.3 – Frond, scour and palaeocurrent relationship, indicating frond axis (FA; dotted arrow) in relation to the palaeocurrent (Pc) as indicated by obstruction scours (OS; solid arrow). A, position of *Trepassia* sp. (blue) within the centre of an obstruction scour (red) (cast SB-2020-007). B, partial frond (a) and arboreomorph (b) showing varying orientation to each other as well as the palaeocurrent (cast SB-2021-041ii). C, example of a partially exposed beothukid crosscut by obstruction scour (cast SB-2020-020(b)iii). D, "S-shaped" arboreomorph (blue) showing uneven exposure of frond within obstruction scour (cast SB-2021-039i). E, beothukid showing damage by scouring and removal of organic material (red) (cast SB-2021-054iii). F, *Avalofractus abaculus* with preserved stem (blue), which is separate from the sedimentary ridge (yellow) within the scour (cast SB-2021-053ix). G, H, examples of swing marks preserved near the tip of obstruction scours. (scale bars – 1 cm)

The Trepassey Formation around the coast of Conception Bay has a total thickness of ~300 m and is composed of tuffites, fine-grained sandstones (T_c), siltstones and mudstones ($T_{d\text{-}e}$), and pelagites (Ichaso *et al*. 2007; Narbonne *et al*. 2009; Brasier *et al*. 2013, fig. 2b). The fossils in the assemblage are preserved in association with flute marks cut into a laminated siltstone (T_d), which are overlain by a fine-grained sandstone (T_c) and laminated mudstone (T_d) (Brasier *et al.* 2013). There is no ash layer on top of the fossiliferous surface, suggesting a different mode of preservation to the typical Conception-Type preservation observed in the region (Narbonne 2005).

2.1.2 The Upper Island Cove Lagerstätte

The Upper Island Cove fossil assemblage is here reported to be composed of ~250 frondose—mainly rangeomorph—organisms. There are additionally numerous holdfasts of unidentified (possibly stemmed/frondose) organisms. The strong preservational relief seen across the Allison Surface presents the opportunity to study the fine details of the rangeomorph fossils to help us better understand their biology and phylogenetic affinity (Narbonne *et al.* 2009).

Ediacaran taxa in the Avalonian Assemblage that are known to have had a stem and most likely lived erect in the water column include *Charniodiscus* spp. (Laflamme *et al*. 2004; Brasier and Antcliffe 2009; Pérez-Pinedo *et al*. 2022); *Arborea spinosa* (Pérez-Pinedo *et al.* 2022) and *Culmofrons plumosa* (Laflamme *et al*. 2012; Liu *et al*. 2016; Hawco *et* al. 2020; McIlroy *et al*. 2022b). Other taxa are likely to have been stemless recliners such as *Fractofusus* (Gehling and Narbonne 2007; Taylor *et al*. 2023; Pérez-Pinedo *et al.* 2023) and *Beothukis* (Brasier and Antcliffe 2009; McIlroy *et al*. 2022b), or are considered to have lived with a horizontal stem and erect frond (e.g. *Charniodiscus procerus*; Pérez Pinedo *et al.* (2022)). On the Allison Surface, the endemic species *Avalofractus abaculus* (Narbonne *et al*. 2009) has a clear stem preserved at the base of the frond (Fig. 2.2A); but both *Beothukis* spp. (Narbonne *et al*. 2009; Hawco et al. 2020; McIlroy *et al*. 2022b Fig. 2.2C) and *Charnia* (Narbonne 2004; Brasier *et al*. 2013; Fig. 2.2D) lack stems.

Most macrofossils in the Avalonian Assemblage are greater than 10 cm in length (e.g. Liu *et al*. 2015, fig. 4f), whereas specimens on the Allison Surface are generally between 2 and 10 cm long (Brasier *et al*. 2013). Their small size has led to suggestions that the Upper Island Cove assemblage is composed of fragmentary (isolated frondlets; Narbonne 2004) or juvenile rangeomorphs (Narbonne *et al*. 2009). The Ediacaran fossils at Upper Island Cove – and older assemblages at Pigeon Cove (Liu *et al*. 2012), the Brasier Surface (Liu 2016) and the MUN surface (Liu *et al.* 2016) – have the potential to inform debate surrounding rangeomorph development and phylogeny (e.g. Dunn *et al*. 2018). While the fossils are small, the determination of whether they are juveniles (Liu *et al*. 2012; Dunn *et al*. 2018) or diminutive adult ecophenotypes (cf. McArthur and Wilson 1967) is equivocal.

Of the abundant holdfasts on the Allison Surface, many are not associated with a frond or even a stem. Though unrelated holdfasts are generally present up-current of the obstruction scours that hold frondose fossils (Brasier *et al*. 2013). Frondless scours commonly have a sediment ridge running along the central axis and may have a holdfast at the up-current end (Brasier *et al.* 2013, fig. 7b; Fig. 2.3F).

2.2 TAPHONOMY AND SEDIMENTOLOGY

Here we present new sedimentological and taphonomic features that build upon the taphonomic model of Brasier *et al*. (2013), which better explain the high fidelity, high relief preservation of many of the fossils on the Allison Surface at Upper Island Cove. Analysis of 250 fossils on the surface and aspects of its sedimentology were conducted in the field, and augmented by the study of 71 casts housed at Memorial University of Newfoundland. Additional observations were made from accessioned material housed at the provincial museum of Newfoundland and Labrador, The Rooms.

2.2.1 Stem-like Obstruction Scours

Some beothukid specimens on the Allison Surface at Upper Island Cove that were previously inferred to have short sheath-like stems at the base of the frond (Narbonne *et al*. 2009) have been reinterpreted as being stemless (Hawco *et al*. 2020; McIlroy *et al*. 2022b) through recognition that the inferred stems are actually sediment ridges within obstruction scours (e.g. Fig. 2.3F). Several specimens previously interpreted as containing remnants of the stem are closely associated with scours in this way (Fig. 2.3A, C, D, F). The obstruction scours are larger than the preserved portions of the specimens within, with some fronds being crosscut by the scour (Fig. 2.3C, E, F).

Taxa with preserved stems on the Allison Surface include *Avalofractus abaculus* and *Charniodiscus* sp. (Narbonne *et al*. 2009), both of which likely had a predominantly erect to recumbent lifestyle (Pérez Pinedo *et al.* 2022). Some obstruction scours contain current generated “swing marks” (Fig. 2.3G, H), likely caused by movement of a tethered erect-living organism that was the locus of the obstruction scour. The presence of such swing marks is considered good evidence for the presence of erect/tethered taxa (McIlroy *et al.* 2021). The stemless taxa in the assemblage should be considered recliners (following McIlroy *et al*. 2021, 2022b).

2.2.2 Holdfasts and Frond Dissociation

There are over 400 holdfasts with associated obstruction scours (Table A.1) across the Allison Surface, with the majority (~75%) not preserving any evidence of a frond. Previous work (Brasier *et al*. 2013) considered that the preserved fronds all belonged to the same organism as the holdfast at the up-current end of the scour. We note herein that there is commonly an offset between the axis of the scour and the axis of the contained frond (Fig. 2.3A-C). This may suggest that these associations are accidental, and that the preserved holdfasts and their scours are from a later community than the fronds. The distance between frond and holdfast has been found to be highly variable (Liu *et al.* 2016; Dececchi *et al*. 2018). More recently it has been considered that this is because they relate to separate non-contemporaneous organisms, with the distance being a reflection of the length of the obstacle scour between a holdfast and unrelated frond, not the length of a connecting stem (Hawco *et al*. 2020; McIlroy *et al.* 2022b). Additionally, the variation in orientation of frond axis versus scour axis (Fig. 2.4; Table A.1) is statistically significant (Mann-Whitney-Wilcoxon test, $\alpha = 0.05$, p-value $<< 10^{-15}$) demonstrating that rangeomorph fronds were aligned relative to a different palaeocurrent than the erosive current that generated the obstruction scours. This may suggest the presence of two or more communities separated by time, an inference that is further supported by the crosscutting of some fronds by holdfasts that must, therefore, postdate them (Fig. 2.5), and also the erosion of some rangeomorphs (e.g. Fig. 2.2D) suggesting that they were already preserved in a firm, partly lithified sediment before scouring occurred.

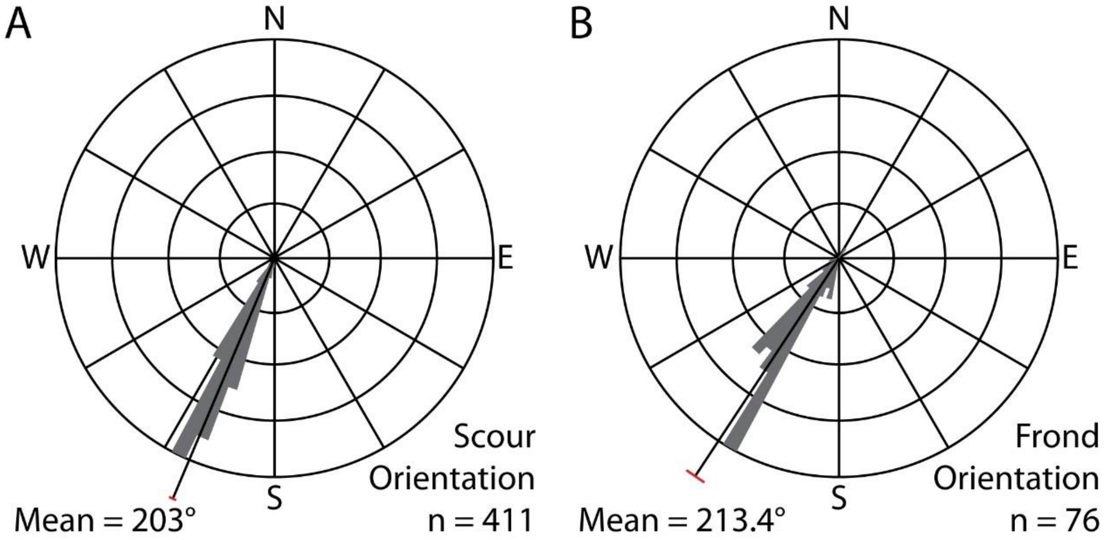


Fig. 2.4 – Rose plots showing the variation in orientation of both obstruction scours and fronds. A, orientation of obstruction scours. B, orientation of 76 well-preserved fronds.

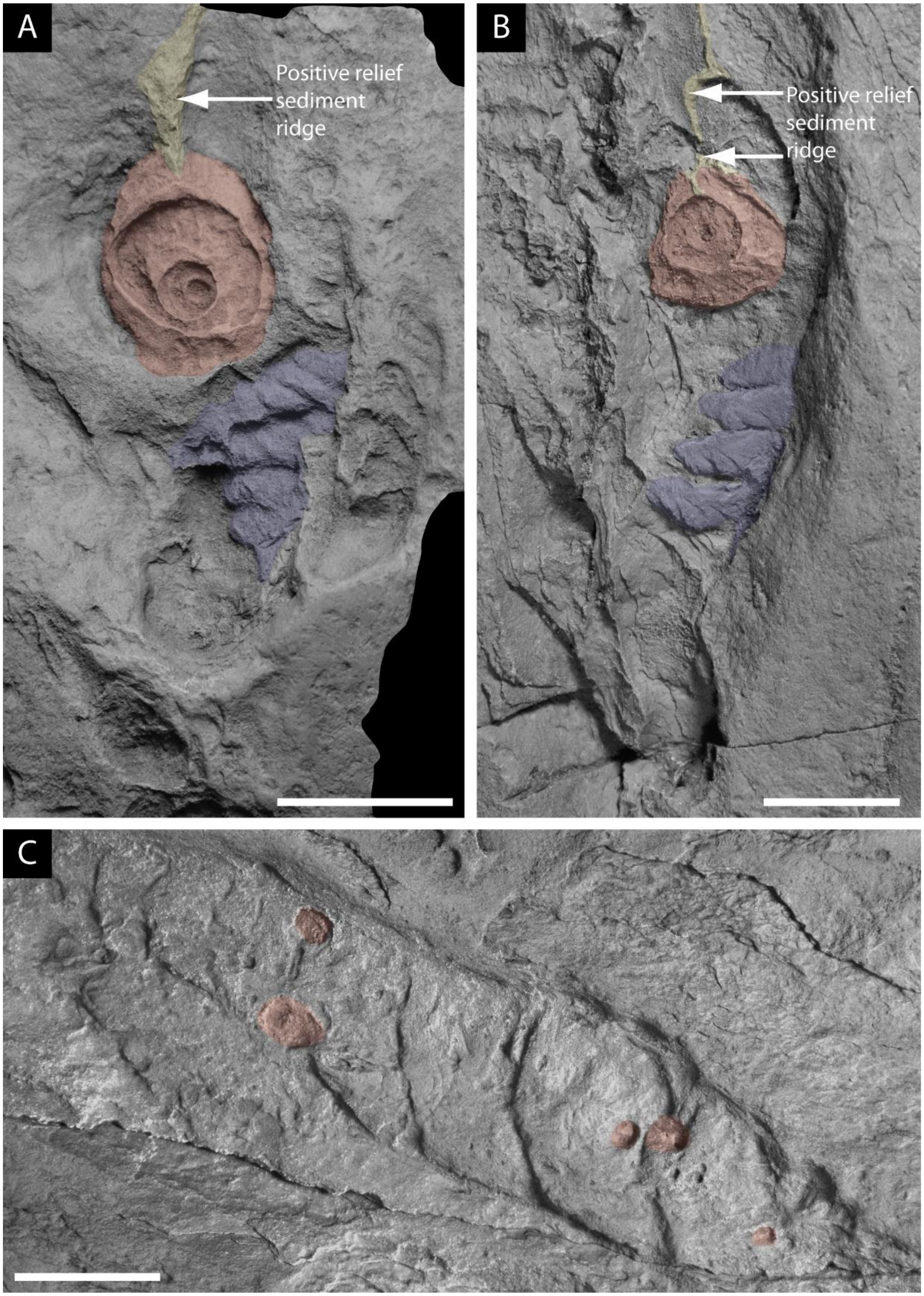

A
Positive relief sediment ridge
B
Positive relief sediment ridge
C

Fig. 2.5 – Fronds crosscut by holdfasts (red) belonging to organisms that lived in a later community of stemmed taxa. A–B, partial beothukids (blue) crosscut by holdfasts and their associated erosional scours (yellow) in close proximity to a frond, note that the holdfasts themselves are in scours that formed contemporaneously (casts SB-2021-055xii (A), SB-2020-001a (B)). C, close up of *Charniodiscus* sp. crosscut by smaller holdfasts with pyritized rims and no evidence of obstruction scours or erosional scours (cast SB-2021-052vii). (scale bars – 1 cm)

While many of the preserved fronds are stemless, some specimens have a stem that is independent of the obstruction scour (Figs 2.2A, F, 2.3F). Many fossils with preserved stems are not directly connected to the holdfast that is related to the point of origin of the obstacle scour (Fig. 2.3F). This suggests that they were buried in the T_d silt prior to being exhumed by the obstruction scours that subsequently formed, by erosion, in the lee of the stems of a later population of erect taxa. There are rare examples of stemmed organisms that are attached to the holdfasts within the obstruction scours (Fig. 2.2F), these are likely fronds preserved in their own obstacle scours as previously suggested by Brasier *et al.* (2013).

2.2.3 Partially Exposed Specimens

Many of the Allison Surface fronds are only partially exhumed; being overlain by the T_d bed that is cut by the obstruction scours, demonstrating that they pre-date the erosional event (Fig. 2.6). This observation explains why many of the fossils are partially eroded (Fig. 2.3E). For the impression of a frond to be scoured by a current at least part of the frond must have been buried in the sediment, with either the upper or lower surface being exposed to the eddying currents generated around an obstruction. Rangeomorph fronds are only found within the confines of scours; they are not observed outside of these erosional structures, further suggesting they were exhumed after their initial burial in the T_d siltstones.

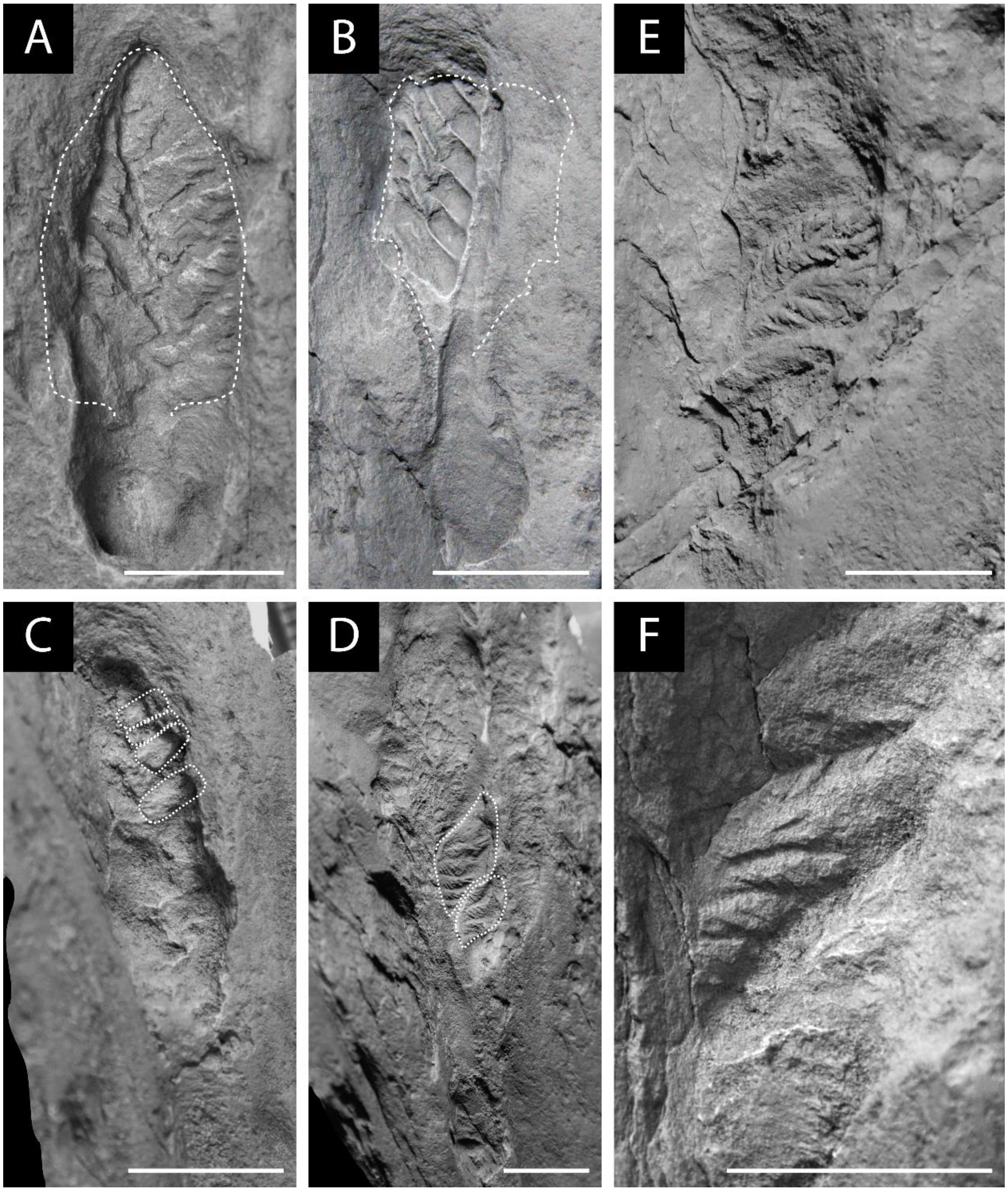


Fig. 2.6 – Partially exhumed specimens within scours, with conservatively inferred continuation of branches beneath the sediment represented by dotted lines. A, beothukid predominantly exposed on the right-hand side of the scour, with left-hand side of frond being partially buried (cast SB-2020-019(b)iii-b). B, left-hand side of *Arborea* sp. exposed within scour, with right-hand side completely buried beneath sediment (cast SB-2021-040ii-a). C, partial preservation of *Charnia* sp. branching which can be seen to continue beneath the sediment (cast SB-2021-050vi). D, well preserved *Trepassia* sp. branches continuing beneath the sediment (SB-2020-020(b)ii). E, partially exhumed *Avalofractus abaculus* branches within scour (cast SB-2021-051ii). F, partially exhumed frond with *Beothukis*/*Culmofrons*-like branching (cast SB-2020-024ii-a). (scale bars – 1 cm)

The presence of organisms in the T_d silt could be due to post-mortem burial of erect taxa or the preserved taxa having a quasi-infaunal mode of life living on—or within—the T_d unit after its deposition. Burial of transported organisms within the T_d siltstone, and the formation of concretions, was previously suggested by Narbonne (2004). However, there is no evidence of the fronds having been entrained in the turbidity current as suggested in the original model (Narbonne 2004) as pointed out by Brasier et al. (2013). Although concretions are known to aid in exquisite soft tissue preservation elsewhere in the fossil record (e.g. Clements *et al*. 2019) there is no sedimentological evidence for nodules having been associated with the Upper Island Cove assemblage.

When comparing the preservation of reclining and purportedly erect taxa there is no clear variation in the depth of scour associated with the two modes of life or that of frondless scours (the depth of scours with fronds is ~1-3 mm, while the depth of frondless scours is ~1 mm). We suggest that the fronds of Upper Island Cove were exhumed by chance, and in most cases independent of the stems that are associated with the obstacle scours. This explains the presence of partly or completely exposed organisms and explains why most obstruction scours on the Allison Surface do not contain fossils.

2.2.4 Current Realignment or Rheotactic Growth

A single *Charnia* specimen from the Allison Surface is preserved with its primary branches reversed relative to the palaeocurrent. Brasier *et al*. (2013, fig. 10b) suggested the branches had been sheared and reversed after felling by "backflow turbulence" within the scour. The up-current portion of the specimen is eroded—likely during scour formation—with the remainder of the specimen being well preserved, but only partly exposed in the scour (Fig. 2.7A). There is no evidence for the typical *Charnia* stem (cf. Ford 1958; Dunn *et al*. 2018), which casts some doubt on its taxonomic assignment. The lack of a stem and partial exhumation of the specimen suggest it may have been reclined upon, or slightly within, the sediment in life and grew parallel to a palaeocurrent but with the tip orientated into the inferred current direction. This is consistent with rheotropic growth rather than felling by a current (McIlroy *et al.* 2022a; Pérez Pinedo *et al*. 2023; rheotropic growth is well known in the Bryozoa, Ryland 1977). Branch reversal would be inconsistent with the tightly constrained branching in the Charnida, for which there is good evidence that the primary branches were connected to one another (McIlroy *et al*. 2022b) and is further supported by 3D scans that show a pneu-like organization, as proposed by Seilacher (1992), in at least some *Charnia*-like specimens (Dunn *et al*. 2021; Butterfield 2022). Several specimens on the surface have their branches orientated into the palaeocurrent (Fig. 2.7B), which is inconsistent with the pre-existing taphonomic model for the Upper Island Cove assemblage, but supports a reclined mode of life among the charnid rangeomorphs (McIlroy *et al*. 2022b). There are additional examples of *Charnia* specimens growing into, as well as in the direction of, sedimentologically determined palaeocurrents in the Ediacaran of Newfoundland (e.g. Fig. 2.7C). A reclined mode of life also helps to explain the high-resolution seen in the fossils, as prolonged contact with the sediment would have allowed for the preservation of finer details, such as the higher orders of branching (Dufour and McIlroy 2017; McIlroy *et al*. 2021).

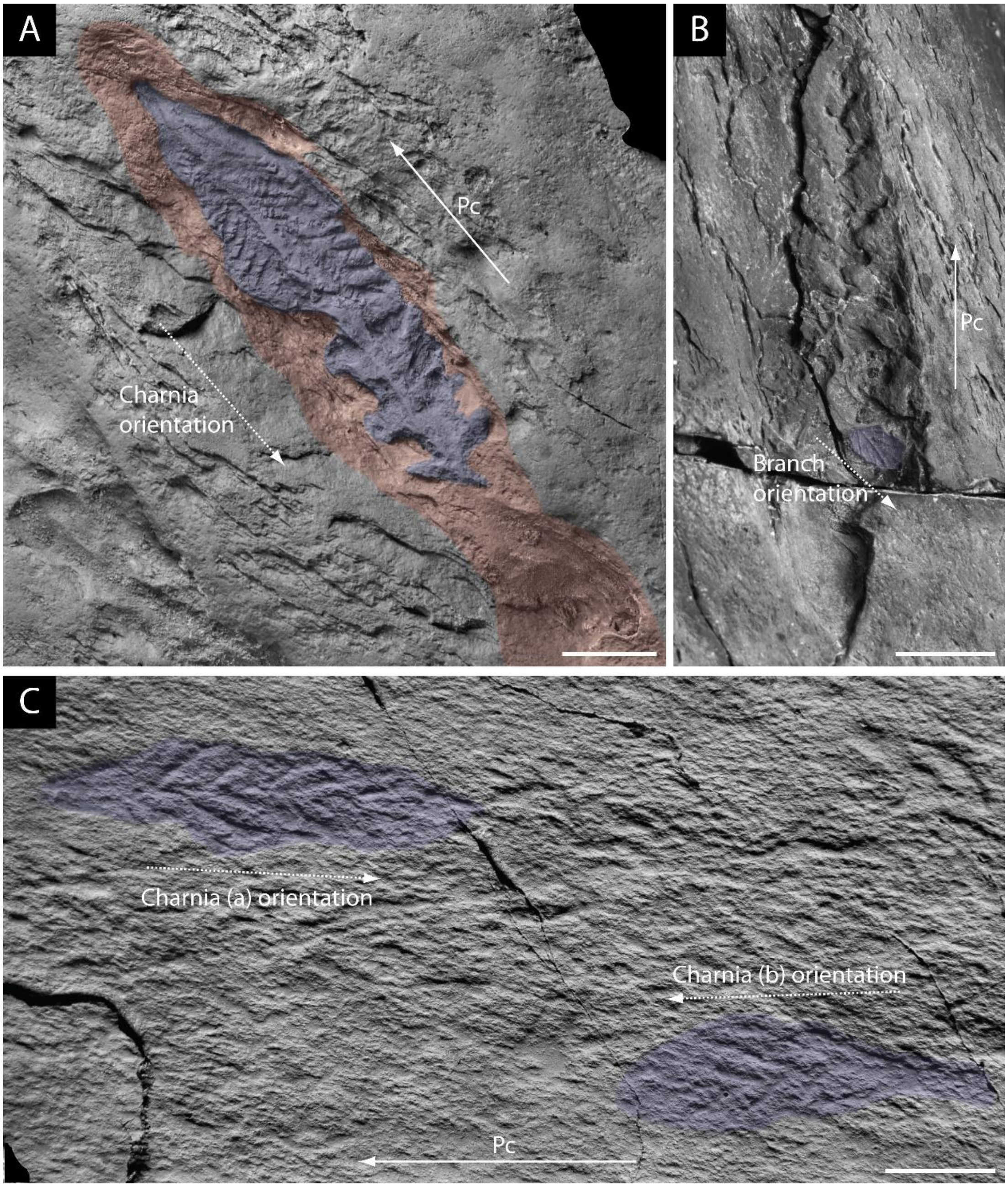


Fig. 2.7 – Specimens reversed relative to the palaeocurrent (Pc). A, *Charnia* sp. (blue) orientated reversed to the palaeocurrent as inferred by obstruction scour (red) (cast SBAS-CM-20-02). B, *Bradgatia* sp. showing branch orientation (blue) reversed to the palaeocurrent (NFM F-757). C, two *Charnia* sp. specimens (blue) from Catalina, Newfoundland orientated towards each other, (a) is

reversed to the palaeocurrent as determined from small flute-like markings on an adjacent slab. (scale bars – 1 cm)

2.2.5 Positive and Negative Epireliefs

Rangeomorph fronds on the Allison Surface from Upper Island Cove are preserved predominantly as negative epireliefs (Narbonne *et al*. 2009; Brasier *et al*. 2013), although fossils containing partial to complete positive epirelief have been documented (Brasier *et al*. 2013; Fig. 2.8). This mixture of positive and negative reliefs (i.e. full relief preservation) is also known from the White Sea Assemblage (Bobrovskiy *et al*. 2019). Specimens preserved in positive relief (Fig. 2.8A) are perhaps better explained as a result of sediment competency (Bobrovskiy *et al*. 2019) than via the pre-existing taphonomic model (Brasier *et al*. 2013), as they lie topographically below the bedding plane and within the erosional obstruction scours.

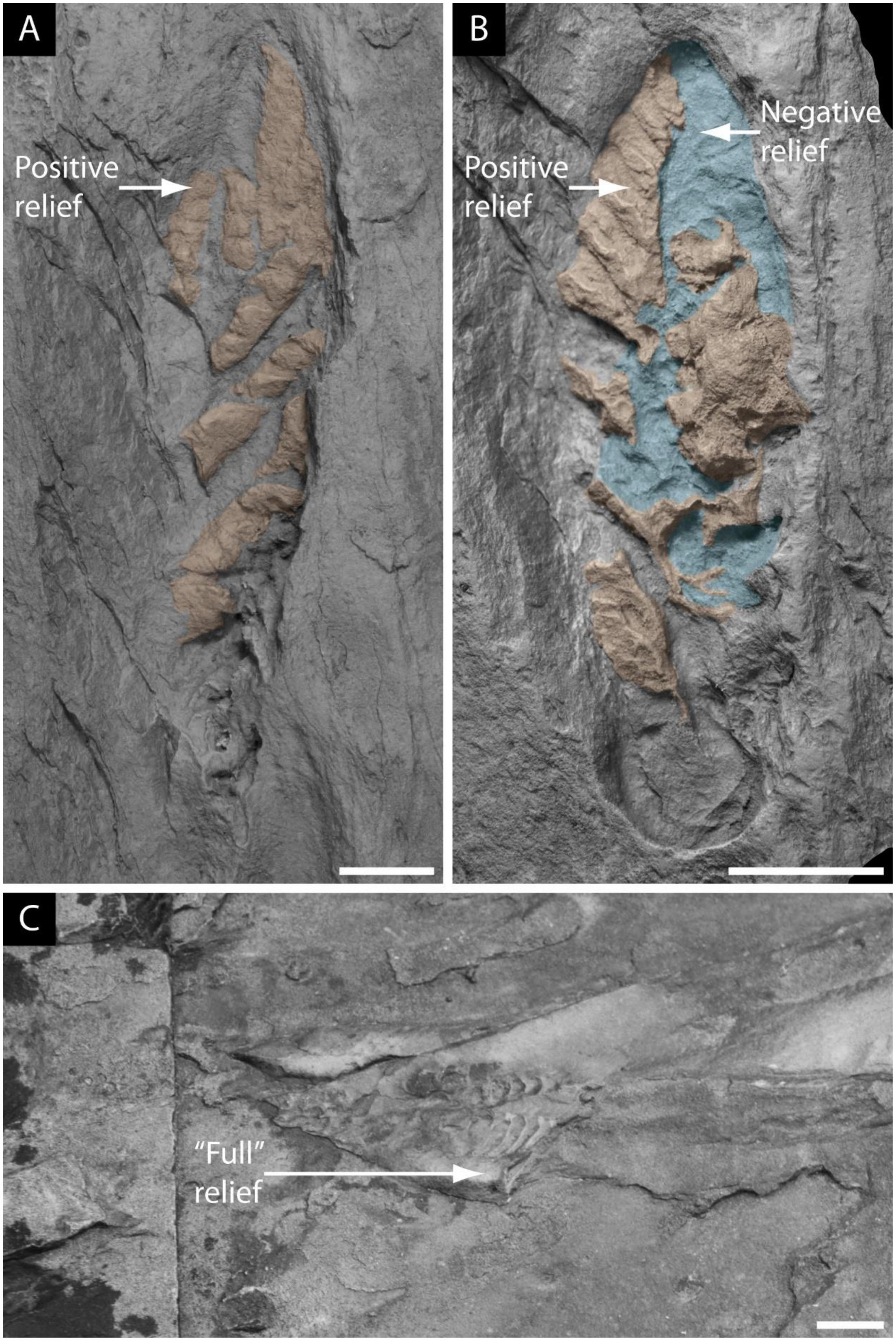

A
Positive
relief
B
Positive
relief
Negative
relief
C
"Full"
relief

Fig. 2.8 – Variation in relief seen on the Allison Surface. A, biserial lanceolate frond preserved in positive relief (orange) (cast SBNO-CM-20-04). B, beothukid preserved in both positive (orange) and negative (light blue) relief (cast SB-2020-020(b)v). C, "full relief" preservation of *Charniodiscus* sp. (cf. nomenclature Seilacher 1964) found directly on top of the fossiliferous surface (uncollected specimen). (scale bars – 1 cm)

Positive relief preservation at Upper Island Cove has previously been explained by the rupturing of the lower surface of the frond, leading to infill by the underlying sediment (Brasier *et al*. 2013, fig. 12b). Full relief preservation is most easily explained by sediment induration around a dead organism (cf. Wade 1968; Bobrovskiy *et al*. 2019). When a buried organism decays between two different sediments the less competent one will infill the cavity to form a cast, thus creating the potential for both positive and negative relief preservation. Our work has additionally revealed a single *Charniodiscus* specimen preserved above the bedding plane entirely in full relief, with no associated obstruction scour (Pérez-Pinedo *et al*. 2022; Fig. 2.8C).

2.2.6 Removal of the T_C Sand

Brasier *et al*. (2013) reported a 1–15 mm thick layer of fine pyritic sandstone on top of the fossiliferous surface, which was inferred to have aided in the preservation of the fronds. This is in keeping with recent work that has suggested that early diagenetic minerals likely aided preservation of Ediacaran fossils (Darroch *et al*. 2012; Becker-Kerber *et al*. 2021). This T_c sand is absent from much of the surface and appears only in isolated patches (Fig. 2.9A). The remains of the ripple toesets (Fig. 2.9B) are of a width that support the reported thickness of 1–15 mm in Brasier *et al*. (2013) for the original sinuous crested bedforms, these T_c sands must have been subsequently eroded prior to lithification and final burial beneath the overlying $T_{d/e}$ unit to explain their absence.

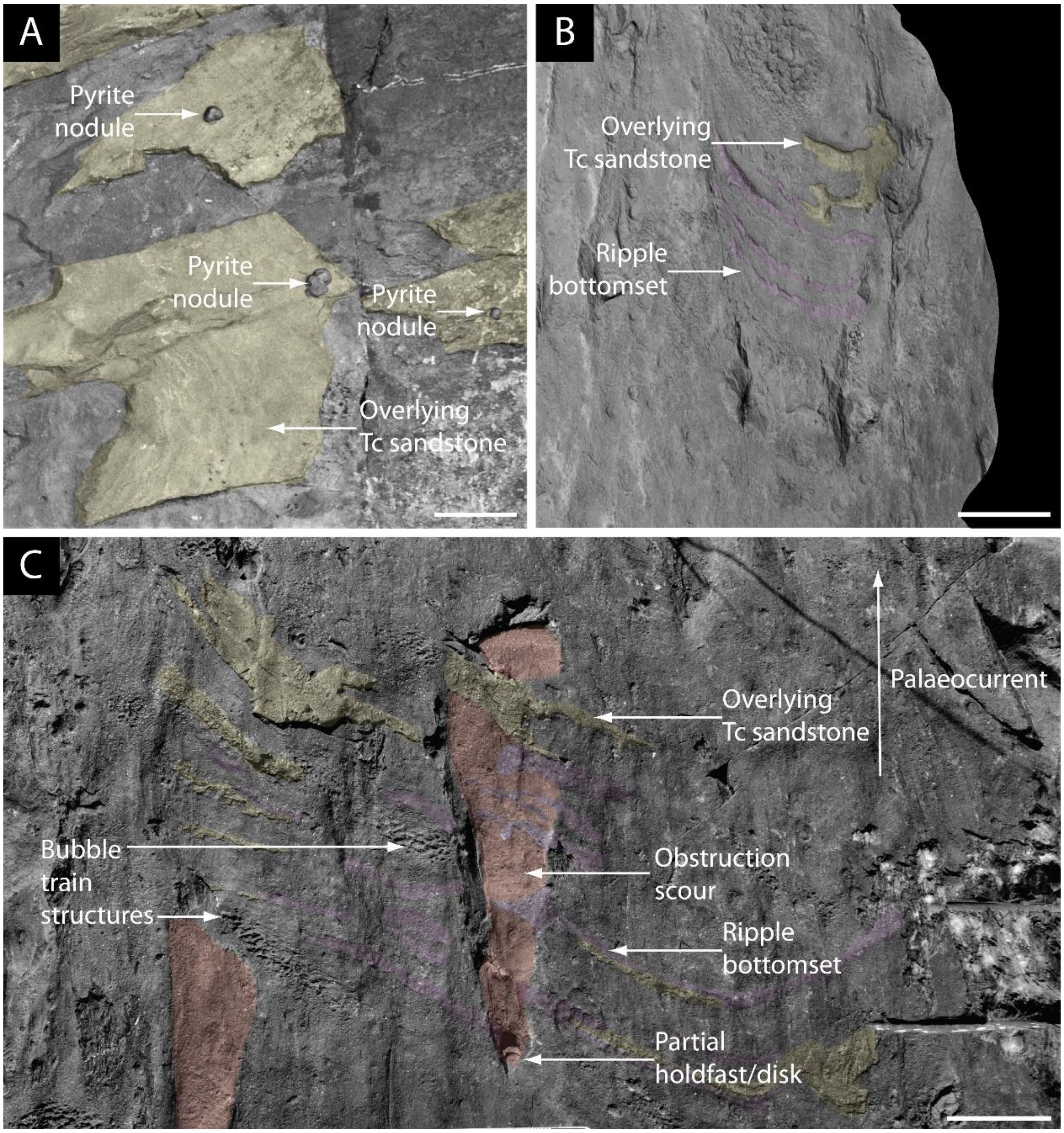


Fig. 2.9 – Sedimentary features on the Allison Surface. A, patches of overlying T_c sandstone (yellow) on top of fossiliferous surface, with pyrite nodules labelled. B, ripple bottomsets (purple) on the fossiliferous surface formed during the deposition of the overlying sands. C, sand-scour relationship

showing that the obstruction scours (red) are crosscut by both the overlying sand and ripple bottomsets, with examples of the "bubble train" structures (Laflamme *et al*. 2011). (scale bars – 2 cm (A, B), 3 cm (C))

Obstruction scours and patches of the overlying T_c sand can often be found in close proximity to one another. Examples of crosscutting are rare, but where present they show sand overlying the scours. This, alongside poorly preserved current ripples (Fig. 2.9B-C) suggests that the sand was deposited almost contemporaneously with scour formation and frond exhumation. This short period of time between scour formation and reburial beneath the T_c sands is likely to have aided in preservation of both positive and negative epirelief impressions (Brasier *et al*. 2013).

2.2.7 Late Colonization by Stemmed Taxa and Community Succession

Previous studies have interpreted the Upper Island Cove biota as a single community (Narbonne *et al*. 2009; Brasier *et al*. 2013). The exhumation of fronds by scours formed around stems (mostly evinced by the preserved bulbous holdfast) brings into question whether these stemmed taxa were part of the same population or if they appeared later as a secondary community. There is evidence for a time interval between the burial of rangeomorph fronds and later colonization by stemmed taxa, such as the offset in frond and scour orientations (Figs 2.3, 2.4; Table A.1) and rare holdfasts that crosscut some specimens (Fig. 2.5). While many holdfasts have associated scour marks, there are also several with no associated erosional structure. These may represent a post-erosional population that postdates the overlying Tc sand and both the rangeomorph and earlier holdfast communities. The community succession of the Upper Island Cove assemblage is thus more complex than previously recognized, possibly occurring over an extended period and across multiple events.

Evidence for the second community is limited to the stemmed (probably erect) taxa in the form of the holdfasts (Figs 2.2, 2.3, 2.5-2.9) and a single specimen of *Charniodiscus* that is preserved above the main fossiliferous surface (Fig. 2.8C). The preserved holdfasts could be associated with *Charniodiscus* or *Avalofractus,* or other taxa known from elsewhere in the Avalonian Assemblage (e.g. Hofmann *et al*. 2008), but it is noted that they are in unusually high relief in comparison to known *Charniodiscus* spp. The full relief *Charniodiscus* is preserved in the T_c sandstone (Pérez-Pinedo *et al*. 2022, fig. 8b) and overlain by associated $T_{d/e}$ units, suggesting this specimen remained in place during the scour generation only to be later buried by T_c sands. The sedimentological and palaeontological evidence indicates that the second community appeared after the burial of the reclined fronds but prior to the deposition of the T_c sand. Previous studies show the fossiliferous surface and overlying Tc sandstone is cut by many cylindrical structures with pyritic rims (Figs 2.5C, A.1) and stems (Brasier *et al*. 2013, fig. 3b, f), which may reflect a later, third, community of erect taxa that appeared after the events that generated the obstruction scours and deposition of the T_c sands.

2.2.8 Pyritized Specimens

The pyritized rims (Figs 2.5C, A.1) and stems on the Allison Surface have been noted to come from later communities, however there is also evidence for pyritization of specimens in the main fossiliferous horizon within the obstruction scours (Fig. 2.10). Stems of some taxa reveal a pyritic veneer (Fig. 2.10A), which was likely the result of early iron sulphide precipitation by sulphur-reducing bacteria around decaying organisms (Darroch *et al*. 2012; Gibson *et al*. 2023). This pyritic veneer can be seen to be cracked, most likely caused by early burial compaction following decay of the tissues. Similar preservation is present in the stem of *Primocandelabrum aelfwynnia* from the UK, which shows partial collapse of a thin, possibly originally pyritic patina (Kenchington and Wilby 2017; Fig. 2.10B). In contrast, stem preservation from elsewhere in Newfoundland, such as the *Charniodiscus procerus* from the Mistaken Point Ecological Reserve (Pérez-Pinedo *et al*. 2022, fig. 6), has a much smoother and rounded stem and as such was most likely further lithified and indurated prior to compaction.

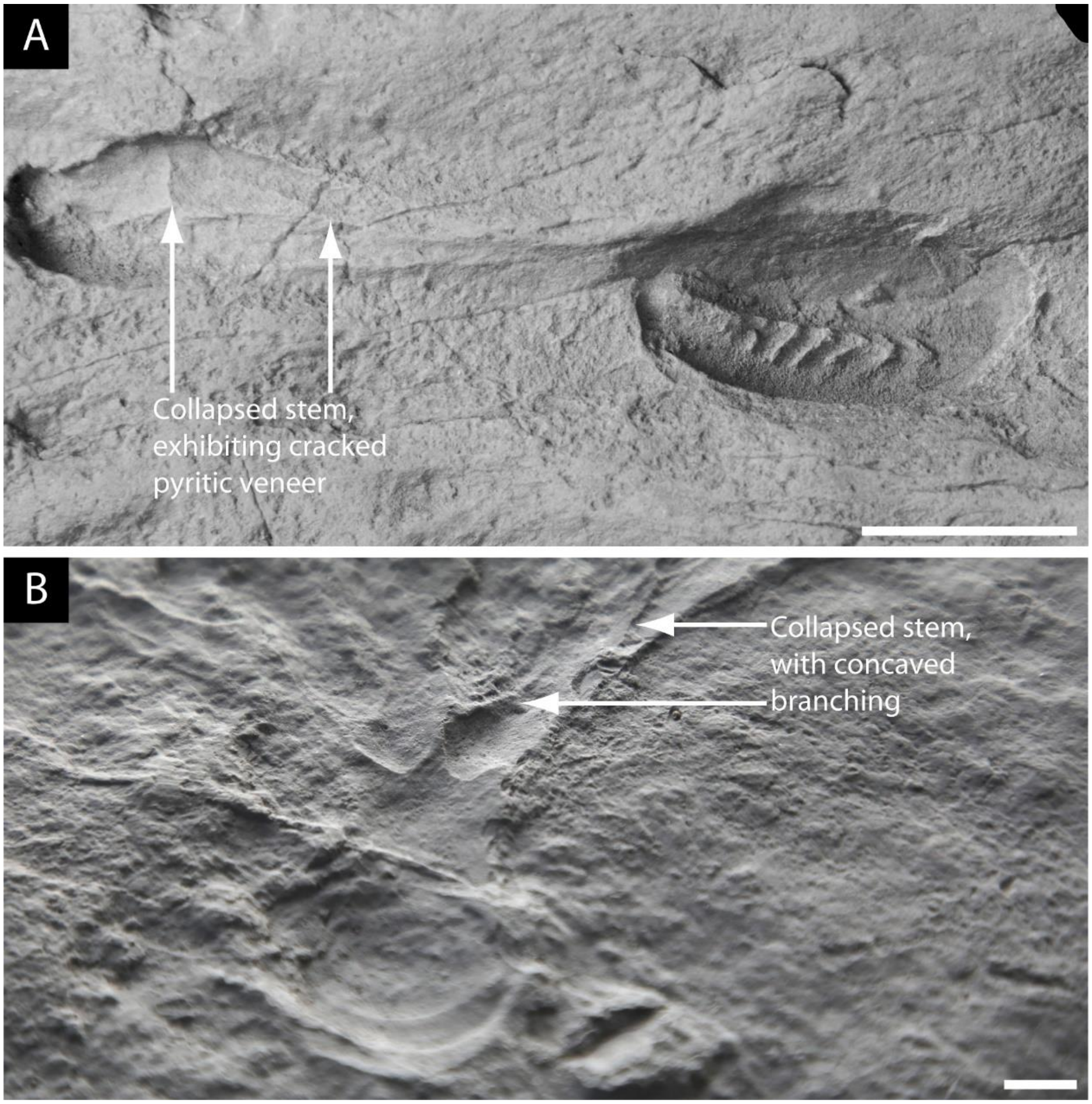


Fig. 2.10 – Partial collapse of positive relief stems. A, partial arboreomorph from Upper Island Cove (cast SB-2021-052viii). B, holotype of *Primocandelabrum aelfwynnia* from Charnwood Forest, Leicestershire, UK (cast taken from mould 3D8 (GSM 105963)). (scale bars – 1 cm)

2.3 THE NEED FOR A NEW MODEL

Our taphonomic and sedimentological observations highlight the need for an updated model for high-relief preservation of frondose taxa within the Upper Island Cove lagerstätte. A new model must include exhumation of buried fronds, rather than the mechanical felling of fronds into the soft seafloor sediment as described previously (Brasier *et al*. 2013).

The preservation of the "reversed charnid" is inconsistent with the Brasier model, which suggested that after being felled the primary branches had been sheared and reversed by hydraulic forces exerted on the surface (Brasier *et al*. 2013). Its position within the obstruction scour, however, shows that it had been buried and later exhumed. Since the obstruction scour cuts into the specimen, the impression of the frond must have preceded the scouring (Fig. 2.7A). A more parsimonious explanation is that the organism was growing on (or slightly within) the sediment in life, orientated parallel to a weak palaeocurrent (cf. McIlroy *et al*. 2022a), this is supported by observations of *Charnia* seen elsewhere in the Avalonian Assemblage which are orientated at 180° to one another but parallel to the palaeocurrent (Fig. 2.7C).

While many stemless fronds in the Upper Island Cove assemblage were likely reclined organisms, organisms with stems and holdfasts (e.g. *Avalofractus* and *Charniodiscus*) were probably alive at the time of current scouring. The *Charniodiscus* specimen found above the bedding plane (Pérez-Pinedo *et al.* 2022), however, suggests that the organisms responsible for the obstacle scours included unrelated arboreomorphs from a stratigraphically higher community. Rare specimens of stemmed taxa connected to the holdfasts within the scours (Fig. 2.2F) are likely from this younger community. There is also evidence from elsewhere in the Avalonian Assemblage for community succession (Liu *et al*. 2011, 2013; Mitchell and Butterfield 2018).

The exclusive preservation of rangeomorph fronds in obstruction scours supports the idea that they were exhumed. This is a more likely explanation than the fronds being felled into their own erosive scours, as no evidence of frond morphology is preserved outside of the scour marks. Had these fronds been felled into their own scours–as suggested by the Brasier model–we might expect to see some evidence of frond impressions and/or swing marks in the sediment around the scours. The previous observation that “shadow zones” are apparently down-current from rangeomorph fronds (Brasier *et al*. 2013, figs 9c, 12) supports the idea that the fronds pre-date the scours, as the impression of the organism must already be present to be scoured.

Stemmed taxa are common in the Avalonian Assemblage, having been considered to be an important part of tiered communities for the partitioning of food resources (Clapham and Narbonne 2002) and/or propagule dispersal (i.e. Mitchell and Kenchington 2018), although the mode of life for many of these taxa are not well understood. On the Allison Surface, the numerous holdfast structures may have belonged to stemmed rangeomorphs (e.g., *Avalofractus*) and arboreomorphs (e.g., *Charniodiscus*; Brasier *et al*. 2013). Well-preserved *Avalofractus* were likely entombed in the T_d silts prior to exhumation by the generation of later scours (Figs 2.2, 2.3).

The rare, mostly poorly preserved, *Charniodiscus* (Figs 2.2F, 2.8C) appear to have been contemporaneous with the eroding current and likely were responsible for the development of the obstruction scours (Figs 2.3, 2.9C). This is consistent with the taphonomic model of Brasier *et al*. (2013; cf. Mir *et al*. 2019). Shallow holdfasts or deep scours may have contributed to the physical removal of most of the stemmed taxa by the eroding current, eventually resulting in a more flute-like morphology of some scours.

2.3.1 New Taphonomic Model

Many of the Upper Island Cove frondose taxa were likely epibenthic recliners that were entombed in the T_d silt prior to exhumation. This mode of life model negates the need for fronds to be felled into obstruction scours, as they would have grown in or on the T_d unit, while allowing for the production of both negative and positive epireliefs as outlined in the new taphonomic model detailed herein (Fig. 2.11).

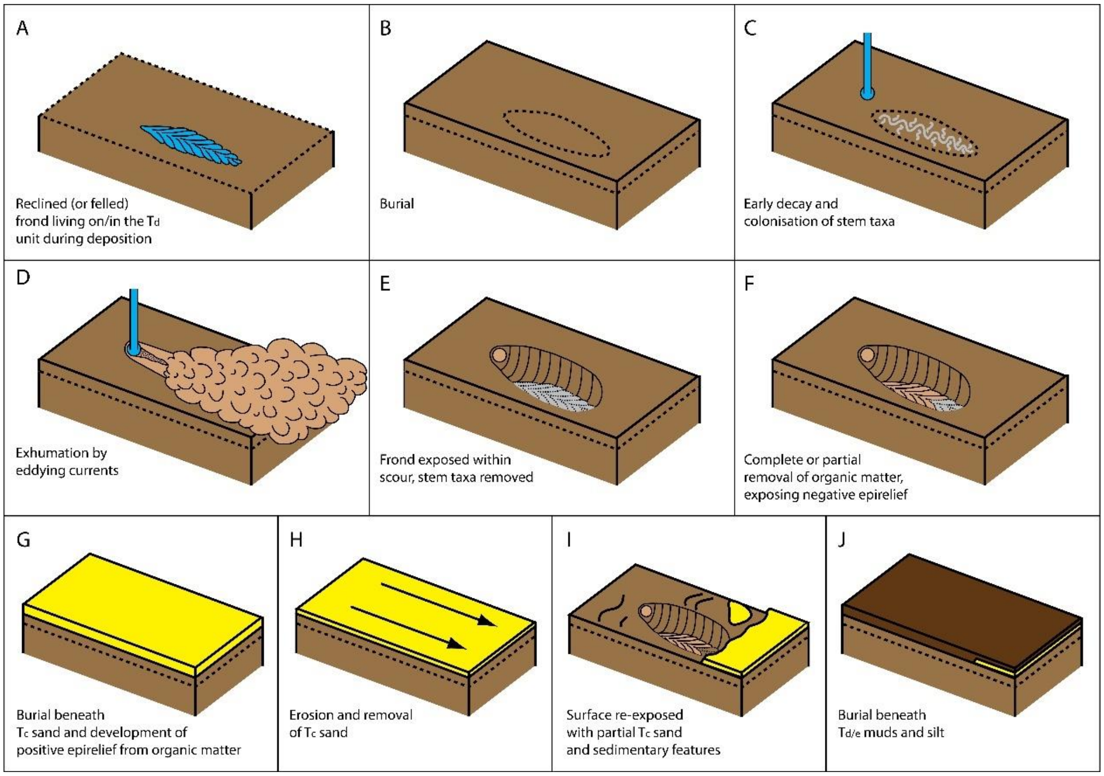


Fig. 2.11 – General taphonomic model for Upper Island Cove preservation. A–C, burial phase. D–F, exhumation phase. G–J, reburial phase, note that the full relief *Charniodiscus* specimen would have been buried and preserved during this phase. Key, living organic tissue = blue, necrotic organic tissue = grey, mudstones (T_{de}) = brown, sandstone (T_c) = yellow.

This new model accounts for all the taphonomic and sedimentological features observed at the site. The concepts in Brasier *et al*. (2013) adequately explain some aspects of the preservation at Upper Island Cove, and are incorporated into the new model, including: the fossiliferous layer comprising the upper surface of the T_d siltstone unit; the generation of obstruction scours around the base of erect taxa as the result of high velocity currents; and the subsequent burial of the surface beneath a T_c sandstone. Aspects of the original model presented in Narbonne (2004) are also explained herein, such as the presence of fronds within the T_d ('T_e'; Narbonne *et al*. 2009) unit and the preservation of partial/fragmentary specimens (Narbonne 2004). This step-by-step model (Fig. 2.11) explains the high-relief, three-dimensional preservation seen in both the stemmed and non-stemmed frondose fossils as well as holdfast fossils at the site, accounting for the variation in positive, negative and mixed preservation (Figs 2.8, 2.12).

Fig. 2.12 – Epirelief variation model, starting in the exhumation phase of Figure 2.11. A, negative epirelief preservation. B, positive relief preservation. C, mixed epirelief preservation. Key, necrotic organic tissue = grey, mudstones (T_{de}) = brown, sandstone (T_c) = yellow, pyritic envelope = dotted line.

Successive taphonomic and sedimentologic processes act on the first community of reclining frondose rangeomorphs (Fig. 2.11A), which were buried within a T_d silt that was deposited across the entire surface (Fig. 2.11B); any erect rangeomorph and arboreomorph fronds present were also buried at this stage, as suggested by the presence of (particularly partial) *Avalofractus* and *Charniodiscus* in obstruction scours (Figs 2.2A, F, 2.3F, 2.6B). The burial of both reclined and erect fronds would explain the comparably high levels of preservation seen across many fossils, as both frond types would have been in direct contact with the sediment above and below (during life for the recliners and post-mortem in the case of the erect taxa). Early anoxic decay and authigenic mineral (likely pyrite) precipitation also occurred around the organisms at this time, aided by the build-up of hydrogen sulphide around the decaying organism produced by sulphur reducing bacteria (Gehling 1999; Darroch *et al*. 2012; Liu 2016; Gibson *et al*. 2023). Previous studies have shown that pyrite is abundant in both the T_d and T_c units at Upper Island Cove (Brasier *et al*. 2013).

Crosscutting of exhumed fronds by holdfasts suggests the erect taxa responsible for the holdfasts and obstruction scours recolonized the sediment surface during the decay phase of the buried fronds (Fig. 2.11C). Sometime after the deposition of the T_d layer, strong currents caused eddying around the bases of this second community of erect taxa (Fig. 2.11D), resulting in the formation of obstacle scours. Only a minority of these scours exposed a buried frond (Fig. 2.11E). Partial to complete exhumation of buried fronds and the removal of the stemmed taxa occurred at this time, sometimes leaving behind the impression of the holdfasts of erect taxa. Swing marks were likely formed during this phase, as tethered organisms were swept by the eroding current (Fig. 2.3G, H), while erect fronds (and remains of partially decayed recliners) were undercut and transported away by the current. In most cases, continued erosion within the scours would have removed any traces of the swing marks.

Post-burial decomposition is likely to have weakened the structural integrity of buried organisms, in a similar manner to the burial fermentation of lutefisk (see Magnus 1555; Legwold 1996). Once the upper surface of the decaying organism was exposed by erosion the current would easily remove decay products leaving behind the impression of the organism in the indurated sediment (Fig. 2.11F). Evidence for partial specimens (Fig. 2.13) shows that erosion before deposition of the T_c sands could remove large portions of the impression prior to preservation.

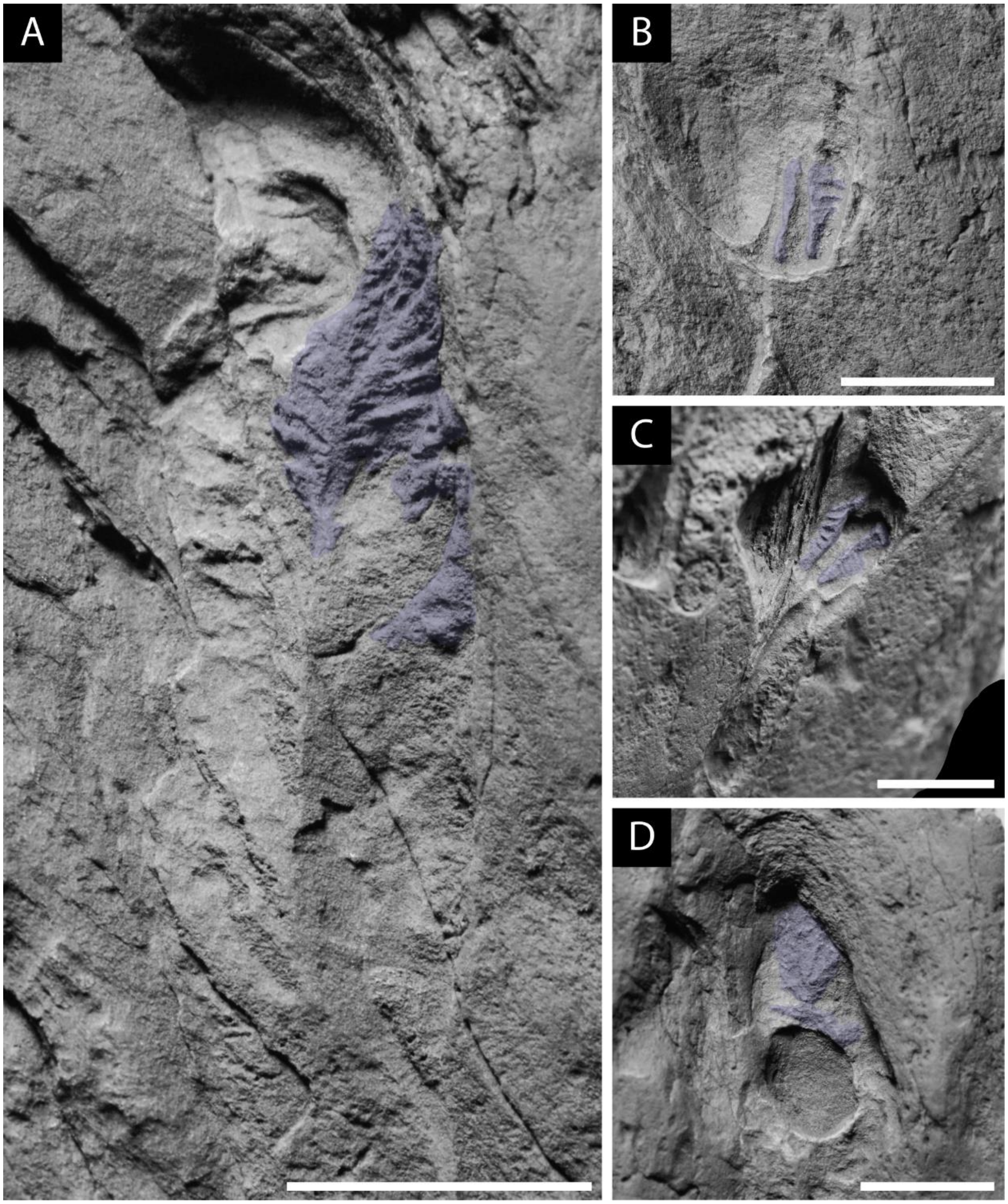


Fig. 2.13 – Fragmented and partial preservation of rangeomorph fronds (blue). A, partial *Trepassia* sp. found at the tip of an obstruction scour (cast SB-2021-054iv). B–C, partial preservation of fronds within scours, not enough branching is preserved for taxonomic diagnoses (casts SB-2020-022ii (B), SB-2020-026ii (C)). D, partial *Avalofractus* sp. found at the tip of an obstruction scour (cast SB-2021-055ix). (scale bars – 1 cm)

Much of the T_c sand was also removed by a subsequent erosion event (Fig. 2.11I), as indicated by its patchy preservation as curved toesets of sinuous crested current ripples both upon the modern surface and in cross-section (Brasier *et al*. 2013, figs 2b, 3; Fig. 2.9). Final burial of the fossiliferous surface occurred after the erosion of the T_c sands, burying the surface beneath $T_{d/e}$ muds and silts (Fig. 2.11J).

2.3.2 Discussion of the New Model

The burial of fronds in the T_d silt before and/or after death explains how both stemmed and non-stemmed taxa can be preserved at similar depths within the obstruction scours. If alive at the time of burial, a lack of oxygen in the sediment would have caused death in immotile Ediacaran organisms (Brett *et al*. 2012). Decomposition during the terminal Neoproterozoic was probably much slower than during the Phanerozoic, in part due to the bacterial matground ecology on the seafloor (Brasier *et al*. 2010; Liu *et al*. 2011) and the lack of scavengers and bioturbation, which did not appear until later in the Ediacaran (McIlroy and Logan 1999; Gehling and Droser 2018). It is thus impossible to ascertain the period of time that elapsed between burial of the fronds and their exhumation. In experiments with modern analogues, quality of the preserved impression degrades rapidly approximately one week after burial in the absence of a microbial mat (Darroch *et al*. 2012; Hancy and Antcliffe 2020). We can infer, however, that a period of time suitable to allow for the colonisation and growth of a subsequent community must have passed, as evinced by large holdfasts crosscutting fronds (Fig. 2.5). Only a small amount of decomposition occurred prior to burial, while organism-sediment interactions may have caused incipient lithification of the T_d silt around the organism, through cementation or organic binding, during life (Dufour and McIlroy 2017; Taylor *et al*. 2021). Early decomposition of body tissue results in the build-up of sulphides in the sediment around dead organisms (Darroch *et al*. 2012), due to the action of sulphur-reducing bacteria; this would have led to the formation of pyrite around buried organisms, as supported by the pyritic veneer seen on the stem of some specimens (Fig. 2.10).

Erect taxa play a critical role in the preservation of the Upper Island Cove assemblage as they are essential for the generation of the obstruction scours that exhumed the buried fronds (Fig. 2.11D). Obstruction scours form in the lee of a seafloor object through the formation of an eddying current, which erodes the top layer of accumulated sediment (e.g. Dżułyński and Walton 1965; Brasier *et al*. 2013). A comparison of obstruction scours preserved at Upper Island Cove with modern examples suggests they were generated in a similar manner (Brasier *et al*. 2013, fig. 7). Arboreomorphs (e.g. *Charniodiscus*) and erect rangeomorphs (e.g. *Avalofractus*) are good candidates as loci for the obstruction scours. As obstruction scours only preserve the partial remains of fronds (Figs 2.3, 2.11E-F) it is possible that full specimens were much larger than can be observed on the Allison Surface. *Bradgatia* specimens (Fig. 2.2B) are often found near each other and, as such, it cannot be ruled out that different scours are exposing different parts of the same specimen. The fossils at Upper Island Cove, therefore, should be treated as either only being partially exposed or fragmentary—largely eroded—exterior casts and molds (Fig. 2.11F).

As ~75% of obstruction scours contain no evidence for preserved fronds (only deep holdfasts) the exhumation of buried fronds was likely coincidental. The presence of buried decaying fronds would have altered the surface sediment rheology aiding in scour generation once scouring had begun, particularly with the current removing the gelatinous/soupy decomposing organism, which would create increased topography and enhanced eddying and scouring. Prolonged exposure to erosive currents would likely remove any evidence of exhumed organisms in some cases. Other sites in the region, such as Adams Cove, show the preservation of holdfasts and sedimentary ridges comparable to Upper Island Cove (Fig. A.2); had these been subjected to prolonged erosive currents, or had buried and decayed fronds in the top layers of the sediment, it is possible that obstruction scours would have been generated at these sites as well. It is plausible that reclined rangeomorph fronds associated with the Allison Surface were more common than the current data suggests, with their lack of preservation either due to not being exhumed or their removal from scours after prolonged exposure.

2.3.3 Positive and Negative Relief Model

Three-dimensional rangeomorph preservation has been observed in the Nama (Crimes and Fedonkin 1996; Dzik 2002; Vickers-Rich *et al.* 2013) and White Sea (Grazhdankin and Seilacher 2005) assemblages, and is most commonly seen as full relief preservation of *Rangea* (e.g. Jenkins 1985; Grazhdankin and Seilacher 2005; Sharp *et al.* 2017). The three-dimensional full relief preservation at Upper Island Cove is unique within the Avalonian Assemblage, where organisms are typically preserved as low positive or shallow negative epireliefs in association with a microbial death mask (cf. Gehling 1999). The only potential evidence of microbial matgrounds at Upper Island Cove are the “bubble train” structures found between the T_d and overlying T_c units (Laflamme *et al*. 2011; Fig. 2.9C) and as such postdate the Upper Island Cove rangeomorph fossils.

Negative epirelief preservation at Upper Island Cove is reminiscent of Flinders-style preservation seen in the White Sea Assemblage (Narbonne 2005; Bobrovskiy *et al*. 2019). In Flinders-style preservation the Ediacaran biota are preserved as positive hyporeliefs on the base of sandstones that overlie mudstones (Bobrovskiy *et al*. 2019). The specimens at Upper Island Cove are preserved as negative epirelief/endorelief specimens on the top of siltstones, that were overlain by the thin (largely eroded) T_c sandstone layer (Fig. 2.11G-J). The preservation could be considered as analogous to Flinders-style preservation, except with the well indurated siltstones preserving the fossils, not the overlying sandstone. Further comparison with the White Sea Assemblage is possible as similar sedimentological structures, in particular fluting and scour marks, are associated with infaunal rangeomorph fronds (Grazhdankin 2004; Grazhdankin and Seilacher 2005).

Negative epirelief preservation can be explained by the burial of organismal impressions beneath the T_c sands shortly after the removal of necrotic organic matter by continued high-velocity currents (Figs 2.11F, 2.12A). The T_c sand contained abundant early pyrite, as seen in cross section, which would have helped to preserve the negative impressions in high relief (Brasier *et al*. 2013). However, this does not explain full or partial positive relief preservation (Fig. 2.8). If, as the previous model suggested, the rupturing of the underside of the rangeomorph frond led to sediment infill from below (Brasier *et al*. 2013, fig. 12c) the positive impressions would show the internal, not external, structure of the frond, of which there is no evidence. This previous explanation also fails to explain why some specimens preserve a combination of both positive and negative relief (Fig. 2.8B).

A more parsimonious explanation for positive relief preservation at Upper Island Cove involves near organism sediment induration by authigenic minerals, especially pyrite. After a buried organism decays, it leaves a void within the sediment; if this void is situated between two differing sediments, the less competent material will fill the void and create a cast of the opposing surface (Wade 1968; Bobrovskiy *et al*. 2019). At Upper Island Cove, after the generation of scours and reburial of the fronds beneath the T_c sand (Fig. 2.11E-G), the underlying T_d silts would have been less competent than the overlying coarser grained and pyrite-rich Tc sands. These T_d silts would have raised to infill the cavity left by the decayed frond, preserving the upper surface of the frond as a cast on the bottom of the T_c sands (Fig. 2.12B). In this manner the preservation of positive relief fronds within scours can be compared to that of the full relief preservation of the *Charniodiscus* positioned on top of the surface (Fig. 2.8C). This model also explains specimens possessing both positive and negative epirelief, representing specimens where decomposed organic matter was only partially removed prior to their reburial beneath the T_c sands (Fig. 2.12C). Study of the taxa present in the Upper Island Cove assemblage thus allows us to observe both sides of a rangeomorph frond and compare variations in morphology.

2.4 CONCLUSION

Our new model builds upon the two previous taphonomic models (Narbonne 2004; Brasier *et al*. 2013) to explain our additional taphonomic observations. The high-relief three-dimensional preservation of both stemmed erect and non-stemmed reclined rangeomorphs can be explained by their presence within the top centimetre of a T_d siltstone.

Having been buried within the T_d unit, the decaying organisms were subsequently exhumed by a current that eroded the seafloor in the lee of a later community of stemmed organisms. Some of the obstruction scours uncovered buried rangeomorph fronds which are either partly or fully exposed by the erosive action of the current, though most of these scours do not exhibit fossils at all.

Where obstruction scours exposed decayed or decaying organic remains the remaining tissues are considered to have been removed by the current, revealing the lower impression of the organism in the underlying silt and becoming preserved as a negative epirelief in partly lithified siltstone, which was then cast by the overlying T_c sands (Figs 2.9, 2.11G) prior to their removal. When the erosion in the obstacle scour was insufficient to erode the top of the buried organism the upper surface of the frond was cast in positive epirelief (Figs 2.8A-B, 2.11B).

This new understanding of the taphonomy at Upper Island Cove suggests that the site contains evidence for community succession, including epifaunal recliners and erect stemmed taxa growing in/on the T_d siltstone. This assemblage was succeeded by at least two communities of erect taxa with holdfasts that penetrated the rangeomorph-bearing T_d siltstone, and preserved pyritic stems that may have extended into the overlying units (Brasier *et al.* 2013). This study highlights the importance of taphonomy in understanding the Ediacaran biota at Upper Island Cove, since it is key to determine completeness, whether the fossil represents the top or the bottom of the organism, and whether features considered biological might be erosional artefacts. In addition, any attempts at analysing community composition at the site need to consider that exposure of the classic rangeomorph fossils is due to the coincidence of buried fossils in relation to obstacle scours. As well as the palimpsest nature of the assemblage, which includes at least three assemblages/communities: 1) the early rangeomorph community of reclined and erect taxa; 2) a community of erect taxa (possibly erect rangeomorphs and arboreomorphs) which caused the formation of the obstacle scours; and 3) a later community of organisms that are preserved only as pyritic tubes in the overlying sedimentary units that postdate the thin sand event.

ACKNOWLEDGEMENTS

J. Hawco, G. Pasinetti, J. Neville, H. Fitzgerald and M. Steele are thanked for their assistance in the field and discussion of the topic, D. Pérez-Pinedo is thanked for both his assistance in the field and advice on statistical analysis, R. Hiscott is thanked for his insight and advice which led to the development of the model presented and, finally, we thank two anonymous reviewers for their constructive comments. In accordance with provincial regulations, no fossils were removed from the Upper Island Cove site. This work is based on field photographs and casts which were made under permit from the Province of

Newfoundland and Labrador, and study of historical specimens accessioned to The Rooms, St. John's, NL. This project was supported by a NSERC Discovery Grant and Discovery Accelerator Supplement to DM, as well as by the Town of Upper Island Cove.

REFERENCES

Anderson, M.M. and Misra, S.B. 1968. Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland. *Nature*, **220**, 680–681, https://doi.org/10.1038/220680a0

Becker-Kerber, B., El Albani, A., Konhauser, K., Abd Elmola, A., Fontaine, C., Paim, P.S.G., Mazurier, A., Prado, G.M.E.M., Galante, D., Kerber, P.B., da Rosa, A.L.Z., Fairchild. T.R., Meunier, A. and Pacheco, M.L.A.F. 2021. The role of volcanic-derived clays in the preservation of Ediacaran biota from the Itajaí Basin (ca. 563 Ma, Brazil). *Scientific Reports*, **11**, 5013, https://doi.org/10.1038/s41598-021-84433-0

Bobrovskiy, I., Krasnova, A., Ivantsov, A., Luzhnaya (Serezhnikova), E. and Brocks, J.J. 2019. Simple sediment rheology explains the Ediacara biota preservation. *Nature Ecology & Evolution*, **3**, 582–589, https://doi.org/10.1038/s41559-019-0820-7

Brasier, M.D. and Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: New insights from laser analysis. *Journal of The Geological Society*, **166**, 363–384, https://doi.org/10.1144/0016-76492008-011

Brasier, M.D., Callow, R.H.T., Menon, L.R. and Liu, A.G. 2010: Osmotrophic biofilms: From modern to ancient. *In*: Seckbach, J. and Oren, A. (eds) *Microbial Mats: Modern and Ancient Microorganisms in Stratified Systems*. Springer, Cellular Origin, Life in

Extreme Habitats and Astrobiology series, **14**, 131–148, https://doi.org/10.1007/978-90-481-3799-2_7

Brasier, M.D., Antcliffe, J.B. and Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124, https://doi.org/10.1111/j.1475-4983.2012.01164.x

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Brett, C.E., Zambito, J.J., Hunda, B.R. and Schindler, E. 2012. Mid-Paleozoic trilobite lagerstätten: Models of diagenetically enhanced obrution deposits. *Palaios*, **27**, 326–345, https://doi.org/10.2110/palo.2011.p11-040r

Butterfield, N.J. 2022. Constructional and functional anatomy of Ediacaran rangeomorphs. *Geological Magazine*, **159**, 1148–1159, https://doi.org/10.1017/S0016756820000734

Callow, R.H.T. and Brasier, M.D. 2009. Remarkable preservation of microbial mats in Neoproterozoic siliciclastic settings: Implications for Ediacaran taphonomic models. *Earth Science Reviews*, **96**, 207–219, https://doi.org/10.1016/j.earscirev.2009.07.002

Clapham, M.E. and Narbonne, G.M. 2002. Ediacaran epifaunal tiering. *Geology*, **30**, 627–630, https://doi.org/10.1130/0091-7613(2002)030%3C0627:EET%3E2.0.CO;2

Clements, T., Purnell, M. and Gabbott, S. 2019. The Mazon Creek Lagerstätte: A diverse late Paleozoic ecosystem entombed within siderite concretions. *Journal of the Geological Society*, **176**, 1–11, https://doi.org/10.1144/jgs2018-088

Crimes, T.P. and Fedonkin, M.A. 1996. Biotic changes in platform communities across the precambrian Phanerozoic boundary. *Rivista Italiana di Paleontologia e Stratigrafia*, **102**, 317–332, https://doi.org/10.13130/2039-4942/5266

Darroch, S.A.F., Laflamme, M., Schiffbauer, J.D. and Briggs, D.E.G. 2012. Experimental formation of a microbial death mask. *Palaios*, **27**, 293–303, https://doi.org/10.2110/palo.2011.p11-059r

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2017. Relating Ediacaran fronds. *Paleobiology*, **43**, 171–180, https://doi.org/10.1017/pab.2016.54

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2018. Phylogenetic relationships among the Rangeomorpha: The importance of outgroup selection and implications for their diversification. *Canadian Journal of Earth Sciences*, **55**, 1223–1239, https://doi.org/10.1139/cjes-2018-0022

Dufour, S.C. and McIlroy, D. 2017. Ediacaran pre-placozoan diploblasts in the Avalonian biota: The role of chemosynthesis in the evolution of early animal life. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 211–219, https://doi.org/10.1144/SP448.5

Dunn, F.S., Liu, A.G. and Donoghue, P.C.J. 2018. Ediacaran developmental biology. *Biological Reviews*, **93**, 914–932, https://doi.org/10.1111/brv.12379

Dunn, F.S., Liu, A.G., Grazhdankin, D.V., Vixseboxse, P., Flannery-Sutherland, J., Green, E., Harris, S., Wilby, P.R. and Donoghue, P.C.J. 2021. The developmental biology of *Charnia* and the eumetazoan affinity of the Ediacaran rangeomorphs. *Science Advances*, **7**, eabe0291, https://doi.org/10.1126/sciadv.abe0291

Dzik, J. 2002. Possible ctenophoran affinities of the Precambrian “Sea-Pen” *Rangea*. *Journal of Morphology*, **252**, 315–334, https://doi.org/10.1002/jmor.1108

Dżułyński, S. and Walton, E.K. 1965. *Sedimentary Features of Flysch and Greywackes*. Elsevier.

Ford, T.D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 211–217, https://doi.org/10.1144/pygs.31.3.211

Gehling, J.G. 1999. Microbial mats in terminal Proterozoic siliciclastics: Ediacaran death masks. *Palaios*, **14**, 40–57, https://doi.org/10.2307/3515360

Gehling, J.G. and Droser, M.L. 2018. Ediacaran scavenging as a prelude to predation. *Emerging Topics in Life Sciences*, **2**, 213–222, https://doi.org/10.1042/etls20170166

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Gibson, B.M., Schiffbauer, J.D., Wallace, A.F. and Darroch, S.A.F. 2023. The role of iron in the formation of Ediacaran ‘death masks’. *Geobiology*, **21**, 421–434, https://doi.org/10.1111/gbi.12551

Grazhdankin, D. 2004. Patterns of distribution in the Ediacaran biotas: Facies versus biogeography and evolution. *Paleobiology*, **30**, 203–221, https://doi.org/10.1666/0094-8373(2004)030%3C0203:PODITE%3E2.0.CO;2

Grazhdankin, D. and Seilacher, A. 2005. A re-examination of the Nama-type Vendian organism *Rangea schneiderhoehni*. *Geological Magazine*, **142**, 571–582, https://doi.org/10.1017/S0016756805000920

Hancy, A.D. and Antcliffe, J.B. 2020. Anoxia can increase the rate of decay for cnidarian tissue: Using *Actinia equina* to understand the early fossil record. *Geobiology*, **18**, 167–184, https://doi.org/10.1111/gbi.12370

Hawco, J.B., Kenchington, C.G. and McIlroy, D. 2019. A quantitative and statistical discrimination of morphotaxa within the Ediacaran genus *Palaeopascichnus*. *Papers in Palaeontology*, **7**, 657–673, https://doi.org/10.5061/dryad.jq7460s

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Hofmann, H.J., O'Brien, S.J. and King, A.F. 2008. Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36, https://doi.org/10.1666/06-087.1

Ichaso, A.A., Dalrymple, R.W. and Narbonne, G.M. 2007. Paleoenvironmental and basin analysis of the late Neoproterozoic (Ediacaran) upper Conception and St. John's groups, west Conception Bay, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 25–41, https://doi.org/10.1139/e06-098

Jenkins, R.J.F. 1985. The enigmatic Ediacaran (late Precambrian) genus *Rangea* and related forms. *Paleobiology*, **11**, 336–355, https://doi.org/10.1017/S0094837300011635

Kenchington, C.G. and Wilby, P.R. 2017. Rangeomorph classification schemes and intra-specific variation: Are all characters created equal? *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 221–250, https://doi.org/10.1144/SP448.19

Laflamme, M., Narbonne, G.M. and Anderson, M.M. 2004. Morphometric analysis of the Ediacaran frond *Charniodiscus* from the Mistaken Point Formation, Newfoundland. *Journal of Paleontology*, **78**, 827–837, https://doi.org/10.1666/0022-3360(2004)078%3C0827:MAOTEF%3E2.0.CO;2

Laflamme, M., Schiffbauer, J.D. and Narbonne, G.M. 2011. Deep-water microbially induced sedimentary structures (MISS) in deep time: The Ediacaran fossil *Ivesheadia*. *In*: Noffke, N. and Chafetz, H. (eds) *Microbial Mats in Siliciclastic Depositional Systems Through Time*. SEPM Special Publications, **101**, 111–123, https://doi.org/10.2110/sepmsp.101.111

Laflamme, M., Flude, L.I. and Narbonne, G.M. 2012. Ecological tiering and the evolution of a stem: The oldest stemmed frond from the Ediacaran of Newfoundland, Canada. *Journal of Paleontology*, **86**, 193–200, https://doi.org/10.1666/11-044.1

Legwold, G. 1996. *The Last Word on Lutefisk: True Tales of Cod and Tradition*. Conrad Henry Press.

Liu, A.G. 2016. Framboidal pyrite shroud confirms the 'death mask' model for moldic preservation of Ediacaran soft-bodied organisms. *Palaios*, **31**, 259–274, https://doi.org/10.2110/palo.2015.095

Liu, A.G., McIlroy, D., Antcliffe, J.B. and Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630, https://doi.org/10.1111/j.1475-4983.2010.01024.x

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2012. A new assemblage of juvenile Ediacaran fronds from the Drook Formation, Newfoundland. *Journal of the Geological Society*, **169**, 395–403, https://doi.org/10.1144/0016-76492011-094

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2013. Exploring an Ediacaran 'nursery': Growth, ecology and evolution in a rangeomorph palaeocommunity. *Geology Today*, **29**, 23–26, https://doi.org/10.1111/j.1365-2451.2013.00860.x

Liu, A.G., Kenchington, C.G. and Mitchell, E.G. 2015. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380, https://doi.org/10.1016/j.gr.2014.11.002

Liu, A.G., Matthews, J.J. and McIlroy, D. 2016. The *Beothukis*/*Culmofrons* problem and its bearing on Ediacaran macrofossil taxonomy: Evidence from an exceptional new fossil locality. *Palaeontology*, **59**, 45–58, https://doi.org/10.1111/pala.12206

Magnus, O. 1555. *Historia de gentibus septentrionalibus (The history of the Nordic people)*. Rome.

Matthews, J.J., Liu, A.G., Yang, C., McIlroy, D., Levell, B. and Condon, D.J. 2020. A chronostratigraphic framework for the rise of the Ediacaran macrobiota: New constraints from Mistaken Point Ecological Reserve, Newfoundland. *GSA Bulletin*, **133**, 612–624, https://doi.org/10.1130/B35646.1

McArthur, R.H. and Wilson, E.O. 1967. *The Theory of Island Biogeography*. Princeton University Press.

McIlroy, D. and Horák, J.M. 2006. Neoproterozoic: The late Precambrian terranes that formed Eastern Avalonia. *In*: Brenchley, P.J. and Rawson, P.F. (eds) *The Geology of England and Wales*, *Second Edition*. Geological Society, London, 9–23, https://doi.org/10.1144/GOEWP

McIlroy, D. and Logan, G.A. 1999. The impact of bioturbation on infaunal ecology and evolution during the Proterozoic-Cambrian transition. *Palaios*, **14**, 58–72, https://doi.org/10.2307/3515361

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Pérez-Pinedo, D., Pasinetti, G., McKean, C., Taylor, R.S. and Hiscott, R.N. 2022a. Rheotropic epifaunal growth, not felling by density currents is responsible for many Ediacaran fossil orientations at Mistaken Point. *Frontiers in Earth Science*, **10**, 849194, https://doi.org/10.3389/feart.2022.849194

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022b. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

Mir, B.H., Lone, M.A. and Bhat, J.A. 2019. Laboratory investigation for development of local scour depth model for varying shapes of obstruction. *International Journal of Hydrology Science and Technology*, **9**, 303–312, https://doi.org/10.1504/IJHST.2019.102319

Mitchell, E.G. and Butterfield, N.J. 2018. Spatial analyses of Ediacaran communities at Mistaken Point. *Paleobiology*, **44**, 40–57, https://doi.org/10.1017/pab.2017.35

Mitchell, E.G. and Kenchington, C.G. 2018. The utility of height for the Ediacaran organisms of Mistaken Point. *Nature Ecology & Evolution*, **2**, 1218–1222, https://doi.org/10.1038/s41559-018-0591-6

Murphy, J.B., Pisarevsky, S.A., Nance, R.D. and Keppie, J.D. 2004. Neoproterozoic—Early Paleozoic evolution of peri-Gondwanan terranes: Implications for Laurentia-Gondwana connections. *International Journal of Earth Sciences*, **93**, 659–682, https://doi.org/10.1007/s00531-004-0412-9

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M. 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442, https://doi.org/10.1146/annurev.earth.33.092203.122519

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 503–523, https://doi.org/10.1666/08-072R1.1

Pérez-Pinedo, D., McKean, C., Taylor, R.S. and McIlroy, D. 2022. *Charniodiscus* and *Arborea* are separate genera within the Arboreomorpha: Using the holotype of *C. concentricus* to resolve a taxonomic tangle. *Frontiers in Earth Science*, **9**, 785929, https://doi.org/10.3389/feart.2021.785929

Pérez-Pinedo, D., Neville, J.M., Pasinetti, G., McKean, C., Taylor, R. and McIlroy, D. 2023. Frond orientations with independent current indicators demonstrate the reclining rheotropic mode of life of several Ediacaran rangeomorph taxa. *Paleobiology*, **49**, 471–492, https://doi.org/10.1017/pab.2023.2

Pisarevsky, S.A., McCausland, P.J.A., Hodych, J.P., O'Brien, S.J., Tait, J.A. and Murphy, J.B. 2012. Paleomagnetic study of the late Neoproterozoic Bull Arm and Crown Hill formations (Musgravetown Group) of eastern Newfoundland: Implications for Avalonia and West Gondwana paleogeography. *Canadian Journal of Earth Sciences*, **49**, 308–327, https://doi.org/10.1139/e11-045

Ryland, J.S. 1977. Taxes and tropisms of bryozoans. *In*: Woollacott, R.M. and Zimmer, R.L. (eds) *Biology of Bryozoans*. Academic Press, 411–436, https://doi.org/10.1016/B978-0-12-763150-9.50018-0

Seilacher, A. 1964. Biogenic sedimentary structures. *In*: Imbrie, J. and Newell, N. (eds) *Approaches to Paleoecology*. Wiley, 296–316.

Seilacher, A. 1989. Vendozoa: Organismic construction in the Proterozoic biosphere. *Lethaia*, **22**, 229–239, https://doi.org/10.1111/j.1502-3931.1989.tb01332.x

Seilacher, A. 1992. Vendobionta and Psammocorallia: Lost constructions of Precambrian evolution. *Journal of the Geological Society*, **149**, 607–613, https://doi.org/10.1144/gsjgs.149.4.0607

Sharp, A.C., Evans, A.R., Wilson, S.A. and Vickers-Rich, P. 2017. First non-destructive internal imaging of *Rangea*, an icon of complex Ediacaran life. *Precambrian Research*, **229**, 303–308, https://doi.org/10.1016/j.precamres.2017.07.023

Taylor, R.S., Matthews, J.J., Nicholls, R. and McIlroy, D. 2021. A re-assessment of the taxonomy, palaeobiology and taphonomy of the rangeomorph organism *Hapsidophyllas flexibilis* from the Ediacaran of Newfoundland, Canada. *Paläontologische Zeitschrift*, **95**, 187–207, https://doi.org/10.1007/s12542-020-00537-4

Taylor, R.S., Nicholls, R., Neville, J.M. and McIlroy, D. 2023. Morphological variation in the rangeomorph organism *Fractofusus misrai* from the Ediacaran of Newfoundland, Canada. *Geological Magazine*, **160**, 146–166, https://doi.org/10.1017/S0016756822000723

Vickers-Rich, P., Ivantsov, A., Trusler, P.W., Narbonne, G.M., Hall, M., Wilson, S.A., Greentree, C., Fedonkin, M.A., Elliot, D.A., Hoffmann, K.H. and Schneider, G.I.C. 2013. Reconstructing *Rangea*: New discoveries from the Ediacaran of southern Namibia. *Journal of Paleontology*, **87**, 1–15, https://doi.org/10.1666/12-074R.1

Wade, M. 1968. Preservation of soft-bodied animals in Precambrian sandstones at Ediacara, South Australia. *Lethaia*, **1**, 238–267, https://doi.org/10.1111/j.1502-3931.1968.tb01740.x

Waggoner, B. 2003. The Ediacaran biotas in space and time. *Integrative and Comparative Biology*, **43**, 104–113, https://doi.org/10.1093/icb/43.1.104

Walker, J.D. and Geissman, J.W. (compilers). 2022. Geologic Time Scale v.6.0. *Geological Society of America*, https://doi.org/10.1130/2022.CTS006C

CHAPTER 3

A palaeobiological and taxonomic reconsideration of the Ediacaran biota of Upper Island Cove, Conception Bay North, Newfoundland: New taxa and the tops and bottoms of Ediacaran fronds

CHRISTOPHER MCKEAN[1*] AND DUNCAN MCILROY[1]

[1]*Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5, Canada*

[*]*Corresponding author (cmckean@mun.ca)*

PREFACE

A version of this chapter will be submitted to the international journal *Papers in Palaeontology* after submission of this thesis. The systematic palaeontology of the three new Ediacaran taxa described in this chapter does not constitute as an official description as outlined in the International Code of Zoological Nomenclature (fourth edition). As such the names of the new taxa described herein are only used within Chapters 3 and 5, with Chapters 1, 2 and 4 identifying specimens based on current published literature. This chapter was devised by Christopher McKean and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from Duncan McIlroy. Collection and analysis of data was conducted by Christopher McKean. The systematic palaeontology(s) presented in this chapter were developed by Christopher McKean, with input from Duncan McIlroy. All figures were constructed by Christopher McKean. Additional support from those not listed as authors can be found in the acknowledgements at the end of this chapter.

ABSTRACT

In recent years great improvements have been made in our approach to the systematic palaeontology of the Ediacaran biota. The Allison Surface, in Upper Island Cove, Newfoundland, was first discovered and described in 2004. A largely overlooked site, recent work has improved our taphonomic understanding of the unique fossils found at the site, which preserve the upper and lower surfaces of several Ediacaran taxa. By applying up-to-date systematics on 258 fossils from the surface three new species have been described for the first time: *Avalofractus dosomitus* sp. nov., *Kannabuchia artkingii* gen. et sp. nov. and *Corellia washageuis* gen. et sp. nov. *A. dosomitus* is an erect rangeomorph that differs from the type species, *A. abaculus*, due to its acicular first-order branching which emanates from a central stalk. *K. artkingii* is an epifaunal rangeomorph with a differentiated upper and lower surface, this rangeomorph preserves sigmoidal furled/rotated first-order branching with unfurled/rotated second- and third-order branching on both surfaces; however, it has a distinct pronounced midline that is only found on the upper surface of the taxon. *C. washageuis* is the first fully reclined arboreomorph and has a unique U-shaped bedding-parallel stem which has individual arboreomorph frondlets branching off of it, these frondlets would have laid on or within the sediment during life. Alongside the newly described taxa, top and bottom surfaces have been documented for the Ediacaran taxa *Arborea*, *Charnia*, *Charniodiscus* and *Bradgatia* at the Allison Surface, allowing for new insights into the palaeobiology of these classic genera.

KEYWORDS

Taxonomy, palaeobiology, Ediacaran biota, Avalonian Assemblage, Precambrian, *Avalofractus*, *Kannabuchia*, *Corellia*

3.1 INTRODUCTION

The Ediacaran biota is composed of the oldest known morphologically complex macrofossils (Narbonne 2005; Boag *et al*. 2016; Matthews *et al*. 2020). The oldest well-dated Ediacaran biotas come from the Avalonian Terrane of England, Wales and southeastern Newfoundland (Narbonne and Gehling 2003; McIlroy and Horák 2006; Clarke *et al*. 2024); despite similarities in age—and their presence on the same microcontinent—there are significant differences between the two assemblages, with many taxa being endemic to Newfoundland (e.g. *Avalofractus abaculus* (Narbonne *et al*. 2009); *Arborea spinosus* (Laflamme *et al*. 2004; Pérez-Pinedo *et al*. 2022); *Beothukis mistakensis* (Brasier and Antcliffe 2009; McIlroy *et al*. 2022b); and *Fractofusus* spp. (Gehling and Narbonne 2007; Taylor *et al.* 2023)). The more cosmopolitan genera such as *Charnia, Bradgatia* and *Primocandelabrum*—and several other elements of the clades Rangeomorpha and Arboreomorpha—are found in older strata in Newfoundland than they are in their Charnian counterparts in the UK (Noble *et al*. 2015; Matthews *et al*. 2020).

The Allison Surface at Upper Island Cove, located in Conception Bay North on the Avalon Peninsula (Narbonne 2004; Fig. 3.1), is best known for its preservation of small three-dimensional rangeomorph fronds with sub-millimetric detail (Narbonne 2004; Narbonne *et al*. 2009; Brasier *et al*. 2013; McKean *et al*. 2023; Fig. 3.2). Due to their size, the fossils on the Allison Surface were originally interpreted as the partial remains of larger rangeomorph organisms (Narbonne 2004). It is now recognised, however, that the assemblage consists of small specimens of taxa known from elsewhere in the Avalonian Assemblage (Narbonne *et al*. 2009; Brasier *et al*. 2013).

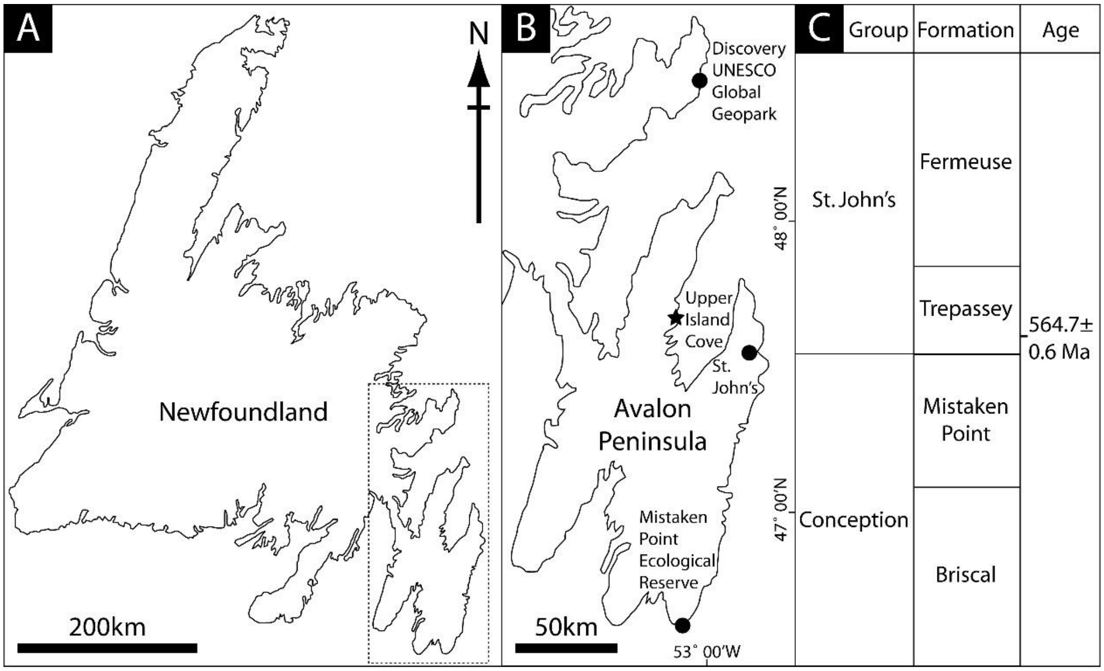


Fig. 3.1 – Map denoting the location of the Upper Island Cove fossil assemblage. A, map of Newfoundland, Canada. B, close-up map of the Avalon Peninsula highlighting the location of the Upper Island Cove assemblage in relation to other Ediacaran fossils localities and the city of St. John's. C, stratigraphic column indicating the formation and age of the Upper Island Cove fossil assemblage (based on Matthews *et al*. 2020)

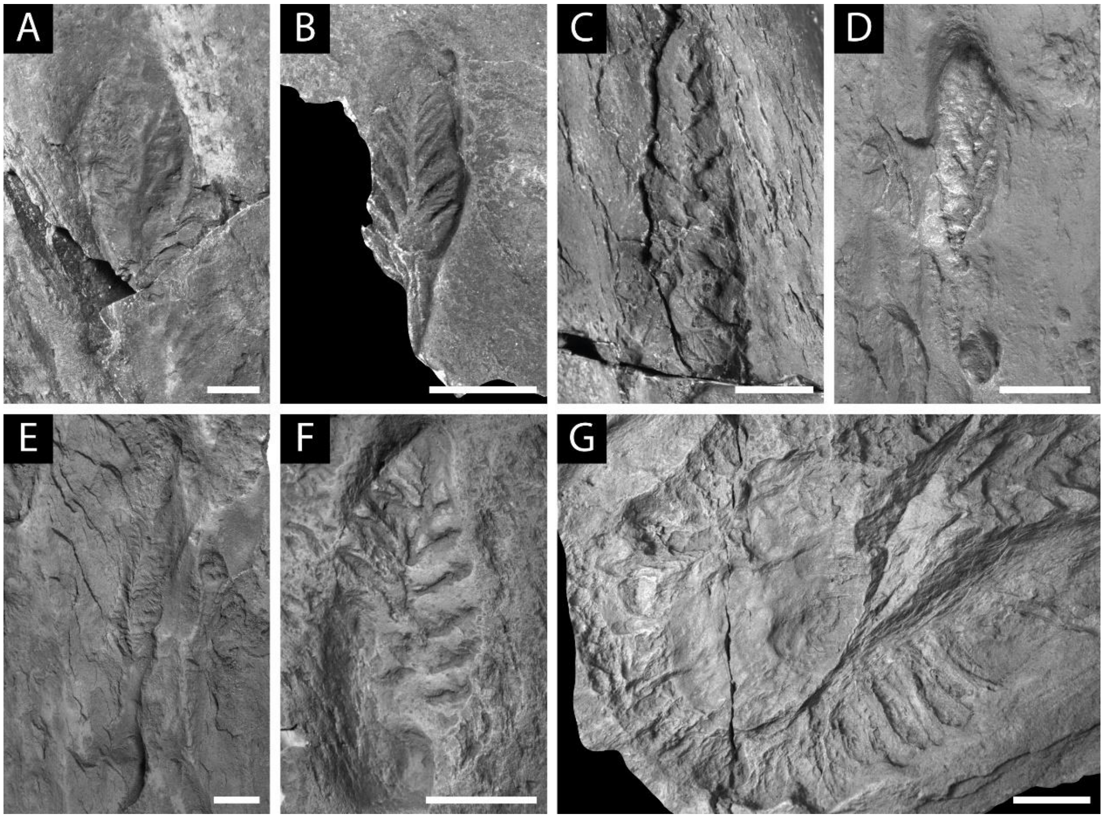


Fig. 3.2 – Selection of taxa from the Upper Island Cove assemblage exhibiting sub-mm detail. A, *Avalofractus abaculus* (NFM F-756). B, *Avalofractus dosomitus* sp. nov. (NFM F-754). C, *Bradgatia* sp. A. (NFM F-757). D, *Charnia gracilis* (cast SB-2021-038iv). E, *Kannabuchia artkingii* gen. et sp. nov. (cast SB-2020-019(b)i). F, *Arborea* sp. (cast SB-2021-041ii-a). G, *Corellia washageuis* gen. et sp. nov. (cast SB-2021-046ii). (scale bars – 1 cm)

The first description of the Allison Surface assemblage inferred that the preserved organisms were juveniles preserved within concretions (Narbonne *et al*. 2009). It was subsequently realised that there are no concretions associated with the fossils, but instead that they are found within erosional scours. This led to the suggestion that the fossils fell into erosional scours in the lee of their stems before being buried by a pyrite-rich T_c sand (Brasier *et al*. 2013). Recent work has demonstrated that the fossils are the partially exhumed remains of previously buried rangeomorph and arboreomorph organisms, that were exposed by erosion in the lee of the stems of a subsequent assemblage of unrelated erect organisms (McKean *et al*. 2023).

The realisation that many of the specimens preserved on the Allison Surface are partially exhumed organisms that had likely already undergone: 1) decay prior to preservation; and 2) erosional modification of the mould of the fossil during exhumation (McKean *et al*. 2023; Fig. 3.3) presents an opportunity to reassess and better understand the taxa present. Other recent advances pertinent to the Allison Surface assemblage since its original discovery and description (Narbonne 2004; Narbonne *et al.* 2009) include: 1) the discovery of over 150 additional specimens (McKean *et al*. 2023); and 2) improved approaches to the systematic description of rangeomorph taxa (Brasier *et al*. 2012). This primarily taxonomic study encompasses all 254 specimens from the main outcrop of the Allison Surface, and four supplementary specimens discovered from an additional outcrop. Such comprehensive taxonomic treatments of assemblages are an important foundation for community-based studies, without which the conclusions are of limited utility (e.g. McIlroy *et al*. 2022a).

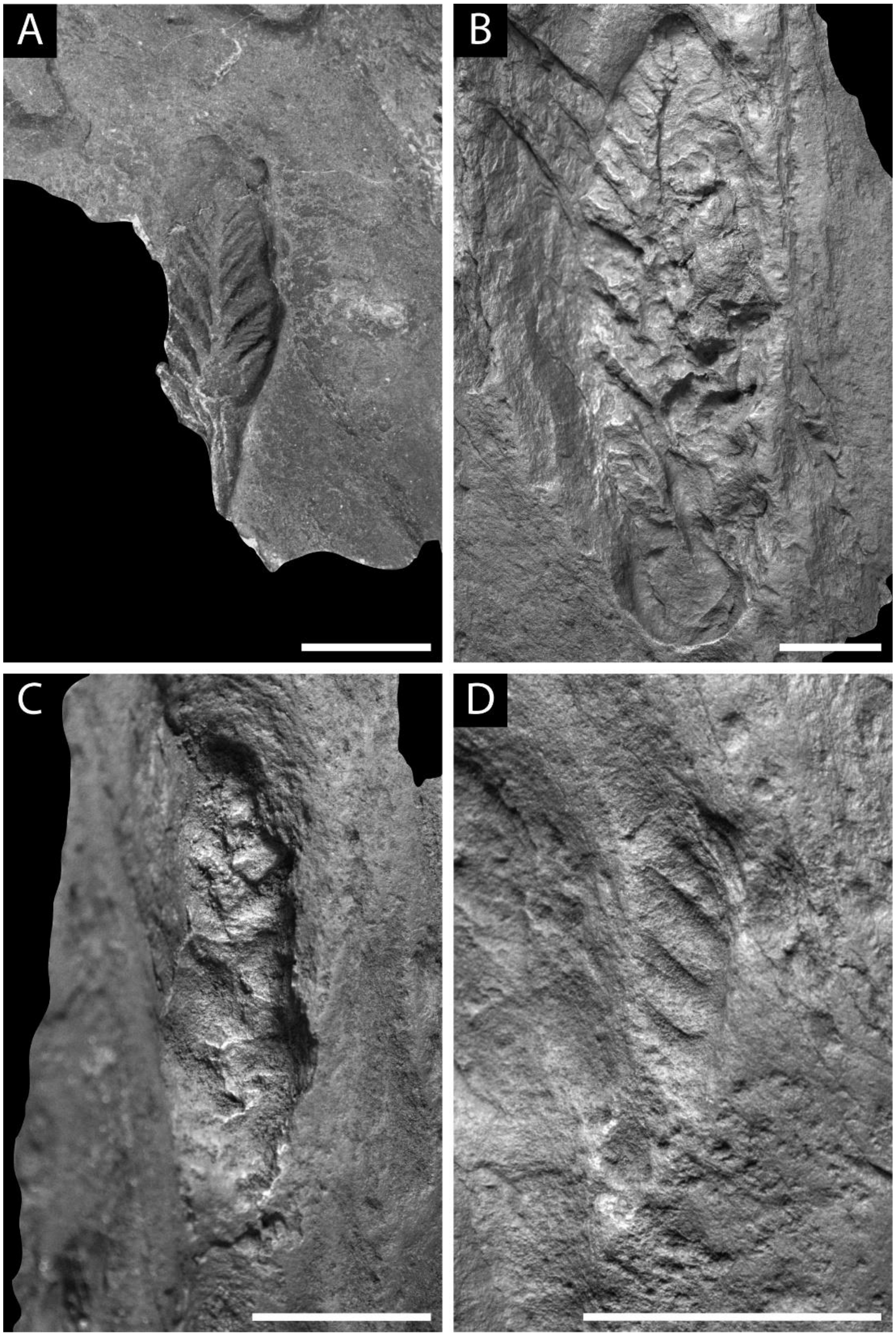


Fig. 3.3 – Fossils from the Upper Island Cove assemblage showing the variation in preservation seen across the locality. A, holotype of *Avalofractus dosomitus* sp. nov., one of the best-preserved specimens from the Upper Island Cove assemblage (NFM F-754). B, partially exhumed *Arborea* sp. showing

positive and negative epirelief preservation (cast SB-2020-020(b)v). C, partially exhumed *Charnia gracilis* preserving only the terminal portion of the specimen with branching continuing beneath the sediment (cast SB-2021-050vi). D, minor preservation of a partially exposed frond (cast SB-2021-053v). (scale bars – 1 cm)

3.2 METHODS

Due to the abundance of fossils in a small area, silicone moulds were made that encompassed the entire fossiliferous portion of the Allison Surface (McKean *et al*. 2024, fig. 8; Fig. 4.8). The Ediacaran fossils found in Newfoundland are most commonly preserved as negative epirelief impressions (Narbonne 2005) and are most easily studied from replica casts created from the silicone moulds in a lab setting (e.g. Figs 3.2D-G, 3.3B-D). All moulds were methodically studied to search for specimens that had not been observed in the field, fossils were each assigned their own number as a suffix to the mould number (see numbers in figure captions; Table B.1). After identifying fossils on the silicone moulds, high quality casts of uniform colour were produced to help recognise subtle structures that can be obscured by colour heterogeneity and poor lighting in the field.

The Rangeomorpha are composed of a frond-like body structure (Narbonne 2004; Brasier *et al*. 2012; Kenchington and Wilby 2017) and are recognised by up to four-orders of self-similar branching (Narbonne *et al*. 2009; Hoyal Cuthill and Conway Morris 2014) based on a basic rangeomorph element in different orientations (Jenkins 1985; Brasier et al. 2012). First- and second-order branching has previously been used for generic assignment of rangeomorph taxa based on relative positioning and appearance of the branches (cf.

Narbonne *et al*. 2009, fig. 12; Brasier *et al*. 2012, figs 1-3). Other key morphological characters such as total number of branches and overall body shape have also been used in taxonomic studies, however, as many of the Allison Surface specimens are only partially preserved (Fig. 3.3), these characteristics cannot be uniformly applied for use in reliable taxonomic diagnosis. As such, this study uses the first- and second-order branching in the rangeomorph specimens to help distinguish between taxa at Upper Island Cove, along with the presence/absence of a stem and third- or higher-order branching where applicable (Table B.2). The presence/absence of third- or higher-order branching varies and is likely to be a taphonomic artefact, as such higher-order branching is not used as taxonomic discriminator herein but is documented.

One of the remarkable features of the Allison Surface fossils is that, in contrast to most specimens from the Ediacaran of Newfoundland, they preserve both the top and bottom of branches as either positive, negative or mixed epirelief moulds (McKean *et al*. 2023). The preservation of frondose taxa at other Ediacaran sites in Newfoundland is most commonly the lower surface of fronds as negative reliefs, with the stems of some taxa being the only evidence for positive relief (e.g. Seilacher 1992; Pérez-Pinedo *et al*. 2022; Pasinetti and McIlroy 2023).

3.3 REVISED TAXONOMY OF THE UPPER ISLAND COVE ASSEMBLAGE

Of the 258 studied specimens from the Allison Surface at Upper Island Cove (Table B.1), most specimens are preserved in negative epirelief (39.53%; 102 fossils), with a similar number of fossils preserved in positive epirelief (31.78%; 82 fossils). A further 72 specimens (27.91%) show a mixture of positive and negative epirelief and have the potential to provide unique insights regarding 3D morphology. It is widely inferred that the top and bottom of rangeomorphs were identical (e.g. Gehling and Narbonne 2007; but see Taylor et al. 2023), however, as the mixed epirelief fossils of the Allison Surface preserve different sides of the organisms it is possible to put this hypothesis to the test (McKean *et al*. 2023). It has been inferred at the Allison Surface that positive epirelief specimens preserve the upper surface and negative epirelief specimens preserve the lower surface of a frond (McKean *et al*. 2023), this is supported by the variation in depth beneath the bedding plane between the two modes of preservation: with positive epirelief fossils being topographically higher than their negative epirelief counterparts. Across this study it was not possible to ascertain the relief of two fossils due to poor preservation.

The assemblage includes 75 specimens that could be assigned to pre-existing genera, which include elements of the Ediacaran biota recognised from across the Avalonian Assemblage (Ford 1958; Boynton and Ford 1995; Flude and Narbonne 2008; Hofmann *et al*. 2008; Narbonne *et al*. 2009; Liu *et al*. 2015) and elsewhere in the world (e.g. Australia (Glaessner and Daily 1959; Nedin and Jenkins 1998; Droser and Gehling 2015), Russia (Glaessner and Wade 1966; Fedonkin *et al*. 2007; Grazhdankin *et al*. 2008) and China (Wang *et al*. 2020; Wu *et al*. 2022)). These 75 specimens include individuals from known species (e.g. *Charnia gracilis* (Wu *et al*. 2022)) and newly recognised morphotypes for classic Ediacaran genera reported herein for the first time. The remaining portion of the assemblage could not be assigned to any previously recognised taxon, with the majority of these fossils being badly degraded/eroded taphomorphs of existing taxa (cf. Liu *et al*. 2011; Antcliffe *et al*.

2014; Matthews *et al*. 2017; McKean *et al*. 2023). Most of these are comparable to iveshediomorphs, in which the morphology preserved is considered to be largely degraded necromass (Liu *et al*. 2011), with others being designated as “insufficiently exhumed fronds” where not enough morphological detail is preserved to allow for an accurate taxonomic diagnosis (McKean *et al*. 2023, fig. 13; Fig. 2.13). Alongside the poorly preserved specimens, 59 well preserved fossils have been described as three new species; *Avalofractus dosomitus* sp. nov., *Kannabuchia artkingii* gen. et sp. nov. and *Corellia washageuis* gen. et sp. non. An overview showing the breakdown of specimens from the Upper Island Cove assemblage into broad categories can be found in the supplementary material (Fig. B.1).

3.3.1 Systematic Palaeontology

Through the analysis and comparison of the abundant fossils found across the Allison Surface we have developed new insights into the taxa preserved at the site. This has allowed for the description of three new taxa, six new morphotypes of classic Ediacaran genera and an updated taxonomic diagnosis for *Avalofractus abaculus*. Each of the three new taxa have been partly named (at either genus or species level) using the Beothuk language: Newfoundland was home to the indigenous Beothuk people prior to the arrival of European colonists. Only a handful of isolated words were recorded from captured individuals in the early 1800s before their extinction. Applicable Beothuk words have been incorporated into the naming of previously described Ediacaran taxa from Newfoundland (e.g. *Beothukis mistakensis* (Brasier and Antcliffe 2009); *Haootia quadriformis* (Liu *et al*. 2014)) to acknowledge and respect the fact that Newfoundland was the traditional territory of the Beothuk.

Clade Rangeomorpha Pflüg 1972

Genus *Avalofractus* Narbonne *et al*. 2009

Type Species— *Avalofractus abaculus* (Narbonne *et al*. 2009) by monotypy.

Emended Generic Diagnosis— Unipolar rangeomorph frond with a basal stem that runs through the centre of the organism. Composed of up to 14 unfurled/displayed first-order branches that are alternately arranged on either side of the central stalk. First-order branches are almost perpendicular to the central stalk at the proximal/basal end of the frond, becoming acute closer to the terminal end of the frond. First-order branches range in length from 0.2 cm to 1.5 cm and taper in length towards the terminal end of the frond. First-order branch width is variable, but length to width ratio is consistent across successive branches. Second-order branches are predominantly unfurled/rotated, with rare alternating unfurled/displayed second-order branches. Rotated third-order branching is rarely preserved.

Remarks— A total of 21 fossils on the Allison Surface have been assigned to the unifoliate genus *Avalofractus*. All specimens are composed of unfurled/displayed first-order branches alternately emanating from a central stem. Two discrete morphotypes have been recognized in *Avalofractus*: 1) specimens with lanceolate, proximally to medially inflated first-order branches that are directly comparable to the holotype of *A*. *abaculus* (Narbonne *et al*. 2009; Fig. 3.4); and 2) specimens with acicular, moderate medial to distally inflated first-order branches that are comparable to the paratype of *A. abaculus* (*Avalofractus dosomitus* sp. nov.; Fig. 3.5). Some additional material could only be determined to generic level (Table B.1). Neither morphotype is considered to be significantly influenced by taphonomy as both morphotypes are preserved in the same positive epirelief preservation. Ecophenotypic variation has also previously been suggested to influence morphological variation within the Ediacaran biota (Liu *et al.* 2016; Hoyal Cuthill and Conway Morris 2017), however, other studies that have addressed morphological variation in the same population treat variation in continuous characteristics as a species-level difference (Kenchington and Wilby 2017). As both species of *Avalofractus* at the Allison Surface are exclusively present within the obstruction scours, and therefore belonged to the same population and were subject to the same environmental factors, we too treat this variation between continuous characteristics in a single population as a species-level difference. Additionally, at least one specimen preserves both the front and back of a first-order lanceolate branch, showing that both sides of the first-order branches preserve the same morphology (Fig. 3.4D), this nullifies the possibility that the two morphotypes are opposite sides of the same taxon and as such they are considered to be separate species herein.

Both morphotypes of *Avalofractus* have previously been reconstructed with a long stem, which comprised up to 50% of the total length of the organism, and a bulbous basal holdfast (Narbonne *et al.* 2009). Most of the structures previously considered to be stems from the Allison Surface (Narbonne *et al.* 2009; Liu *et al.* 2016; Dececchi *et al.* 2017) have more recently been reinterpreted as taphonomic/sedimentological artefacts in the form of obstruction scours (Hawco *et al.* 2020; McIlroy *et al.* 2022b; McKean *et al.*

2023). The remnants of genuine stems can be seen in both morphotypes of *Avalofractus* (Figs 3.4A-B, 3.5A-B, F) though these are proportionally shorter than previously invoked, being cut off just below the basal first-order branches. *Avalofractus* is considered to have been an erect taxon with a short stem (McKean *et al*. 2023), though some other frondose species are inferred to have had a reclining stem (Pérez-Pinedo *et al*. 2022; Pasinetti and McIlroy 2023). Both morphotypes of *Avalofractus* have a central stalk running through the centre of the frond, with first-order branches alternating either side of this structure to give the genus a distinctive glide-plane symmetry (Brasier *et al*. 2012; Figs 3.4, 3.5). Due to this we consider the presence of a central stalk with alternating unfurled/displayed branching a genus-level characteristic in *Avalofractus*.

None of the specimens have a basal holdfast attached to the stem as originally described in Narbonne *et al*. (2009), with the previously documented holdfasts now being recognised as belonging to separate organisms upstream of the fossil, which were responsible for the obstacle scours within which these fronds are found (McKean *et al*. 2023). One specimen of *A*. *dosomitus* has a structure near to the basal portion of the organism which could be seen as evidence for a holdfast structure, however, it could also be interpreted as the base of the frond or as a poorly preserved first-order branch (Fig. 3.5F). As such, while the presence of a basal holdfast cannot be ruled out, specimens with this structure present will need to be identified for this to be included in the generic diagnosis.

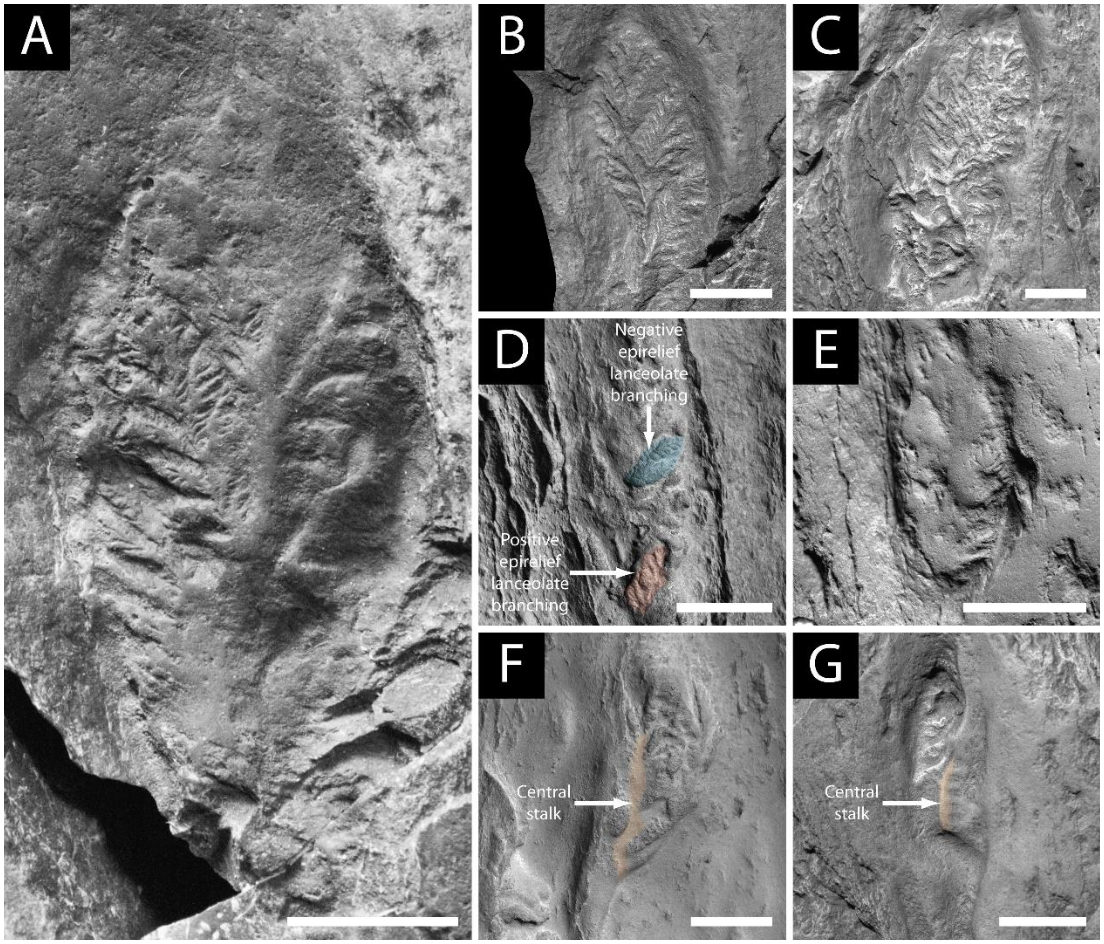


Fig. 3.4 – *Avalofractus abaculus* specimens. A, holotype of *A*. *abaculus* (NFM F-756). B, paratype of *A*. *abaculus* (cast SB-2022-059i). C, poorly preserved specimen showing tousled branching (cast SB-2021-051vii). D, mixed-relief specimen preserving lanceolate first-order branching on either side of the frond (positive epirelief = orange, negative epirelief = light blue) (cast SB-2021-042vii-b). E, partial specimen preserving the tip of a first-order branch (cast SB-2021-045i). F-G, partial specimens exhibiting the central stalk (orange) (casts SB-2021-043x (F), SB-2021-043iii (G)). (scale bars – 1 cm)

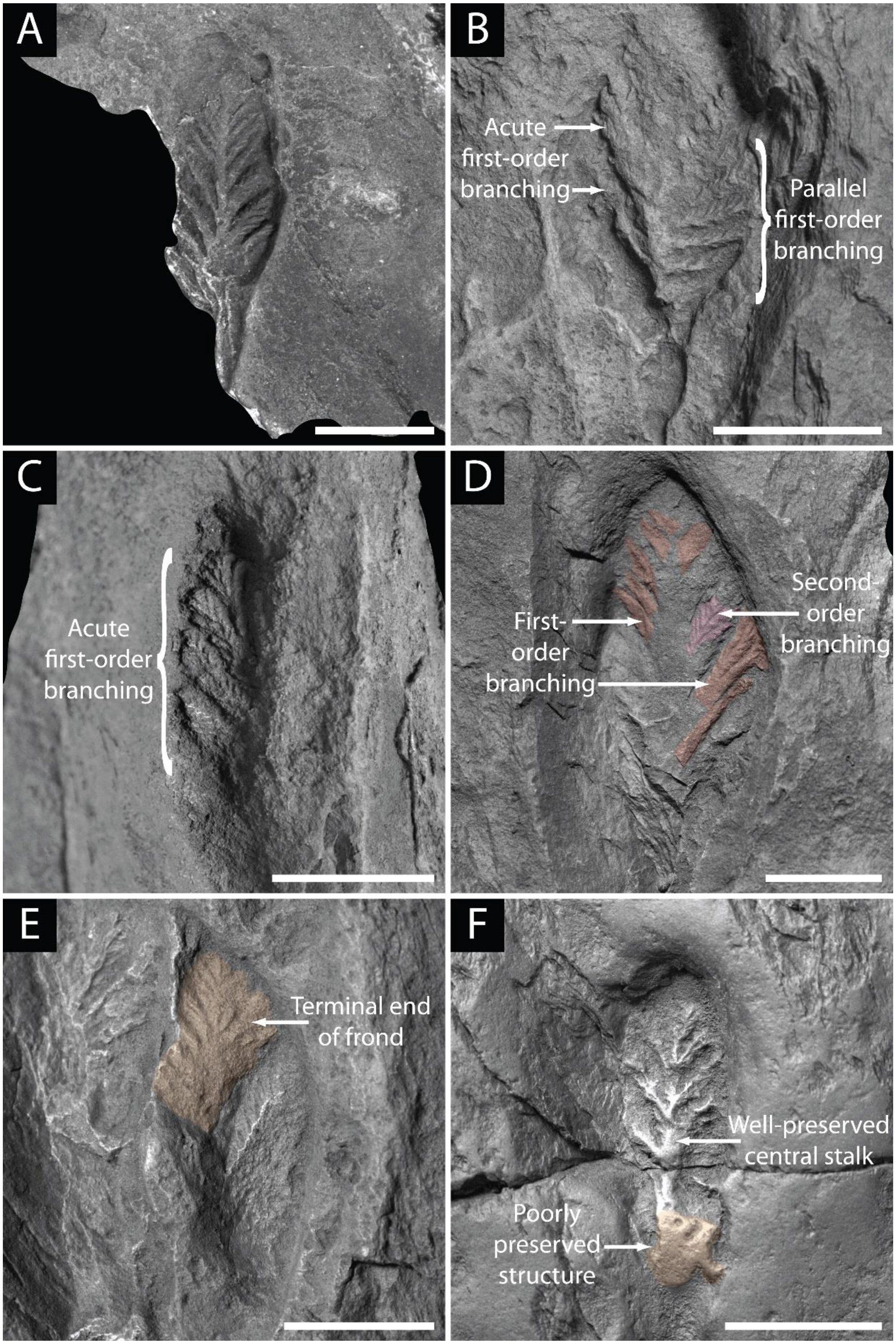

A
B
Acute
first-order
branching
Parallel
first-order
branching
C
Acute
first-order
branching
D
First-
order
branching
Second-
order
branching
E
Terminal end
of frond
F
Well-preserved
central stalk
Poorly
preserved
structure

Fig. 3.5 – *Avalofractus dosomitus* sp. nov. specimens. A, holotype of *A. dosomitus* (NFM F-754). B, paratype of *A. dosomitus* showing acute (left) and parallel (right) first-order branches to the central stalk (cast SB-2021-053ix). C, paratype of *A. dosomitus* with well-preserved first- and second-order branches (cast SB-2022-062v). D, largest specimen of *A. dosomitus* highlighting first-order (red) and second-order branches showcasing the chevron-like arrangement (pink), note the central stalk in this specimen is not preserved (cast SB-2022-061vi). E, specimen preserving the terminal end of *A. dosomitus* (orange) (cast SB-2020-028vii-b). F, specimen with little branching preserved, but shows clear preservation of the central stalk and basal structure (orange) (cast SB-2022-064ii). (scale bars – 1 cm)

Avalofractus abaculus Narbonne *et al*. 2009

Figs 3.2A, 3.4A-G

2004	Long-stemmed rangeomorph frond	Narbonne, fig. 3a.
2008a	Long-stemmed rangeomorph	Laflamme and Narbonne, fig. 4.5.
2009	*Avalofractus abaculus*	Narbonne *et al*., fig. 3.3-6.
2014	*Avalofractus*	Laflamme, fig. 1.1-2.
2023	*Avalofractus abaculus*	McKean *et al*., fig. 2a.
2024	*Avalofractus abaculus*	McKean *et al*., fig. 10a-c.

Type Material— The holotype (NFM F-756; Fig. 3.4A) is housed at The Rooms, provincial museum of Newfoundland and Labrador; the paratype remains in the field, but a plastotype is to be accessioned to The Rooms (SB-2022-059i; Fig. 3.4B).

Material— Eleven specimens are known from the Allison Surface at Upper Island Cove, ten of which remain *in situ*; the extraction of the holotype pre-dates our work.

Emended Specific Diagnosis— Unipolar rangeomorph frond with a stalk that runs through the centre of the organism, terminating in a basal stem. Composed of approximately eight unfurled/displayed lanceolate first-order branches. First-order branches are alternately arranged on either side of the central stalk at acute angles. Distal first-order branches overlap more basal branches, with first-order branch length ranging from 0.4 cm to 1.5 cm, tapering in length towards the terminal end of the frond. First-order branches show proximal to medial inflation, width ranges from 0.2 cm to 0.75 cm with the length to width ratio of 2:1 being consistent across successive branches. Up to 13 second-order branches can be found per first-order branch, these are predominantly unfurled/rotated and rarely unfurled/displayed. Rotated third-order branches are sometimes preserved.

Description— *Avalofractus abaculus* has lanceolate, medially-inflated first-order branches (Fig. 3.4A-C). The holotype of *A. abaculus* was badly damaged during its removal from the locality (see McKean *et al*. 2024, fig. 10a-c; Fig. 4.10A-C), it is 4.9 cm in length and composed of at least four first-order branches (Narbonne *et al*. 2009), however, only one of these branches preserves second- or higher-order detail (Fig. 3.4A). The stalk is clearly preserved in the axial portion of most fronds, and in many first-order branches (Fig. 3.4F-G). The newly designated paratype has three complete lanceolate first-order branches on the right side of the central stalk at an acute angle directed towards the terminal end of the frond, with unfurled branching across all orders (Fig. 3.4B). Both the holotype and paratype of *A. abaculus* show the basal-most first-order branches being overlapped by the terminal branches, which reduce in size towards the terminal end of the organism (Fig. 3.4A-B). Second-order branches are predominantly rotated with distal inflation, and third-order branches are rotated but with no recognisable inflation. Up to 13 second-order branches can be seen on the right basal first-order branch of the *A. abaculus* paratype (Fig. 3.4B), with other first-order branches preserving less (the one well preserved branch on the *A. abaculus* holotype preserves nine second-order branches; Fig. 3.4A). Second-order branches appear acicular towards the proximal end of the first-order branch and become increasingly lanceolate at the distal end of the first-order branch (Fig. 3.4B). Third-order branches, where preserved, are seen in an en-echelon arrangement (Fig. 3.4A-B). Many of the poorly preserved *A. abaculus* specimens only preserve details in the tip of the first-order branches (Fig. 3.4E). All *A. abaculus* specimens have positive epirelief preservation, though some have a combination of positive and negative epirelief (Fig. 3.4C-D; Table B.1). The negative epirelief in these specimens is largely featureless, however one specimen does preserve a partial first-order branch which is lanceolate and composed of unfurled/rotated second-order branches (Fig. 3.4D).

Remarks— The holotype of *A. abaculus* was damaged during or after extraction, by comparison of the photograph in the type description (Narbonne *et al.* 2009; also see Laflamme 2014, fig. 1.1-2) versus the accessioned holotype (cf. McKean *et al.* 2023, fig. 2a; McKean *et al*. 2024, fig. 10a-c; Figs 2.2A, 4.10A-C). The lack of third-order branching in some specimens could either be due to both sides of the organism being dissimilar, which is known from other Ediacaran frondose taxa (Dunn *et al*. 2019a, 2019b; Butterfield 2022; Taylor *et al*. 2023), or partial decay prior to casting in the erosional scour (McKean *et al*. 2023). One mixed epirelief specimen preserves both sides of a first-order branch; despite both the positive and negative epirelief branches being partial, both can be inferred to be lanceolate in shape with unfurled/rotated second-order branches (Fig. 3.4D). This indicates that *A*. *abaculus* had a similar rangeomorph branching morphology on both the front and back of the frond to at least the second-order (Gehling and Narbonne 2007). The rangeomorph branching in erect fronds likely aided in either feeding strategies, such as suspension feeding or osmotrophy (Jenkins 1985; Laflamme *et al*. 2009; Butterfield 2022), or as recently suggested acted as gas exchange structures for the rangeomorph organism (Darroch *et al*. 2023). Regardless of the function both sides of the organism would likely have the same function, explaining why both sides of *A*. *abaculus* have similar branching (Fig. 3.4D). It is possible that the branches in *Avalofractus* could be considered as a functional analogue to the polyps seen at the tips of modern day pennatulaceans, which are adapted for multiple functions including gas exchange and feeding (Williams *et al*. 2012).

A poorly preserved *A*. *abaculus* (Fig. 3.4C) is of note as—despite preserving very little gross-scale morphological data due to degradation of the frond—it can be seen to have tousled first-order branches (cf. Taylor *et al*. 2023). This is consistent with *Avalofractus* being an erect taxon (cf. Narbonne *et al*. 2009; McKean *et al*. 2023), which collapsed and was buried within the T_d silt prior to fossilization. This different mode of preservation to the reclining rangeomorphs helps to explain why most *A*. *abaculus* are poorly preserved. It also suggests that the first-order branches of *Avalofractus* were independent from one another and moveable, perhaps only passively.

Avalofractus dosomitus sp. nov.

Figs 3.2B, 3.3A, 3.5A-F

2004	Isolated rangeomorph frondlet	Narbonne, fig. 2a-b.
2005	Rangeomorph element	Narbonne, fig. 2c.
2007	Rangeomorph fronds	Ichaso *et al*., fig. 3c.
2007	Rangeomorph module	Narbonne *et al*., fig. 75.
2008a	*Rangea*-type rangeomorph	Laflamme and Narbonne, fig. 1c.
2008a	Rangeomorph element	Laflamme and Narbonne, fig. 4.1.
2008b	Rangeomorph frond	Laflamme and Narbonne, fig. 2.4.
2009	*Avalofractus abaculus*	Narbonne *et al*., fig. 3.1-2.
2011	*Avalofractus*	Erwin *et al*., fig. 2g.
2012	*Avalofractus abaculus*	Brasier *et al*., figs 6a, 8a.
2013	*Avalofractus abaculus*	Laflamme *et al*., fig. 1.1-2.
2014	*Avalofractus abaculus*	Ghisalberti *et al*., fig. 1c-d.
2014	*Avalofractus abaculus*	Hoyal Cuthill and Conway Morris, fig. 2a.
2015	*Avalofractus abaculus*	Briggs, fig. 1a.
2015	*Avalofractus abaculus*	Liu and Conliffe, fig. 6g.
2015	*Avalofractus abaculus*	Liu *et al*., fig. 2a.
2016	*Avalofractus*	Mason and Narbonne, fig. 6.1.
2017	*Avalofractus abaculus*	Hoyal Cuthill and Conway Morris, Fig. 1a.
2017	*Avalofractus abaculus*	Liu *et al*., figs. A8g, B3a.
2018	*Avalofractus*	Darroch *et al*., fig. i.

2018	*Avalofractus abaculus*	Landing *et al*., fig. 3a.
2021	*Avalofractus abaculus*	Dunn *et al*., fig. 5d.
2023	*Avalofractus abaculus*	McKean *et al*., fig. 3f.
2024	*Avalofractus abaculus*	McKean *et al*., figs 2b, 10d-e.

Type Material— The holotype (NFM F-754; Fig. 3.5A) is housed at The Rooms, provincial museum of Newfoundland and Labrador; the two paratypes remain in the field, but a plastotype of each is to be accessioned to The Rooms (casts SB-2021-053ix, SB-2022-062v; Fig. 3.5B-C).

Material—Eight specimens are known from the Allison Surface at Upper Island Cove, seven of which remain *in situ*; the extraction of the holotype pre-dates our work.

Etymology— *dosomitus* is a Latinisation of the Beothuk word for pin—"dosomite"—in recognition of the acicular, pin-like shape of the first-order branches.

Specific Diagnosis— Unipolar rangeomorph frond with a stalk that runs through the centre of the organism, terminating in a basal stem. Composed of up to 14 unfurled/displayed acicular first-order branches. First-order branches are alternately arranged on either side of the central stalk; they are perpendicular at the basal end of the frond but at an acute angle close to the terminal end of the frond. First-order branches are clearly separate from one-another with no overlap; these first-order branches range in length from 0.2 cm to 0.9 cm, tapering in length towards the terminal end of the frond. First-order branches show moderate medial to distal inflation or no inflation; width ranges from <0.1 cm to 0.3 cm with the length to width ratio of 3:1 being consistent across successive branches. Up to 11 second-order branches can be found per first-order branch and, like first-order branches, are separate from one another. Second-order branches are predominantly unfurled/rotated, but rarely unfurled/displayed, and are arranged en-echelon. Rotated third-order branches are sometimes preserved.

Description— *Avalofractus dosomitus* has acicular first-order branches which show slight distal inflation (Fig. 3.5A-D) or no inflation (Fig. 3.5A-B, E), with the holotype preserving both types of inflation (Fig. 3.5A). The holotype is the best-preserved specimen of this taxon (Fig. 3.5A), with other specimens only being partially preserved but showing clear morphological similarities in first- and higher-order branching allowing them to be assigned to the taxon (Fig. 3.5B-F). The central stalk running through the centre of *A. dosomitus* is preserved in the holotype, paratype and one other specimen and can be seen to run from the base to tip of the organism (Fig. 3.5A-B, F). The holotype of *A. dosomitus* is 1.75 cm in length and composed of 15 acicular unfurled/displayed first-order branches, with up to 10 unfurled/rotated second-order branches per first-order branch (Fig. 3.5A). Only one other specimen preserves a high number of second-order branches per first-order branch (n. 11; Fig. 3.5D). The holotype and most other specimens exhibit unfurled/rotated second-order branches (Fig. 3.5A, C-E), with only the paratype exhibiting any evidence for unfurled/displayed second-order branches (Fig. 3.5B). All specimens show first-order branches that do not overlap with their neighbouring branches and are clearly distinct from one another (Fig. 3.5). Although not overlapping, first-order branches are found in close-proximity to their neighbouring branches in most specimens (Fig. 3.5A, C-E), with the holotype and paratype also showing first-order branches that have clear separation from the neighbouring branches (Fig. 3.5A-B, F). All specimens have the largest first-order branches at the basal part of the frond, with the size of the branching tapering towards the terminal end of the organism (Fig. 3.5). Aside from one of the paratypes (Fig. 3.5B), all specimens have their first-order branches exclusively at an acute angle to the central stalk oriented towards the terminal end of the frond (Fig. 3.5). The paratype has three first-order branches orientated perpendicular to the central stalk on the right side of the frond, with partial first-order branches on the left side being orientated at an acute angle distally (Fig. 3.5B).

The second-order branches of *Avalofractus dosomitus* are acicular and predominantly unfurled/rotated (Fig. 3.5A, C-E), with rare unfurled/displayed branching in the paratype (Fig. 3.5B). Second-order branches show predominantly no inflation (Fig. 3.5A-E), however minor medial inflation in the holotype (Fig. 3.5A) and minor distal inflation in the paratype is noted in some branches (Fig. 3.5B). Third-order branching is rare, but where preserved is furled/rotated (Fig. 3.5C).

Remarks— The holotype of *Avalofractus dosomitus* (Fig. 3.5A) is the best preserved and most commonly figured specimen from the genus. The holotype of *A. dosomitus* was first described as a partial 'frondlet'—synonymous with first-order branch in modern parlance (Brasier *et al.* 2012)—of a larger specimen (Narbonne 2004). The specimen was then redescribed by Narbonne *et al.* (2009) as a nearly perfectly preserved juvenile specimen of *A. abaculus*. The *A. dosomitus* morphotype is known to be up to 2.5 cm in length (Fig. 3.5D), in comparison the paratype of *A. abaculus* is just under 3 cm in length (Fig. 3.4B). Therefore *A. dosomitus* is not a juvenile form of *A. abaculus*, but its own taxon. Additionally, both the branch shape and branch architecture of *A. dosomitus* are different from that of the medially inflated lanceolate *A. abaculus* (Fig. 3.4), as the branches of this new taxon are clearly acicular with no or little inflation (Fig. 3.5).

The first-order branches of *A. dosomitus* are independent from their neighbouring branches and are perpendicular (Fig. 3.5B) to acute (Fig. 3.5A, D) angles relative to the midline, suggesting a similar level of flexibility to that seen in *A. abaculus*. The second-order branching is arranged in a chevron-like style (Fig. 3.5B-D), similar to the arrangement of some of the second- and third-order branches in *A. abaculus* (Fig. 3.4A-B). Third-order branching is preserved in a single specimen (Fig. 3.5C), but this appears to be detail on the surface of second-order branches, perhaps to increase the surface area to volume ratio for feeding (Dufour and McIlroy 2017; McIlroy *et al*. 2021) and is not thought to constitute a higher order of branch as envisioned previously (Hoyal-Cuthill and Conway Morris 2014).

The genus *Avalofractus* is predominantly known from the Allison Surface, but specimens have also been recognised from the Mistaken Point Ecological Reserve (Mason and Narbonne 2016). These specimens preserve the same acicular first-order branching as *A. dosomitus* (Mason and Narbonne 2016, fig. 6.1; Fig. 3.5) and have therefore been recognised as such in this study. Not only does this increase the spatiotemporal range of the new taxon to older, deeper-water communities within the Avalonian Assemblage (Wood *et al*. 2003; Ichaso *et al*. 2007; Mason and Narbonne 2016; Matthews *et al*. 2020), but also highlights *A. abaculus* as an endemic species to Upper Island Cove.

Clade Rangeomorpha Pflüg 1972

Genus *Bradgatia* Boynton and Ford 1995

Type Species— *Bradgatia linfordensis* (Boynton and Ford 1995) by monotypy.

Generic Diagnosis— "Frond unipolar, with subsidiary growth tips present in mature specimens, at the distal ends of large first-order branches. First- to second-order branches tend to be distally inflated. First-order branches comprise two rows of second-order branches with the freedom to overlap and rotate. First-order branches arranged in radiating series, alternating along a furled central axis. Towards their bases (and often in juvenile stages), first- to second-order branches typically furled and sometimes rotated, but rangeomorph elements become progressively displayed and unfurled in the direction of growth. A basal disc is not confirmed" (emended diagnosis of Brasier *et al*. 2012).

Remarks— The multifoliate genus *Bradgatia* (Boynton and Ford 1995; Flude and Narbonne 2008; Fig. 3.6) is moderately abundant on the Allison Surface (26 fossils, approx. 10% of the biota). The genus *Bradgatia* needs revision with a number of morphotypes having been loosely mentioned in the literature, with the type species being seldom mentioned in the Newfoundland sections in preference to the informal moniker 'Cabbage *Bradgatia*' (Flude and Narbonne 2008). The material presented here does little to clarify those issues.

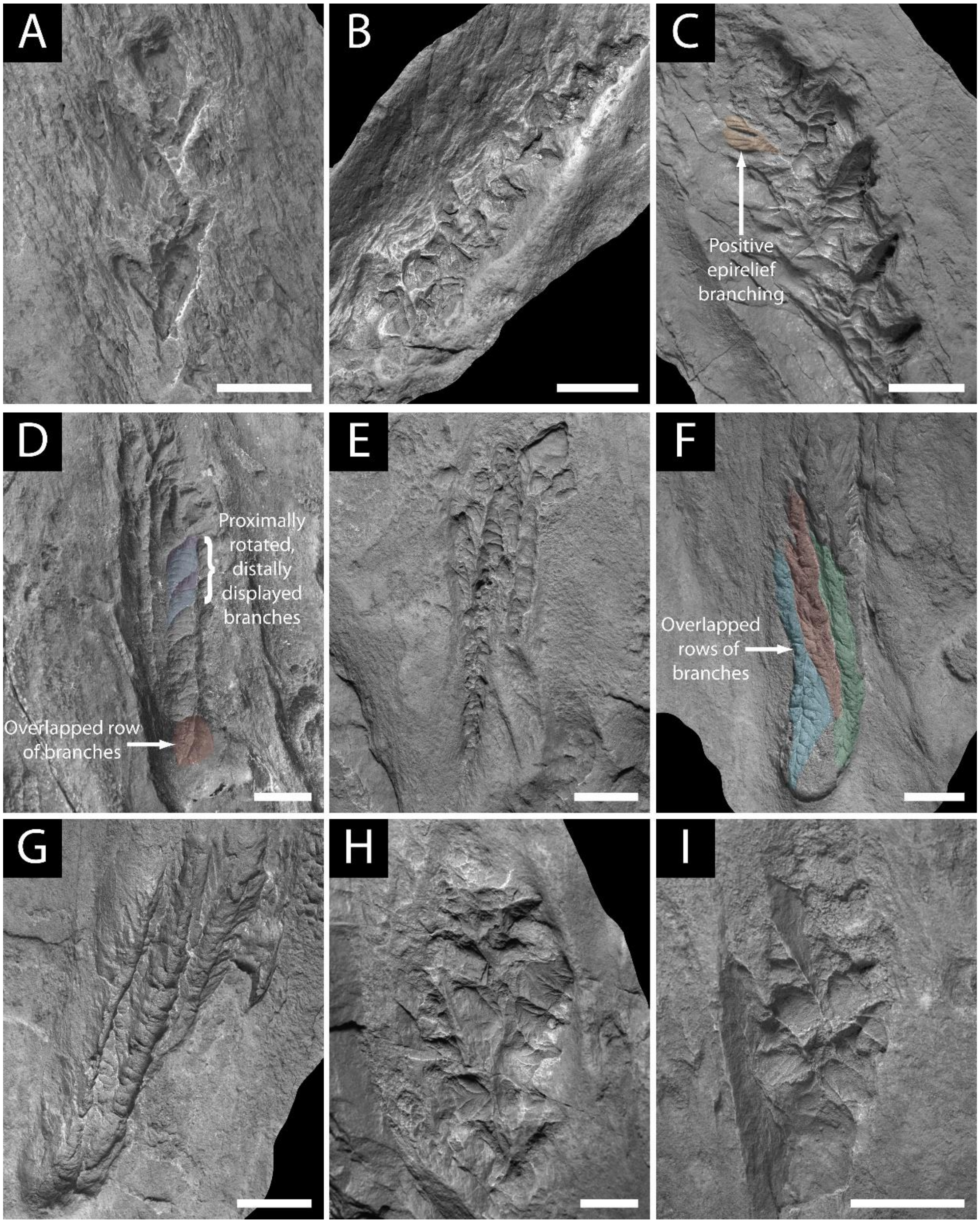


Fig. 3.6 – *Bradgatia* sp. specimens. A-B, *Bradgatia* sp. A. specimens showing clear arboriform outline in shallow scours (casts SB-2021-041i (A), SB-2021-050viii (B)). C, *Bradgatia* sp. A. specimen with branching appearing on vertical edges of the scour and preserving the only known example of upper surface branching seen in the genus (orange) (cast SB-2021-052i). D-G, *Bradgatia* sp. B. showing the

‘I-shape’ morphology (Flude and Narbonne 2008) and multifoliate branching (NFM F-755 (D); casts SB-2021-053iv (E), SB-2022-058i (F), SB-2022-058iii (G)). H-I, *Bradgatia* sp. C. (casts SB-2021-050v (H), SB-2022-062vi (I)). (scale bars – 1 cm)

The three morphotypes detailed herein exhibit rows of distally inflated first-order branches that are predominantly unfurled/displayed, with evidence for overlapping of branches, allowing for their generic assignment to *Bradgatia* (Boynton and Ford 1995; Brasier *et al*. 2012). Several of the *Bradgatia* specimens preserved on the surface have proximally furled/rotated first-order branches that become progressively more unfurled/displayed towards the distal tip (Fig. 3.6), similar in architecture to the rangeomorph *Beothukis mistakensis* known from elsewhere in the Newfoundland assemblage (McIlroy *et al*. 2022b). Unlike most unifoliate taxa, the branching in several of the *Bradgatia* specimens are not current orientated (e.g. McKean et al. 2023, fig. 7b; Figs 2.7B, 3.2B, 3.6H); this supports the hypothesis presented in other studies that some species of *Bradgatia* were epibenthic recliners (McIlroy et al. 2022a; Pérez-Pinedo *et al*. 2023). Several specimens have distally upward curved branches oriented at a high angle to bedding suggesting that *Bradgatia* grew quasi-infaunally (Fig. 3.6C, H), with the distal portions of its branches exposed to the water to allow for circulation of oxygen to the lower surface of the organism (cf. McIlroy *et al*. 2021).

Bradgatia sp. A.

Figs 3.2C, 3.6A-C

2004	Short-stemmed rangeomorph frond	Narbonne, fig. 3b-c.
2008a	Short-stemmed rangeomorph	Laflamme and Narbonne, fig. 4.4.
2008b	Rangeomorph frond	Laflamme and Narbonne, fig. 2.5.
2009	*Beothukis mistakensis*	Narbonne *et al*., fig. 4.1-4.
2022b	[non] *Beothukis mistakensis*	McIlroy *et al*., fig. 2c.
2023	*Bradgatia* sp.	McKean *et al*., fig. 7b.
2024	cf. *Bradgatia* sp.	McKean *et al*., fig. 2a.

Material— Fourteen specimens are known from the Allison Surface at Upper Island Cove, 13 of which remain *in situ*; the extraction of NFM F-757 pre-dates our work.

Description— *Bradgatia* sp. A. is composed of at least two rows of rangeomorph branches, the high angle of the lower surface branches in relation to the bedding give the specimens an arboriform outline in the scours (Fig. 3.6A-C). Specimens are partially exhumed fronds that have been found up to 4.8 cm in length (Fig. 3.6B-C). The majority of specimens exclusively preserve the lower surface of the organism (Fig. 3.6; Table B.1), however, a single mixed epirelief specimen preserves the upper surface of the organism (Fig. 3.6C). This upper surface preserves first- and second-order branching and is furled/rotated at both orders. Upper surface branches are found exclusively orientated in the direction of the palaeocurrent (Fig. 3.6A-C). Lower surface branching is distally inflated, unfurled/displayed at the first-order, with specimens having branches oriented both in the direction of the palaeocurrent and reversed to it (McKean *et al*. 2023; Fig. 3.2B).

On the lower surface *Bradgatia* sp. A. rows can be made up of >10 first-order branches (Fig. 3.6B), with up to ten second-order branches per first-order branch (Fig. 3.6C). Second-order branches at the distal tip of some first-order branches bifurcate and develop into additional first-order branches (Fig. 3.6C). Second-order branches across both initial and secondary first-order branches are unfurled/rotated, with up to fourth-order branching being visible on the best-preserved specimens (Fig. 3.6C). Many of the less well-preserved specimens exhibit little discernible branching detail and are only identifiable by their arboriform outline (Fig. 3.6B).

Remarks— *Bradgatia* sp. A. differentiates from the other two morphotypes in that only two rows of branching can be observed (Fig. 3.6A-C). *Bradgatia* sp. B. and sp. C. are both composed of multiple rows of branches (Fig. 3.6D-I), as seen in *Bradgatia* known from elsewhere in the Avalonian Assemblage (Flude and Narbonne 2008; Brasier *et al*. 2012; Liu *et al*. 2016, fig. 2). It is therefore likely that *Bradgatia* sp. A. also is a multifoliate frond. However, possibly due to partial exposure during scouring (McKean *et al*. 2023), all *Bradgatia* sp. A. specimens discovered on the Allison Surface thus far are noted to only preserve two rows of rangeomorph branching and the taxon has therefore been treated as such (Fig. 3.6A-C).

Bradgatia sp. A. is the only taxon within the genus to preserve positive epirelief branching (Fig. 3.6C), however, this shows that at least one species had differentiated upper and lower surfaces as has been shown for another reclined rangeomorph found in Newfoundland: *Fractofusus* (Taylor *et al*. 2023). The dissimilar upper and lower surface of reclining *Bradgatia* is consistent with the upper and lower surface of recliners having different functions, with the more fractal-like lower surface being adapted to hosting symbionts and the upper surface being adapted for either oxygen/nutrient capture/excretion (Dufour and McIlroy 2017; McIlroy *et al.* 2021, 2022b; Taylor *et al*. 2023; Pérez-Pinedo *et al.* 2024). The steep angled lower surface of *Bradgatia* sp. A. also suggests that the taxon may have had a quasi-infaunal lifestyle, as suggested for other Ediacaran taxa (Grazhdankin 2004; Grazhdankin and Seilacher 2005; McIlroy *et al*. 2021; Taylor *et al*. 2023), with only the tips of the branches being exposed above the sediment. The angled, unfurled/displayed first-order branches with unfurled/rotated second-order branches also bear a resemblance to the *Bradgatia* sp. known from the Rawnsley Quartzite, Flinders Ranges, South Australia (Droser and Gehling 2015, fig. 1e: Fig 3.6C).

Bradgatia sp. B.

Fig. 3.6D-G

2004	Plumose rangeomorph	Narbonne, fig. 2c-d.
2008	*Bradgatia*	Flude and Narbonne, fig. 4.
2008a	Plumose rangeomorph frond	Laflamme and Narbonne, fig. 4.3.
2013	*Bradgatia* sp.	Brasier *et al*., fig. 1e-g, 9e.
2023	‘I-shaped’ *Bradgatia* sp.	McKean *et al*., fig. 2b.

Material— Nine specimens are known from the Allison Surface at Upper Island Cove, eight of which remain *in situ*; the extraction of NFM F-755 pre-dates our work.

Description— *Bradgatia* sp. B. is a multifoliate frond composed of six or more rows of parallel first-order rangeomorph branches, occurring in pairs that are joined by a concealed midline (Fig. 3.6D, F). Paired rows of branches can be seen to overlap other paired rows, most commonly occurring at the basal/down current section of the organism, with overlapped branches being crosscut entirely and preserving no further details (Fig. 3.6F). These specimens exclusively preserve the lower surface of the organism (Table B.1) which are up to approximately 6 cm in length, with their appearance within the scours giving them a distinct 'I-shaped' appearance (cf. Flude and Narbonne 2008). Per row there are approximately eight unfurled, sigmoidal first-order branches, with proximal rotation that becomes displayed towards the distal margins of the individual branches (Fig. 3.6D). Up to eight distally inflated second-order branches are seen per first-order branch, these branches are unfurled/rotated with distal inflation and are orientated perpendicular to the concealed midline in each paired row (Fig. 3.6D-E). Unfurled/rotated third-order branching is visible in some *Bradgatia* sp. B. specimens and is perpendicular to the second-order branches (Fig. 3.6E-F). Most branching in *Bradgatia* sp. B. is orientated in the direction of the palaeocurrent, however, the most terminal paired rows show evidence for branching reversed in direction relative to the palaeocurrent (Fig. 3.6D, F).

Remarks— *Bradgatia* sp. B. is the previously documented 'I-shaped' *Bradgatia* discussed in Flude and Narbonne (2008), this shape is likely a result of scour exhumation preferentially removing the overlying sediment with the paired rows of first-order branches that are orientated into a similar orientation to the palaeocurrent (McKean *et al*. 2023, fig. 4; Fig. 2.4). Fossils from this species of *Bradgatia* best show the beothukid-like branching noted from the Allison Surface specimens (*sensu* McIlroy *et al*. 2022b): first-order branches can be seen to be rotated proximally close to the midline and become progressively displayed towards the distal tips of the branches (Fig. 3.6D), this gives support to the three-dimensional structure of rangeomorph units as put forward in Brasier *et al*. (2012). This species of *Bradgatia*, in addition to *Bradgatia* sp. C., is preserved exclusively in negative epirelief, suggesting that much of the decayed/decaying tissues were removed during the scouring process (McKean et al. 2023, figs 10, 11; Figs 2.10, 2.11). The organic material had likely degraded due to decay and necrosis prior to exhumation (cf. Darroch et al. 2012; Hancy and Antcliffe 2020). Despite *Bradgatia* being a common genus on the Allison Surface, it is worth noting that many *Bradgatia* sp. B. specimens are found in close proximity to one another (e.g. specimens SB-2022-058i (Fig. 3.6F) and SB-2022-058iii (Fig. 3.6G)). Elsewhere in the Avalonian Assemblage *Bradgatia* is known to reach sizes in excess of 10s of cm (Boynton and Ford 1995, figs 3, 4, 7, 9; Flude and Narbonne 2008, fig. 3; Liu *et al*. 2016, fig. 2). *Bradgatia* sp. B. shows similar overlapping, unfurled, sigmoidal first-order branches to tentative *Bradgatia* specimens discovered near Salient Mountain in British Columbia, which are also >10 cm in size (Hofmann and Mountjoy 2010, fig. 5a). It thus cannot be ruled out that some of the *Bradgatia* found on the Allison Surface may be multiple adjacent exposures of the same buried specimen. While all specimens do taper to a proximal point this can be explained as a taphonomic artefact caused by scour morphology (McKean *et al*. 2023), with some of the *Bradgatia* specimens being clearly crosscut by the scours as seen by the branching in the most terminal section of the scours (Fig. 3.6D, F). The possibility of a single organism presenting itself as multiple specimens should be taken into consideration for palaeoecological studies that focus on species abundance (e.g. Clapham *et al*. 2003).

Bradgatia sp. C.

Fig. 3.6H-I

Material— Three *in situ* specimens are known from the Allison Surface at Upper Island Cove.

Description— *Bradgatia* sp. C. is a multifoliate frond which preserves only a handful of well-preserved, overlapping rangeomorph branches surrounded by unrecognisable necrotic material (Fig. 3.6H-I). The best-preserved specimen is composed of five distally inflated first-order branches which are unfurled/displayed, spatulate in shape and positioned at a steep angle relative to the bedding plane with no discernible common orientation (Fig. 3.6H). The most complete, and largest, first-order branch has a length of 0.6 cm and a width of 0.8 cm. Other less complete branches record comparable lengths and widths that range between approximately 0.5 cm and 0.6 cm, with branches being slightly wider than they are long (Fig. 3.6H). The distal tip of these branches is oriented downwards towards the underlying sediment, with the proximal base of the branches being close to the level of the uppermost layer of the fossiliferous surface (Fig. 3.6H-I). Up to four-orders of branching are preserved in *Bradgatia* sp. C., though it is not possible to fully describe the fourth-order branches due to them only being partially preserved. Up to five second-order branches can be found per first-order branch, these are unfurled/rotated with medial to distal inflation with each having up to five third-order branches that are furled/rotated. There are no branches in *Bradgatia* sp. C. that are orientated in the direction of palaeocurrent flow, all preserved branches can be seen to be perpendicular to or oriented into the direction from which the palaeocurrent originated (Fig. 3.6H-I).

Remarks— *Bradgatia* sp. C. is known from only three poorly preserved specimens (Fig. 3.6H-I; Table B.1), which are only identifiable to the genus due to their distally inflated, overlapping, unfurled/displayed first-order branches (Brasier *et al*. 2012; Fig. 3.6H-I). Much of the negative epirelief impression is composed of necrotic/partially preserved impressions of the organism; if not for the well-preserved first-order branches, these specimens would have been recognised as taphomorphs. The general body plan and the observation that the branches are oriented perpendicular and reversed to the inferred palaeocurrent (Fig. 3.6H) means that *Bradgatia* sp. C. is most comparable to 'U- and O-shaped' *Bradgatia* (Flude and Narbonne 2008). It has previously been suggested that the variation in the shape of *Bradgatia* is caused by a combination of taphonomy and ontogeny (Flude and Narbonne 2008); while we do not rule this out it is more likely that the difference between *Bradgatia* sp. B. (I-shaped) and *Bradgatia* sp. C. (U- and O-shaped) is taxonomic due to the difference in first-order branch morphology (medially inflated, sigmoidal, unfurled/rotated to unfurled/displayed first-order branches vs. distally inflated, spatulate, exclusively unfurled/displayed first-order branches). Unlike *Bradgatia* sp. A. and *Bradgatia* sp. B. the partial preservation of *Bradgatia* sp. C. specimens means there are no discernible rows of branches present, as such it is not possible to tell if this species would have been structured with similar rows. However, the gross morphology and positioning of the preserved branches suggests that the taxon would have consisted of multiple rows (Fig. 3.6H-I). Only by finding more complete specimens of *Bradgatia* sp. C. will a better understanding of the morphology of this taxon be obtained. Like *Bradgatia* sp. A. the steep angled lower surface of *Bradgatia* sp. C. suggest that this taxon also had a quasi-infaunal lifestyle (Grazhdankin 2004; Grazhdankin and Seilacher 2005; McIlroy *et al*. 2021; Taylor *et al*. 2023). Unlike *Bradgatia* sp. A., however, the branches of *Bradgatia* sp. C. are seen to be growing into the sediment (Fig. 3.6H-I), which may be the result of different styles of rheotropic growth (McIlroy *et al*. 2022a).

Clade Rangeomorpha Pflüg 1972

Genus *Charnia* Ford 1958

Type Species— *Charnia masoni* (Ford 1958).

Generic Diagnosis— "Frond uniterminal, comprising two rows of non-conjoined first order branches arranged alternately along a central axis, presenting as a zig-zag medial suture. First order branches typically show proximal inflation, whereas (non-conjoined) second-order units show moderate-to-medial inflation. All first to fourth order branches are aligned in subparallel series. Second order branches are oriented basally, whereas first and third order branches are oriented apically. First order branches comprise rangeomorph elements that are rotated and undisplayed, while second order branches are comprised of rangeomorph elements that may be rotated and either furled or unfurled. There is variation in the presentation of third and fourth order rangeomorph branch elements, which can be displayed and unfurled, displayed and furled, undisplayed and furled, or undivided. A basal disc is present in some specimens" (emended diagnosis of Dunn *et al*. 2019b).

Remarks— Nine fossils from the Allison Surface have been assigned to the genus *Charnia* (Ford 1958; Brasier *et al*. 2012). All specimens assigned to the genus exhibit the characteristic rotated/furled first- and second-order charnid branching (Narbonne *et al*. 2009; Dunn *et al*. 2019b; Fig. 3.7). Second-order branching can commonly be traced across first-order branching (cf. McIlroy *et al*. 2022b), however the positive epirelief branches of the *Charnia* specimens found on the Allison Surface are not in continuity with neighbouring branches meaning it is not possible to trace them across (Fig. 3.7A-B). The charnids include: *Charnia gracilis* (Wu *et al*. 2022; Figs 3.3C, 3.7A–C); partially preserved *Charnia masoni* (Ford 1958; Brasier *et al*. 2012; Dunn *et al*. 2019b; Fig. 3.7D); and specimens that can only be assigned to a generic level (Fig. 3.7E–F).

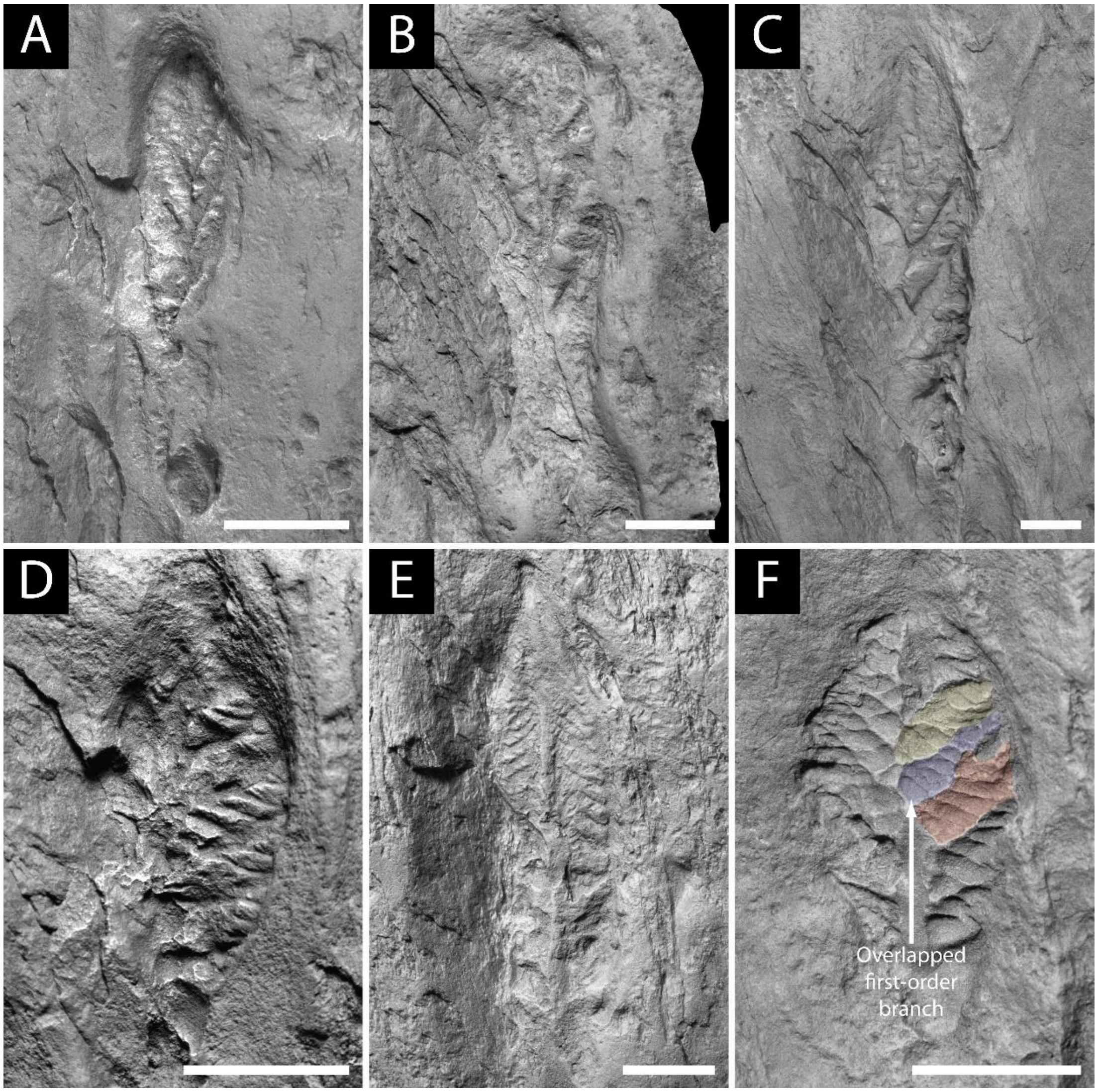


Fig. 3.7 – *Charnia* sp. specimens. A-C, *Charnia gracilis* specimens (casts SB-2021-038iv (A), SB-2021-040iv (B), SBNO-CM-20-04 (C)). D, partial *Charnia masoni* specimen (cast SB-2021-055xi). E, *Charnia* sp. A. specimen reversed to the palaeocurrent (cast SBAS-CM-20-02). F, negative relief *Charnia* sp. B. specimen (cast SB-2020-019(b)iii-a). (scale bars – 1 cm)

Charnia gracilis Wu *et al.,* 2022

Figs 3.2D, 3.3C, 3.7A-C

2020	Specimen from Spaniard's Bay	Hawco *et al*., fig. 3f.
2022	*Charniodiscus gracilis* sp. nov.	Wu *et al.* p. fig. 2.3-2.4.
2023	*Charnia* sp.	McKean *et al*., fig. 6c.
2023	Biserial lanceolate frond	McKean *et al*., fig. 8a.
2024	*Charnia gracilis*	McKean *et al*., fig. 12a.

Type Material— The holotype (NIGP161629) is located in the Shibantan Member, Dengying Formation found in the Yangtze Gorges area, South China (Wu *et al*. 2022).

Material— Four *in situ* specimens are known from the Allison Surface at Upper Island Cove.

Specific Diagnosis— "A *Charnia* species characterized by a slender petalodium consisting of relatively long, thin, and straight first-order branches that have a parallel-sided blade-like shape. First-order branches emanate alternately from the central axis at an acute angle, typically ≤20°. First-order branches are composed of a series of rectangular or rhomboid second-order branches arranged acutely to perpendicularly to the first-order branches" (Wu *et al.* 2022).

Description— *Charnia gracilis* specimens with 'blade-like' first-order branches showing slight proximal inflation. Although only partial, each of the Upper Island Cove specimens preserves up to six rotated/furled first-order branches, which are up to 1.8 cm in length and alternate at an acute angle across a concealed midline (Fig. 3.7A, C). Each first-order branch is composed of up to five rotated/furled second-order branches that are rhombohedral in shape and arranged at an acute to perpendicular angle in relation to the first-order branch (Fig. 3.7B, C). There is no evidence for third- or higher-order branching in any of the specimens. Each specimen is preserved in positive epirelief within an erosional scour (Figs 3.3C, 3.7A-C), with the first-order branching continuing beyond the scour into the surrounding sediment (Figs 3.3C, 3.7A). Despite this the *C. gracilis* specimens preserved on the Allison Surface have the same narrow frond shape as the holotype (Wu *et al*. 2022, fig. 2.4), with the largest specimen being ~5.8 cm in length and ~1.7 cm wide (Fig. 3.7C).

Remarks— Three specimens from the main outcrop of the Allison Surface, and an additional specimen from the new outcrop, were previously described as biserial, lanceolate fronds (McKean *et al*. 2023, fig. 8a; Fig. 2.8A), and are now recognised as belonging to the recently described *Charnia gracilis* from the Shibantan biota of South China (Wu *et al*. 2022; Figs 3.3C, 3.7A–C). Like the holotype of *C. gracilis* the Allison Surface specimens are narrow fronds with straight/blade-like first-order branching (Wu *et al*. Fig. 3.7A-C), differentiating them from the classic sigmoidal first-order branching seen in *C. masoni* (Laflamme *et al*. 2007; Dunn *et al*. 2019b). To date *C. gracilis* has only been described from the Shibantan biota of China in the terminal Ediacaran (~550-543 Ma), where it was found to co-occur with *C. masoni* (Huang *et al*. 2020; Xiao *et al*. 2020; Yang *et al*. 2021; Wu *et al*. 2022). The recognition of the species within the Avalonian Assemblage extends the species geographic and temporal range by over 15 million years (Matthews *et al*. 2020).

Charnia masoni Ford 1958

Fig. 3.7D

[non] 2009	*Charnia* cf. *C. masoni*	Narbonne *et al*., fig. 11.1-2.
2013	*Beothukis*	Brasier *et al*., fig. 11c-d.
2023	Partial beothukid	McKean et al., fig. 5a.

Type Material— The holotype (LEIUG 2328) is housed at the Leicester City Museum, New Walk, Leicester; originally being collected from the Woodhouse Beds, Maplewood Group (Antcliffe and Brasier 2008), Charnwood Forest, UK.

Material— Three *in situ* specimens are known from the Allison Surface at Upper Island Cove.

Specific Diagnosis— "*Charnia* with ovate to parallel-sided petalodium consisting of sigmoidal first-order branches emanating alternately at an acute angle, typically >20°. First-order branches composed of series of near-rectangular second-order branches arranged acutely to almost perpendicularly to the first-order branches" (emended diagnosis of Wu *et al*. 2022).

Description— *Charnia masoni* specimens that exclusively preserve the right side of a frond, with up to seven medially inflated sigmoidal first-order branches (McKean *et al*. 2023, fig. 5a; Figs 2.5A, 3.7D). First-, second- and third-order branching is furled/rotated, with each order of branching being subparallel to one another (Brasier *et al*. 2012; Fig. 3.7D). Maximum frond length is 2.3 cm, with the maximum length of a first-order branch being 0.8 cm (Fig. 3.7D). The longest first-order branch is composed of six second-order branches, with the two distalmost second-order branches preserving third-order branching.

Remarks— Three partially preserved specimens have been assigned to the species *Charnia masoni* (Ford 1958; Brasier *et al*. 2012; Wu *et al*. 2022; Fig. 3.7D; Table B.1). Although specimens associated with *Charnia masoni* have been recognised from the surface for over a decade (e.g. *Charnia* cf. *C. masoni* (Narbonne *et al*. 2009, fig. 11)), the three specimens now assigned to this species had previously been described as 'beothukids' (McKean *et al*. 2023, fig. 5a; Fig. 2.5A). When comparing the branching architecture of these specimens to *Beothukis*, however, it can be seen that they do not preserve the radial branching as described in the emended diagnosis for that genus (McIlroy *et al*. 2022b) and are thus reassigned. All three specimens are composed exclusively of the right side branches of a frond, with varying levels of detail preserved (the best-preserved specimen being figured herein; Fig. 3.7D). Both first- and second-order branching in all specimens shows slight medial inflation giving the first-order branches a sigmoidal appearance (Fig. 3.7D), as has been noted for other *C. masoni* fossils located elsewhere (Laflamme *et al*. 2007; Dunn *et al*. 2019b). The partial preservation of all three specimens means there is no evidence for a basal disc or alternating branching across the midline. The alignment of the first-order branching, however, does suggest that the specimen would have preserved the furled central-axis and zig-zag suture that is diagnostic of the genus (Dunn *et al*. 2019b; Fig. 3.7D). The angle of the first-order branches in relation to the inferred midline is approximately 60°, further supporting an affinity with *C. masoni* (Wu *et al*. 2022).

Charnia sp. A.

Fig. 3.7E

2013	*Charnia* sp.	Brasier *et al*., fig. 10b.
2023	*Charnia* sp.	McKean *et al*., fig. 7a.

Material— One *in situ* specimen is known from the Allison Surface at Upper Island Cove.

Description— *Charnia* sp. A. is a partially preserved unipolar rangeomorph frond measuring 5.2 cm by 1.2 cm and is orientated in the opposite direction to the palaeocurrent (McKean *et al*. 2023, fig. 7a; Figs 2.7A, 3.7E). The specimen has a total of 24 furled/rotated, distally inflated first-order branches that are alternately arranged on either side of the frond, tightly constrained to their neighbouring branches and show some evidence for sigmoidal branching (Fig. 3.7E). Size and shape of first-order branches varies on either side of the frond, with left-side branches having a maximum width of 0.1 cm and right-side branches having a maximum width of 0.2 cm. The thicker first-order branches are straight, almost 'blade-like', whereas the thinner branches are curved towards their distal tip (Fig. 3.7E). The midline itself has not been preserved, but branches on either side of the frond can be seen to alternate. Up to four second-order branches can be found preserved sporadically per first-order branch; where present they can be seen to be furled/rotated, predominantly rhombohedral in shape and oriented perpendicularly to the first-order branches (Fig. 3.7E). Third- and higher-order branches are not preserved.

Remarks— *Charnia* sp. A. is unique in that it is the only species of *Charnia* found on the Allison Surface that is reversed to the palaeocurrent, which has been determined from the orientation of the obstruction scours that the fronds are found within (Brasier *et* al. 2013, fig. 10b; McKean *et al*. 2023, fig. 7a; Figs 2.7A, 3.7E). While the midline is not preserved, alternating branching on either side of the frond suggest this taxon had a concealed midline with a zig-zag suture (Fig. 3.7E). When comparing the branch architecture on either side of the midline there is a differentiation between the left- and right-side branches of *Charnia* sp. A. Variation in branch architecture either side of the midline has been noted in other Ediacaran taxa known from elsewhere in the Avalonian Assemblage, such as the holotype of *Beothukis mistakensis* (McIlroy *et al*. 2022b, fig. 5). The thicker first-order branches, located on the right side of the scour (left side of the frond), can be seen to have a similar 'blade-like' shape to that of *C. gracilis* (Wu *et al*. 2022).

Charnia sp. B.

Fig. 3.7F

2004	*Charnia*-like frond	Narbonne, fig. 3d.
2009	*Charnia* cf. *C. masoni*	Narbonne *et al*., fig. 11.1-2.
2013	*Charnia* sp.	Brasier *et al*., fig. 11a.
2023	*Charnia* sp.	McKean *et al*., fig. 2d.

Material— One *in situ* specimen is known from the Allison Surface at Upper Island Cove.

Description— *Charnia* sp. B. is a well-preserved unipolar rangeomorph frond preserved in negative epirelief, rhombohedral in shape and measuring 2.2 cm by 1.3 cm (Fig. 3.7F). First- and second-order branches are clearly furled/rotated and tightly constrained to the directly adjacent branches. Five complete and two partial J-shaped first-order branches are preserved in the specimen, which are alternately arranged either side of a concealed midline (Fig. 3.7F). The first-order branching shows proximal-inflation, as is commonly seen in *C. masoni* (Brasier *et al*. 2012), whereas second-order branches show either no inflation or slight distal inflation (Fig. 3.7F). Width of first-order branches varies across the frond, ranging between <0.1 cm to 0.35 cm, with examples of large first-order branches overlapping smaller, more terminal, branches. Length of first-order branches is more consistent, with the longest branches being ~0.75 cm (Fig. 3.7F). A maximum of six second-order branches can be found per first-order branch: these branches are located on the more basal first-order branches and are rectangular to rhombohedral in shape. They show slight distal or no inflation, are arranged perpendicularly to the first-order branches, and show no to little change in size from the axis to the distal edges of the frond (Fig. 3.7F). Third- and higher-order branches are not preserved.

Remarks— *Charnia* sp. B. is the only *Charnia* to be preserved exclusively in negative epirelief on the Allison Surface (Table B.1). This specimen preserves a unique rhombohedral shape, although this may be a taphonomic artefact caused by scouring (McKean *et al*. 2023). The specimen also lacks the clear sigmoidal structure of *C. masoni* (Laflamme *et al*. 2007; Dunn *et al*. 2019b) or the 'blade-like' branching of *C. gracilis* (Wu *et al*. 2022), with the first-order branches instead being structured in a J-shape (Fig. 3.7F), as such it is possible that *Charnia* sp. B. is an undescribed species within the genus. While the branching is largely constrained, as seen in other *Charnia*, the first-order branching can be seen to crosscut or overlap other first-order branches (Fig. 3.7F), a feature that has not previously been reported in any other *Charnia* species. The inflation of second-order branches is variable within the specimen, with slight distal inflation or no inflation at all. Unlike other species of *Charnia*, the rows of second-order branches in this taxon show little to no change in size from the midline to distal edges of the frond (Fig. 3.7F). Previous studies have suggested that this specimen exhibits the remnants of an 'internal stalk' (Narbonne 2004, fig. 3d; Narbonne *et al*. 2009, fig. 11.3), however, this interpretation has been brought into question (Grazhdankin and Seilacher 2005) and was recently explained as a taphonomic artefact caused by scouring during exhumation that occurred before final casting by the overlying T_c sandstone (McKean *et al*. 2023). Despite the erosional scour crosscutting the proximal portion of the frond, a zig-zag axis and alternating branching are preserved (Fig. 3.7F).

Clade Rangeomorpha Pflüg 1972

Genus *Kannabuchia* gen. nov.

Type species— *Kannabuchia artkingii* sp. nov.

Etymology— *Kannabuchia* is a Latinisation of the Beothuk word for long—"kannabuch"— in recognition of the long and slender shape of the genus.

Generic Diagnosis— As per species.

Remarks— As per species.

Kannabuchia artkingii sp. nov.

Figs 3.2E, 3.8

2007	Rangeomorph fronds	Ichaso *et al*., fig. 3d.
2009	*Beothukis mistakensis*	Narbonne *et al*., fig. 5.1.
2009	*Trepassia wardae*	Narbonne *et al*., fig. 10.
2012	*Trepassia wardae*	Brasier *et al*., fig. 4c.
2013	*Beothukis mistakensis*	Brasier *et al*., fig. 9d.
2013	*Trepassia wardae*	Brasier *et al*., fig. 10a.
2013	Specimen preserved as a dark impression	Laflamme *et al*., fig. 2.4.
2015	*Beothukis mistakensis*	Liu and Conliffe, fig. 6e.
2015	*Trepassia wardae*	Liu and Conliffe, figs 6j, 8c.
2016	*Beothukis mistakensis*	Xiao *et al*., fig. 4d.
2017	*Beothukis mistakensis*	Liu *et al*., fig. A8e.
2017	*Trepassia wardae*	Liu *et al*., figs. A8j, B2c.
2022a	[non] *Beothukis mistakensis*	McIlroy *et al*., fig. 2b.
2023	*Beothukis* sp.	McKean *et al*., fig. 2c.
2023	*Trepassia* sp.	McKean *et al*., fig. 2e, 3a, 6d, 13a.
2023	*Charniodiscus* sp.	McKean *et al*., fig. 5c.
2024	cf. *Trepassia* sp.	McKean *et al*., fig. 2c.

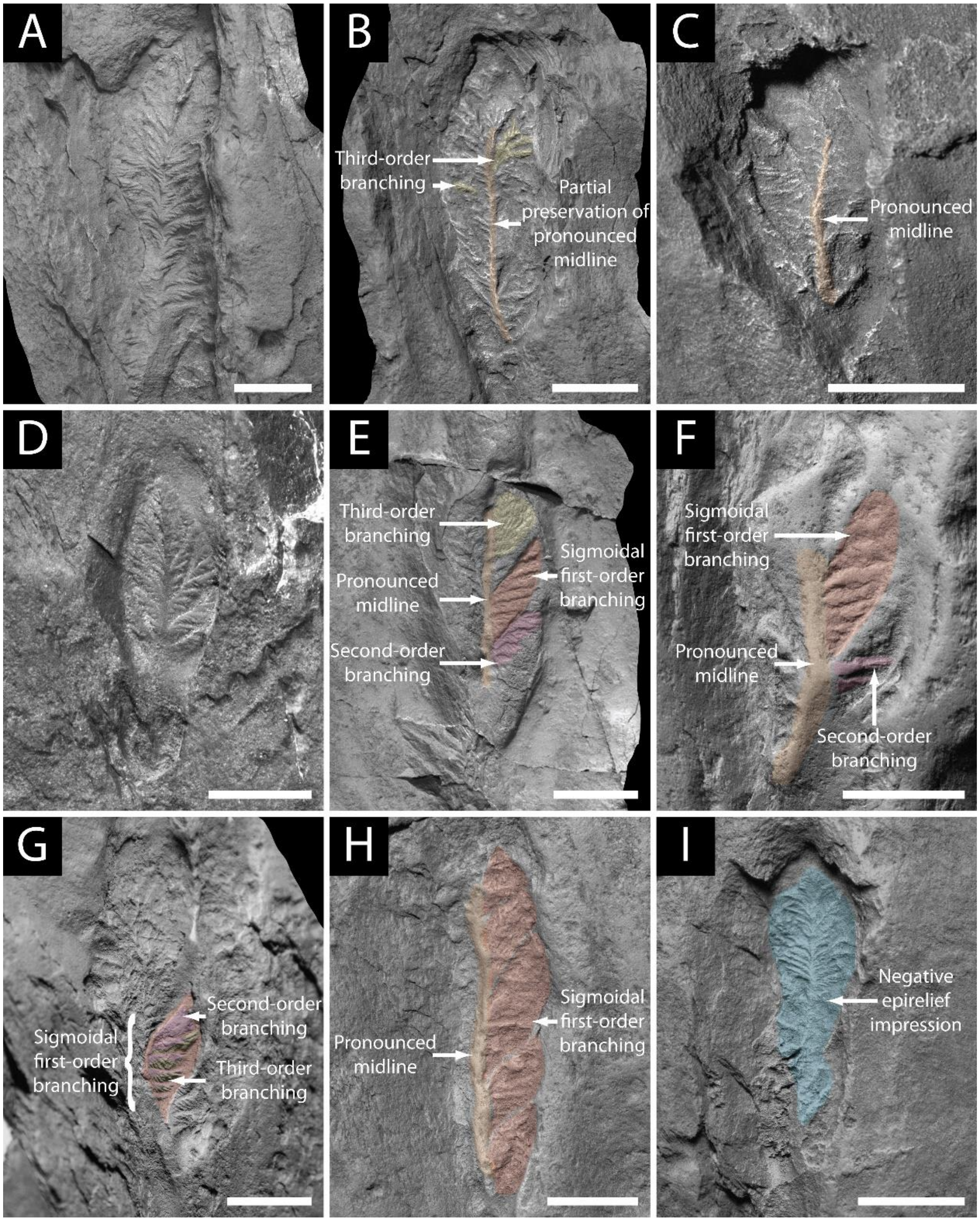


Fig. 3.8 – *Kannabuchia artkingii* gen. et sp. nov. specimens. A, holotype of *Kannabuchia artkingii* (cast SB-2021-055iv). B, partial *K. artkingii* specimen showing clear third-order branching (yellow) (cast SB-2021-055i). C, partial *K. artkingii* specimen showing the pronounced midline (orange) (cast SB-2022-056ii). D, paratype of *K. artkingii*, note that the pronounced midline has not been preserved

in this specimen (NFM F-758). E, partial *K. artkingii* specimen with clear branching up to the third-order (first-order = red, second-order = pink, third-order = yellow) (cast SB-2021-051v). F, partial *K. artkingii* specimen showing the pronounced midline (orange) (cast SB-2021-042i). G, partial *K. artkingii* specimen with clear branching up to the third-order (first-order = red, second-order = pink, third-order = yellow) (cast SB-2020-020(b)ii). H, partial *K. artkingii* specimen showing the pronounced midline (orange) (cast SB-2021-051iv). I, Negative epirelief *K. artkingii* preserving the lower surface of the organism (light blue) (cast SB-2022-056i-b). (scale bars – 1 cm)

Type Material— The holotype remains in the field, but a plastotype is to be accessioned to The Rooms, provincial museum of Newfoundland and Labrador (SB-2021-055iv; Fig. 3.8A); the paratype is already housed in The Rooms (NFM F-758; Fig. 3.8D).

Material— Forty-nine specimens are known from the Allison Surface at Upper Island Cove; the extraction of the paratype pre-dates our work.

Etymology— *artkingii* named after Arthur (Art) King to recognise his decades of work mapping the Avalon Peninsula and his discovery of Ediacaran fossils in the Conception Bay North region in the 1980s.

Diagnosis— Narrow unipolar rangeomorph frond with at least three-orders of self-similar branching and a pronounced central midline seen on the upper surface of the organism. Composed of up to five sigmoidal first-order branches that alternate either side of the pronounced midline. First-order branches are positioned at an acute angle to the midline, are furled/rotated with moderate to medial inflation and are in direct contact with their neighbouring branches with no overlap. Approximately five to eight unfurled/rotated second-order branches are found per first-order branch; they are straight to slightly curved, perpendicular to the midline and are separate from their neighbouring second-order branches yet show no evidence for overlap. Third-order branches are unfurled/rotated, with some evidence for displayed branching; these branches are perpendicular to the second-order branches and are primarily oriented towards the base of the organism, apart from the third-order branches at the apex of the frond which are orientated terminally.

Description— *Kannabuchia artkingii* has sigmoidal, moderate to medially inflated, furled/rotated first-order branches that regularly alternate either side of a straight to curved pronounced central midline on the upper surface of the organism (Fig. 3.8). The frond is narrow and slender as seen by the holotype which is 5 cm in length and 1.2 cm at its maximum width (Fig. 3.8A). Other specimens have a reduced length to width ratio, such as the paratype which is 1.8 cm by 0.9 cm (Fig. 3.8D), but still present a narrow and slender body plan. Upper surface first-order branches are composed of unfurled/rotated second- and third-order branches giving *Kannabuchia* a feather-like appearance (Fig. 3.8B, E). Upper surface second-order branches are oriented perpendicular to the midline of the frond (Fig. 3.8E, G), they have no inflation to slight medial inflation (Fig. 3.8F) and appear either with a slight curve and separation from their neighbours (Fig. 3.8A-C) or are rectangular in shape and in close proximity with their neighbouring branches (Fig. 3.8D-F). Some fronds show a combination of both second-order branch morphologies (Fig. 3.8A-E). No overlap is seen in any order of branching within *Kannabuchia*. Upper surface third-order branches are oriented perpendicular to second-order branches and towards the base of the organism (Fig. 3.8A, D, G). However, in specimens that preserve the apex of the frond it can be seen that third-order branching is orientated towards the terminal end of the frond (Fig. 3.8B, E).

Specimens are preserved in positive, mixed and negative epirelief (Table B.1), which shows variation in the upper and lower surfaces of the frond. The mixed and negative epirelief specimens of *Kannabuchia* show that the lower side of the organism is composed of the same regularly alternating sigmoidal furled/rotated first-order branches and unfurled/rotated second- and third-order branches as the upper surface (Fig. 3.8A, C, I). The pronounced midline/axial structure on the upper surface, most clearly visible in partial/decayed specimens (Fig. 3.8B, C, E, F, H), is not present on the lower surface. Instead, an unconcealed midline is present (Fig. 3.8I). Lower surface second-order branching is narrower than that seen on the upper surface of *Kannabuchia*, with neighbouring branches coming into direct contact with each other (Fig. 3.8G).

Remarks— A total of 49 specimens from the Allison Surface have been identified as *Kannabuchia artkingii* (Fig. 3.8), making it one of the most abundant taxa from the site. Previously described as *Trepassia* (Narbonne *et al*. 2009), the specimens found at Upper Island Cove are morphologically disparate from the type material and the emended species diagnosis described in Brasier *et al*. (2012) but are similarly long and narrow. *Trepassia* is described as being composed of irregularly spaced primary branches with a straight central axis, with irregular second- and third-order branches that are exclusively rotated/furled branching at all orders (Narbonne *et* al. 2009; Brasier *et al*. 2012). *Kannabuchia*, however, has regular alternating (subparallel of Brasier *et al*. (2012)) branching either side of a straight to curved pronounced axial structure/central midline (Fig. 3.8A, C, E-F), with consistent second- and third-order branching that is rotated/unfurled (Fig. 3.8E, G), with some evidence for displayed branching in the third-order (Fig. 3.8B, E).

The pronounced midline, here interpreted as an axial stalk that marks the frond axis on the upper surface of *Kannabuchia*, is one of the most distinguishable features of the genus (Fig. 3.8A-F). It is clearest in poorly preserved specimens (Fig. 3.8C, F). It is likely that the stalk was surrounded by branches, which can be seen to partly overlap the structure in some specimens (Fig. 3.8C). The stalk likely provided structural integrity to the frond and allowed for communication between branches. As the structure is only present on the upper surface—which is not preserved in most rangeomorphs—it raises the possibility that similar structures may have been present in other rangeomorph taxa (i.e. taxa with concealed midlines (cf. Brasier *et al*. 2012)).

It is unknown if the pronounced stalk could be the continuation of a stem, as is known in several rangeomorphs (e.g. *Primocandelabrum* (Hofmann *et al*. 2008; Kenchington and Wilby 2017); *Avalofractus* (Figs 3.4B, 3.5F)), though it seems likely. The current lack of a basal stem or holdfast in *Kannabuchia* means there is no morphological evidence for an erect mode of life (null hypothesis as outlined in McIlroy *et al*. (2022b)). As such *Kannabuchia* can be interpreted as an epibenthic recliner similar to the Allison Surface *Bradgatia* and other well-known recliners from the Avalonian Assemblage, such as *Fractofusus* (Gehling and Narbonne 2007; Taylor *et al*. 2023) and *Beothukis* (McIlroy *et al*. 2021, 2022b).

Two types of upper surface branching are recognized in *Kannabuchia*: 1) specimens that have thinner second-order branches which show clear separation from neighbouring branches and are slightly curved (type a; Fig. 3.8A-C); 2) specimens that have rectangular second-order branches, which are in close proximity to one another (type b; Fig. 3.8D-F). Since this distinction is only seen in the second-order branching—and both types of branches are rotated and unfurled—it is likely that this is either intraspecific variability or due to decay processes (e.g. Brasier *et al*. 2013; Kenchington and Wilby 2017; Laflamme *et al*. 2018; Dunn *et al*. 2019a). Some specimens show a combination of the two types of second-order branching (Fig. 3.8A, E, H), which argues against the presence of two species within *Kannabuchia*.

Kannabuchia is predominantly preserved as moulds of the upper surface of the frond (Fig. 3.8A-F), with 17 specimens showing mixed relief (Fig. 3.8A, C, G, H) and a single specimen exclusively preserving the lower surface in negative epirelief (Fig. 3.8I). This allows us to consider the 3D morphology of this taxon. Branch architecture is similar on both sides of the frond, with the pronounced midline replaced by an unconcealed midline (Fig. 3.8I). Negative epirelief branches can be seen to be raised to the midline and go deeper into the scour towards their distal margin (Fig. 3.8I). This is similar to *Bradgatia* sp. C. (Fig. 3.6H-I) which has also been inferred to be an epifaunal recliner. Like the upper surface, there is no evidence for a basal stem or holdfast at the base of the lower surface, further distinguishing *Kannabuchia* from the type material of *Trepassia wardi* (Narbonne and Gehling 2003).

Clade Arboreomorpha Erwin *et al*. 2011

Genus Arborea Glaessner and Wade 1966

Type Species—Arborea arborea Glaessner (in Glaessner and Daily 1959)

Generic Diagnosis— "Frond with ovate bifoliate petalodium composed of prominent stalk and multiple parallel primary branches stemming between 45° and 90° from stalk.

Petalodium tapers distally. Primary branches sinusoidal to rectangular. Primary branching stalk runs the entire length of the branch. Secondary branches oval, broaden distally and taper proximally, where they are anchored to the primary branching stalk. Secondary branches lack branching subdivisions" (emended diagnosis of Laflamme *et al*. 2018).

Remarks— A total of 25 fossils from the main outcrop of the Allison Surface have been assigned to the Arboreomorpha (Erwin *et al*. 2011). Of the arboreomorphs, 17 can be considered to be *Arborea* (Fig. 3.9), due to the presence of bifoliate branching, a planar leaf-like gross morphology, and evidence for a backing sheet across all specimens (see Pérez-Pinedo *et al*. 2022). The presence of the Arboreomorpha at Upper Island Cove has been previously documented (Brasier *et al*. 2013), with *Arborea* being invoked in scour generation at the site (McKean *et al*. 2023).

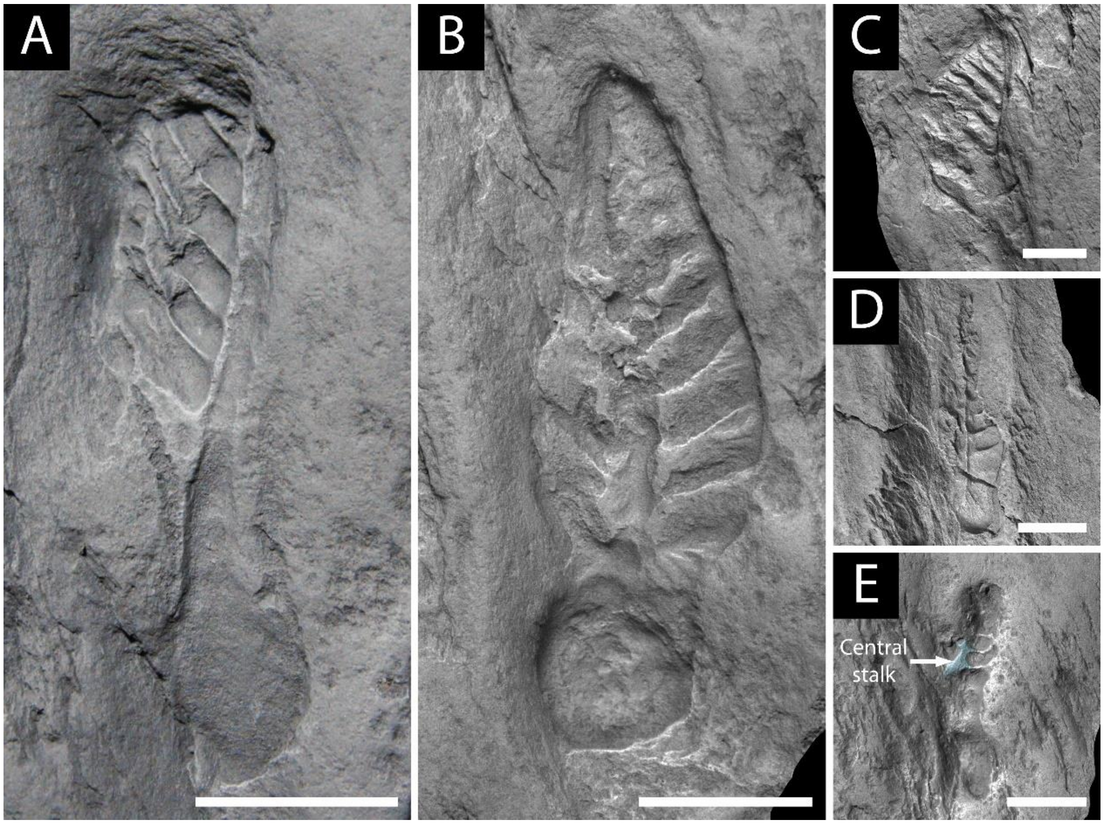


Fig. 3.9 – *Arborea* sp. specimens. A, negative epirelief impression of the 'back' of *Arborea* sp. showing outline of the backing sheet (cast SB-2021-040ii-a). B, positive epirelief impression of the 'front' of *Arborea* sp. showing the individual 'pea-pod' primary branches and the impression of a bulbous holdfast at the base of the organism (cast SB-2021-040ii-b). C, positive epirelief specimen of the 'front' of *Arborea* sp. (cast SB-2020-021v). D-E, negative epirelief specimens showing the 'back' of *Arborea* sp. (casts SB-2020-027iv (D), SB-2021-045iv (E)). (scale bars – 1 cm)

Arborea sp.

Figs 3.2F, 3.3B, 3.9

2020	Specimen from Spaniard's Bay	Hawco *et al*., fig. 3d.
2023	*Arborea* sp.	McKean *et al*., fig. 6b

2023	Arboreomorph	McKean *et al*., fig. 3b, d.
2023	Beothukid	McKean *et al*., figs 3e, 5b, 6a, 8b.

Material— Seventeen *in situ* specimens are known from the Allison Surface at Upper Island Cove.

Description— *Arborea* sp. is a unipolar bifoliate frond with both its front and back surfaces being known (*sensu* Dunn *et al*. 2019a). It has a central stalk that runs down the centre of the organism, terminating in a bulbous holdfast at its base (Figs 3.2F, 3.9B). The front of the organism shows at least nine primary branches either side of a central stalk (Fig. 3.9B). Comparing branching on either side of the stalk shows the typical peapod units in positive epirelief (Laflamme *et al*. 2018; Dunn *et al*. 2019a, fig. 6; Figs 3.2F, 3.9B). These primary branches are rectangular in shape, with tapering on their distal and proximal edges (Fig. 3.9B-C), positioned at an acute angle (50° to 70°) to the stalk and curve towards the terminal tip of the frond (Fig. 3.9A-B). Secondary branches are rectangular and broaden towards their distal tip and are most commonly preserved at the tips of the primary branches, to which they are parallel (Fig. 3.9B-C). However, where secondary branches are preserved closer to the central stalk they are angled towards the base of the organism, showing that they radiate across the primary branch (Fig. 3.9B). The central stalk running the length of *Arbore*a sp. terminates in a bulbous holdfast directly below the frond (Figs 3.2F, 3.9B). The back of the organism preserves the backing sheet characteristic of the genus (Dunn *et al*. 2019a; Pérez-Pinedo *et al*. 2022) and preserves no evidence for the branching beyond the junctions between the primary branches (Fig. 3.9A, D, E). The outline of the central stalk is preserved on both the front and back of the organism and can be seen to be slightly curved (Fig. 3.9A-B).

Remarks— The only arboreomorphs previously identified to species level from Newfoundland are *Arborea spinosus* and *Charniodiscus procerus* (Laflamme *et al*. 2004; Pérez-Pinedo *et al*. 2022). *Arborea* sp. is distinct from these two taxa in that it does show any evidence for the spine found at the tip of *Arborea spinosus* (Laflamme *et al*. 2004; Singer *et al*. 2012) and unlike *Charniodiscus procerus* the taxon has a backing sheet and a more leaf-like shape (Laflamme *et al*. 2004; Pérez-Pinedo *et al*. 2022). *Arborea* sp. bears a resemblance to the frondose taxon *Pambikalbae hasenohrae* from South Australia (Jenkins and Nedin 2007, fig. 3). *Pambikalbae* preserves a similar structure to the negative epirelief *Arborea*, preserving a backing sheet and showing clear separation between the primary branches as in the Upper Island Cove material (Dunn *et al*. 2019a; Pérez-Pinedo *et al*. 2022; Fig. 3.9A, E). *Pambikalbae* lacks any fractal rangeomorph branching (Jenkins and Nedin 2007) and, therefore, is likely an arboreomorph (Erwin *et al*. 2011; Laflamme *et al*. 2018; Pérez-Pinedo *et al*. 2022). The zig-zag longitudinal sutures originally reported in *Pambikalbae* (Jenkins and Nedin 2007, fig. 4c) appear in some negative epirelief specimens of the Upper Island Cove *Arborea* sp. (Fig. 3.9A), but due to the offset seen in the primary branches of *Arborea* sp. at Upper Island Cove we consider this to be a post-mortem feature.

Specimens of *Arborea* sp. are found in both positive and negative epirelief in the Upper Island Cove assemblage (Fig. 3.9A-B; Table B.1), with previous studies showing that *Arborea* has different ‘front’ and ‘back’ sides (Jenkins and Gehling 1978; Laflamme *et al*. 2018; Dunn *et al*. 2019a; Pérez-Pinedo *et al*. 2022; Fig. 3.9). Positive epirelief specimens are most common (Table B.1) and preserve primary branches with proximal secondary branches perpendicular to the primary branch (Fig. 3.9B) and parallel secondary branches that are found at their distal tips (Fig. 3.9B-C). Tertiary branches have been reported from arboreomorphs elsewhere (Dunn *et al*. 2019a; Grimes *et al*. 2023) but cannot be demonstrated in the Upper Island Cove material with the exception of one tentative specimen (Table B.1).

Recently discovered *Arborea* from China preserve a *Hiemalora*-type holdfast at the end of a stem (Wang *et al*. 2020), while the Upper Island Cove material preserves a bulbous holdfast at the base of the stalk (Figs 3.2F, 3.9B). The presence of a bulbous holdfast at the base of the frond is comparable to another recently described arboreomorph; *Akrophyllas longa* (Grimes *et al*. 2023). However, *Akrophyllas* lacks any evidence for a backing sheet and only preserves the central stalk on the back side of the organism (Grimes *et al*. 2023). When comparing *Arborea* sp. to the type species, *Arborea arborea* (Glaessner and Daily 1959), it can be seen that the Upper Island Cove species lacks any evidence for the basal stem that connects the frond to holdfast (Laflamme *et al*. 2018; Dunn *et al*. 2019a). Instead, in *Arborea* sp. the basal holdfast is attached directly to the base of the frond (Figs 3.2F, 3.9B), though a basal stem may not be seen in the plane of preservation as considered for *Arborea spinosus* (Pérez-Pinedo *et al.* 2022).

Partial exhumation of the fronds means that the central stalk of *Arborea* sp. is typically either poorly preserved or obscured by the sediment, however, it can be seen on both the front and back surface of the taxon (Fig. 3.9A-B). As such it is not possible to determine whether branches are alternately or bilaterally arranged on either side of the specimens, however, both arrangements are present in *Arborea* (Dunn *et al*. 2019a). On the front surface the stalk is in lower relief than the surrounding branches (Fig. 3.9B), which may be due to postmortem collapse of the structure as has been suggested for the holotype of the arboreomorph *Charniodiscus concentricus* (Pérez-Pinedo *et al*. 2022).

Clade Arboreomorpha Erwin *et al*. 2011

Genus *Charniodiscus* Ford 1958

Type Species— *Charniodiscus concentricus* Ford 1958

Generic Diagnosis— "Unipolar frondose arboreomorphs with basal disc, stem, a bifoliate frond without a backing sheet and loosely constrained branches. The bases of the branches are commonly straight and attached to the stem at nearly right angles but are distally curved forming a sub-conical frond in life. Outer surface of the branches of the sub-conical frond has transverse ridges orthogonal to the long axis of the branches. The internal surface of the branch has similar oblique ridges close to the junction with the stem" (emended diagnosis of Pérez-Pinedo *et al*. 2022).

Remarks— Two specimens of *Charniodiscus* (Fig. 3.10) have been found on the new outcrop of the Allison Surface and are preserved in different reliefs; one in 'full-relief' above the fossiliferous surface (Fig. 3.10A) and the other in mixed relief within an erosional scour (Fig. 3.10B). Despite the difference in preservation both specimens are to be considered *Charniodiscus* as they are bifoliate fronds that lack a backing sheet (Pérez-Pinedo *et al*. 2022).

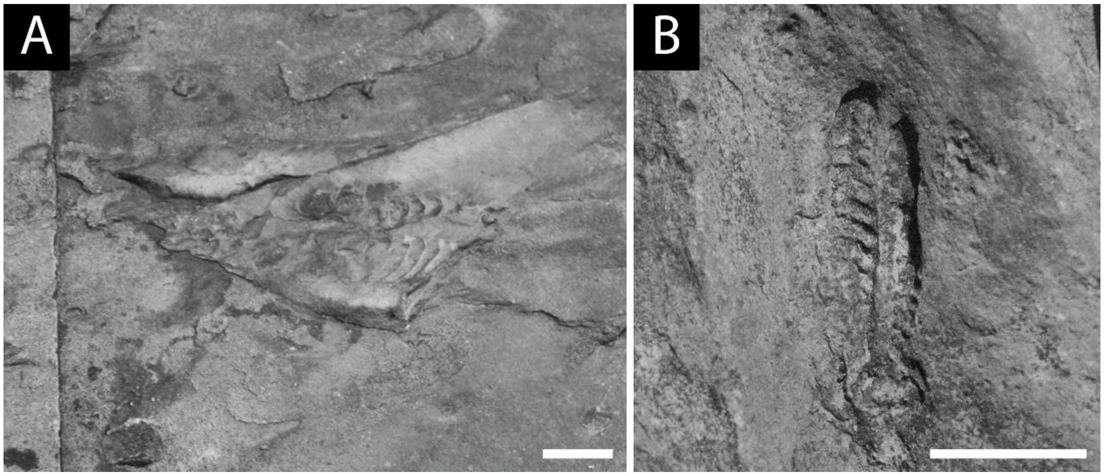


Fig. 3.10 – *Charniodiscus* cf. *C. concentricus* specimens. A, 'full-relief' specimen preserved above the fossiliferous surface (field photo). B, *Charniodiscus* sp. preserved within a large obstruction scour with stem attached to holdfast (field photo). (scale bars – 1 cm)

Charniodiscus cf. *C. concentricus*

Fig. 3.10

2022	*Charniodiscus* sp.	Pérez-Pinedo *et al*., fig. 8.
2023	*Charniodiscus* sp.	McKean *et al*., figs 2f, 8c.

Type Material— The holotype (LEIUG 2383) is housed at the Leicester City Museum, New Walk, Leicester; originally being collected from the Woodhouse Beds, Maplewood Group (Brasier and Antcliffe 2009), Charnwood Forest, UK.

Material— Two *in situ* specimens are known from the newly discovered outcrop of the Allison Surface at Upper Island Cove.

Specific Diagnosis— "*Charniodiscus* with basal disc, stem, and a bifoliate frond, lacking a supporting backing sheet, composed of approximately 25 independent branches that were strongly curved inward and upward in life to form a sub-conical frond, which becomes lanceolate to ovate upon collapse/compression" (emended diagnosis of Pérez-Pinedo *et al*. 2022).

Description— *Charniodiscus* cf. *C. concentricus* is a sub-conical to lanceolate bifoliate frond, with a central stalk that leads to a basal stem and holdfast (Fig. 3.10). Curved branches are oriented to the terminal end of the frond, with collapse being apparent in the basal section of the frond (Fig. 3.10A). The two specimens range in size from 2.1 cm by 0.55 cm (Fig. 3.10B) to 4.9 cm by 2.2 cm (Fig. 3.10A), with the widest part of the organism being found in the medial portion of the frond (Fig. 3.10B). Approximately 10 primary branches are preserved in both specimens, with the junctions between the primary branches being well preserved (Fig. 3.10). Primary branches are broadly rectangular in shape, slightly tapering at their distal edge (Fig. 3.10A) and are angled at 55° to 60° to a slightly curved central stalk (Fig. 3.10B). There is no evidence for secondary or tertiary branching in either specimen (Fig. 3.10). The holdfast at the base of the stem is elliptical in shape and has no evidence of any *Hiemalora*-like structures (Fig. 3.10B).

Remarks—Although only partially preserved these specimens can be recognised as *Charniodiscus* cf. *C. concentricus* due to the preservation of the sub-conical to lanceolate shaped frond and upward curved primary branches (Pérez-Pinedo *et al*. 2022). The basal stem and central stalk of *Charniodiscus* is evident in the specimen preserved within the obstruction scour; this shows that the stalk was visible on the 'back' side of the frond (Fig. 3.10B). The central stalk is visible on both sides of *Charniodiscus* (Laflamme *et al*. 2004, figs 2-4; Pérez-Pinedo *et al*. 2022, figs 3, 6, 7), with the only arboreomorph known to preserve the stalk on a singular side being *Akrophyllas* (Grimes *et al*. 2023), however, the full-relief specimen preserves no evidence for the stalk or basal stem (Fig. 3.10A). This is due to the specimen being cut off towards the terminal end of the frond beyond the extent of the stalk on the front surface (see Brasier and Antcliffe 2009, fig. 12; Pérez-Pinedo *et al*. 2022, fig. 3). Where the specimen is cut off it reveals a cross sectional view of the internal structure of the organism, where the primary branches of the frond can be seen to be curved around a lumen which has been infilled with sediment (Pérez-Pinedo *et al*. 2022, fig. 8c; Fig. 3.10A). The sub-conical shape of *Charniodiscus* would have allowed for water to pass through the lumen and likely would have aided in filter/suspension feeding strategies (Laflamme *et al*. 2018; Pérez-Pinedo *et al*. 2022).

Clade Arboreomorpha Erwin *et al*. 2011

Genus *Corellia* gen. nov.

Type species— *Corellia washageuis* sp. nov.

Etymology— *Corellia* is named after the fictional planet in which Han Solo’s famous Corellian YT-1300 light freighter spaceship, the Millennium Falcon, was built in the Star Wars franchise, as both the spaceship and genus share a similar shape.

Generic diagnosis— As per species.

Remarks— As per species.

Corellia washageuis sp. nov.

Figs 3.2G, 3.11

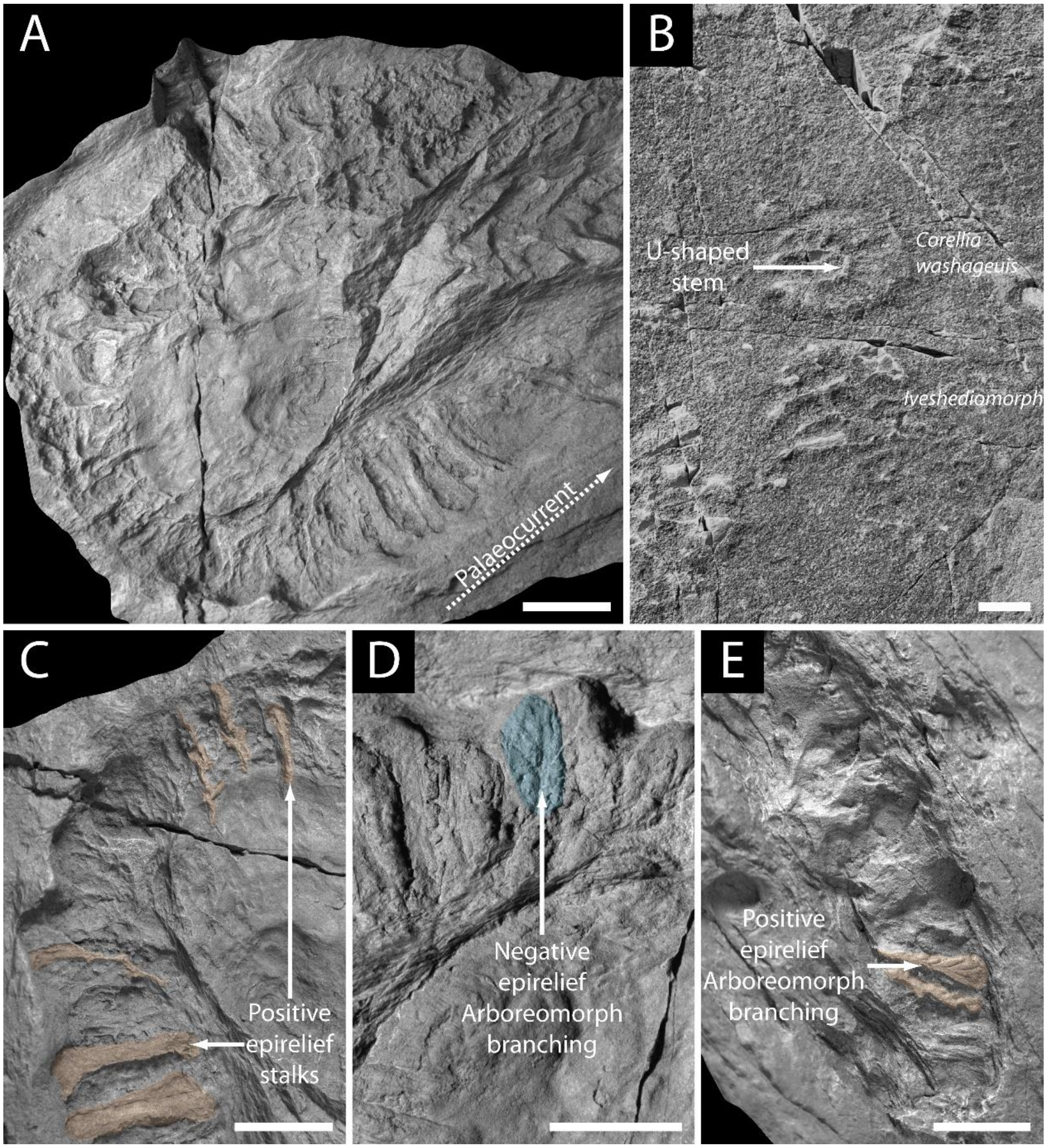


Fig. 3.11 – *Corellia washageuis* gen. et sp. nov. specimens. A, holotype of *Corellia washageuis* from the Allison Surface, Upper Island Cove (cast SB-2021-046ii). B, paratype of *Corellia washageuis*,

found in the Mistaken Point Ecological Reserve, preserving the curved U-shaped stem to which the individual stalks of the taxon are connected (field photo). C, close-up of the holotype showing the stalks that are attached to the individual branches (orange) (cast SB-2021-046ii). D, close-up of the holotype preserving the negative impression of an arboreomorph branch (light blue) (cast SB-2021-046ii). E, paratype of *Corellia washageuis* specimen from the Allison Surface preserving a positive epirelief arboreomorph branch (orange) (cast SB-2020-029i). (scale bars – 1 cm (A, C-E), 5 cm (B))

Type Material— The holotype and paratypes remain in the field, but plastotypes of the holotype and paratype from Upper Island Cove are to be accessioned to The Rooms, provincial museum of Newfoundland and Labrador (casts SB-2021-046ii, SB-2020-029i; Fig. 3.11A, C-E).

Material— Two *in situ* specimens are known from the Allison Surface at Upper Island Cove, with an additional *in situ* specimen located on the E-Surface at Watern Cove in the Mistaken Point Ecological Reserve.

Etymology— *washageuis* named for the Beothuk word for the moon "washageuis" which is in reference to the crescentic shape of the species.

Specific Diagnosis— Crescentic multipolar arboreomorph composed of numerous small bifoliate spatulate frondlets arranged perpendicular to their attachment site on a bedding-parallel U-shaped stem. On both the lower and upper sides of the organism only the primary branches are preserved. There are up to 7 primary branches per frondlet which are attached to the U-shaped stem by thick, strongly lineated stalks that run through the centre of the frondlet.

Description— The holotype of *Corellia washageuis* preserves small bifoliate frondlets with non-fractal branching, which are spatulate in shape and emanate from the margin of a poorly preserved central region (Fig. 3.11A, C-D). These frondlets can be seen to be attached to a curved U-shaped stem by thick stalks, as seen from the Mistaken Point specimen (Fig. 3.11B), which have longitudinal lineations similar to those seen in *Arborea* (Dunn *et al*. 2019a). The stalks and their associated frondlets radiate from their attachment sites on the U-shaped stem (Fig. 3.11A-B). *Corellia washageuis* can be seen to be one of the larger Ediacaran specimens preserved on the Allison Surface, with the holotype measuring approximately 6.5 cm by 5.4 cm (Fig. 3.11A). The Mistaken Point specimen is larger than its Upper Island Cove counterpart being up to 13 cm in length (Fig. 3.11B). The frondlets preserve arboreomorph branching, which can be seen to preserve exclusively primary branching on the upper and lower surfaces and lack any evidence for a backing sheet (Fig. 3.11D-E). Only two frondlets are preserved in the Upper Island Cove material; they show that branching is thicker on the lower surface of *Corellia washageuis*, with frondlet size ranging from 0.95 cm by 0.4 cm on the lower surface to 1.1 cm by 0.3 cm on the upper surface (Fig. 3.11A, D-E). The holotype preserves positive epirelief stalks on top of the negative relief frondlets (Fig. 3.11C). These stalks are attached to the base of the frondlets, continuing internally into the structure as they are not present on their external surface (Fig. 3.11C-D).

Remarks— *Corellia washageuis* has a unique crescentic shape (Fig. 3.11A-B), most comparable to *Onega stepanovi* from the White Sea Assemblage (Keller and Fedonkin 1977; Fedonkin *et al*. 2007). Unlike *Onega*, however, *Corellia* has bifoliate arboreomorph branching and thick stalks on the outer rim of the crescentic, or U-shaped, stem and does not taper at the apex (Fig. 3.11). As the holotype is preserved within an obstruction scour, there is a risk that the general body shape exhibited is a taphonomic artefact (McKean *et al*. 2023). This can be ruled out for *Corellia* however, as the specimen located in the Mistaken Point Ecological Reserve also preserves a similar crescent moon-like shape (Fig. 3.11B). Other than *Corellia* the only other Ediacaran taxon in which branching is attached to a curved structure is in the pedicle rod of the rangeomorph *Pectinifrons*, known from the Mistaken Point Ecological Reserve, Discovery UNESCO Global Geopark and at Green Head, Conception Bay North (Bamforth *et al*. 2008; Pérez-Pinedo *et al*. 2023).

The individual arboreomorph frondlets that compose the outer rim of *Corellia* are oriented perpendicular and reversed/with no relation to the palaeocurrent, as determined by the orientation of the obstacle scours, due to their relative position on the U-shaped stem (Fig. 3.11A, D, E). This lack of orientation to the palaeocurrent suggests that they were reclined on or slightly within the sediment during life (McIlroy *et al*. 2021, 2022b; Pérez-Pinedo *et al*. 2023). Along with the lack of a basal stem or holdfast structure, this suggest that *Corellia* was an epibenthic recliner similar to *Bradgatia*, *Fractofusus* and, potentially, *Pectinifrons* (Gehling and Narbonne 2007; Pérez-Pinedo *et al*. 2023; Taylor *et al*. 2023). It has previously been suggested that other arboreomorph genera had a recumbent lifestyle (Laflamme *et al*. 2018; Pérez-Pinedo *et al*. 2022), however, *Corellia* is the first arboreomorph suggested to have an entirely reclined mode of life. The lineated stalks that attach the frondlets to the U-shaped stem are not visible on the upper surface of *Corellia* (Fig. 3.11E) but are visible on its lower surface above the negative epirelief impression of the frondlets (Fig. 3.11C-D). This suggests that the stalks attaching the frondlets to the U-shaped stem were an internal structure in *Corellia* and that they were likely composed of a more resistant material than the frondlets, allowing for their fossilisation (cf. Pérez-Pinedo *et al*. 2022).

3.3.2 Unclassified specimens

Taphomorphs (Partially decayed fronds)

A total of 72 of the fossils found on the Allison Surface have been recognised as taphomorphs or 'partially decayed fronds' (Fig. 3.12), making it the largest single grouping from the surface. These specimens are comparable to the iveshediomorphs, which are widely considered to be the decayed remains of Ediacaran taxa that preserve little discernible original morphology beyond a gross outline (Liu *et al*. 2011; Antcliffe *et al*. 2015). At Upper Island Cove, all Ediacaran fossils have undergone some level of postmortem decay and other post fossilization processes, and as such could be recognised as 'taphomorphs' (Matthews *et al*. 2017; McKean *et al*. 2023, fig. 10c; Fig. 2.10C); however, over half of the fossils present can still be assigned to either a pre-existing or newly described taxon (e.g. Figs 3.2-3.11; Table B.1).

Specimens that are so poorly preserved that it has not been possible to give them a taxonomic identification have been classified as taphomorphs. Taphomorph preservation on the Allison Surface is variable, with some specimens exhibiting a general frond-like body-plan (Fig. 3.12B, E) and others being composed of little more than an impression of the necrotic material that was once present (Fig. 3.12A). Over a third of the taphomorphs are preserved in mixed epirelief (Fig. 3.12A-E; Table B.1), this is likely due to the weak lutefisk-like (see Magnus 1555; Legwold 1996) nature of the organism that, in the case of the poorly preserved material, was removed during exhumation without adequate mineralization of the encasing organism-sediment interface (McKean *et al*. 2023).

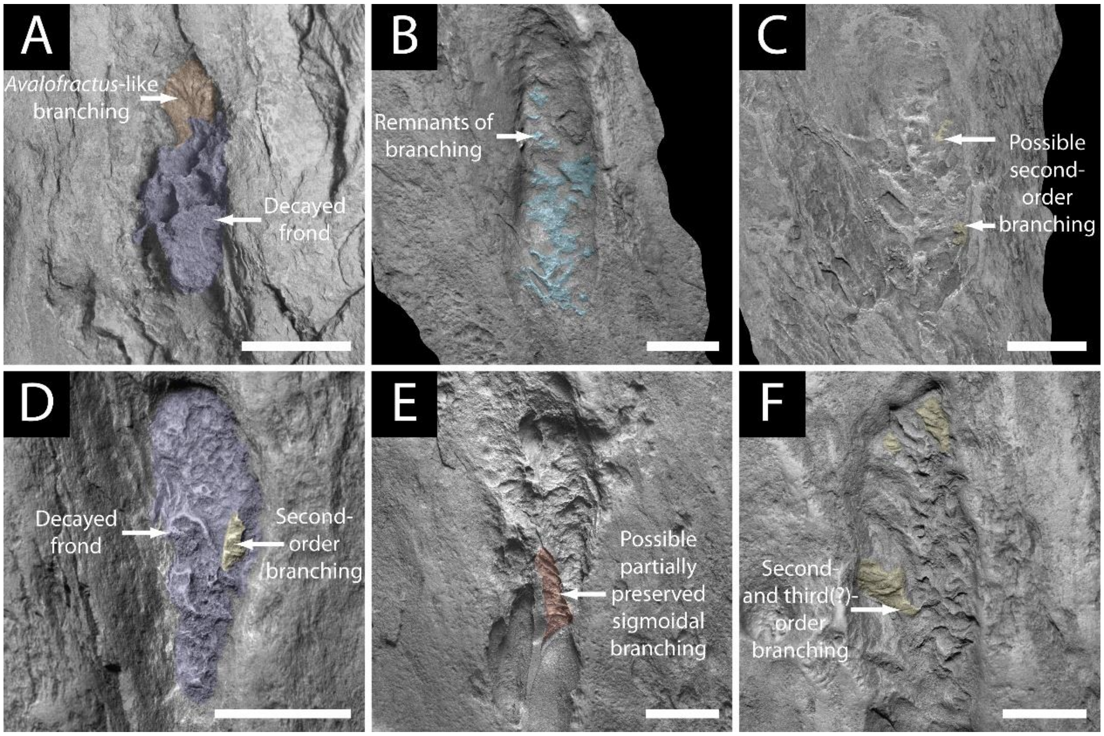


Fig. 3.12 – Taphomorph (partially decayed frond) specimens, not enough morphological detail is preserved to allow for a taxonomic diagnosis. A, largely decayed frond (dark blue) with some branching preserved up-current (orange) which is reminiscent of *Avalofractus* sp. (cast SB-2019-001d). B, mixed epirelief taphomorph that preserves faint remnants of branching and a midline (light blue) (cast SB-2020-028ii). C, mixed epirelief taphomorph which preserves some evidence for second-order charnid branching (yellow) (cast SB-2021-035ii). D, largely decayed frond (dark blue) with unidentifiable features and some second- and, possibly, third-order branching on the right side of the frond (yellow) (cast SB-2021-042vi). E, mixed relief decayed frond preserving traces of sigmoidal branching (red) (cast SB-2022-056i-a). F, mixed epirelief taphomorph that is highly decayed on the right side of the specimen; some preserved second- and, possibly, third-order branching is preserved on the left side of the frond (yellow) (cast SB-2022-067). (scale bars – 1 cm)

Taphomorphs and iveshediomorphs are known from a range of sites across the Avalonian Assemblage (Liu *et al*. 2011; Kenchington and Wilby 2014). While the degradation of organic matter means that these specimens cannot be used in taxonomic studies, their abundance on the Allison Surface is worth noting in regards to taphonomy, organism abundance and palaeoecology. Iveshediomorphs are often recorded alongside identifiable Ediacaran taxa (Liu *et al*. 2011, figs 5-6), as is also seen with the taphomorphs on the Allison Surface. The lack of any predators or scavengers in the Newfoundland material means that microbially mediated decay could occur over a prolonged period of time (McIlroy and Logan 1999; McIlroy *et al*. 2021). As such many Ediacaran fossil surfaces in Newfoundland preserve not just a snapshot of a single community, but potentially several generations of communities in various stages of decay (Liu *et al*. 2011, 2013; Mitchell and Butterfield 2018; McKean *et al*. 2023).

Insufficiently exhumed fronds (indet.)

In addition to the 72 unidentifiable taphomorphs/partially decayed fronds, an additional 47 fossils found on the Allison Surface have been assigned as ‘insufficiently exhumed fronds’ as they preserve little more than the partial branches of unidentifiable frondose taxa (McKean *et al*. 2023; Fig. 3.13; Table B.1). Some partial rangeomorph and arboreomorph specimens have been successfully assigned to taxa (e.g. Figs 3.4F, G, 3.5C, 3.8F, 3.9E), however, the vast majority of the partial specimens preserve such little detail that it is not possible to ascertain what order of branching is preserved (e.g. McKean *et al*. 2023, fig. 13c-b; Figs 2.13C-B, 3.13).

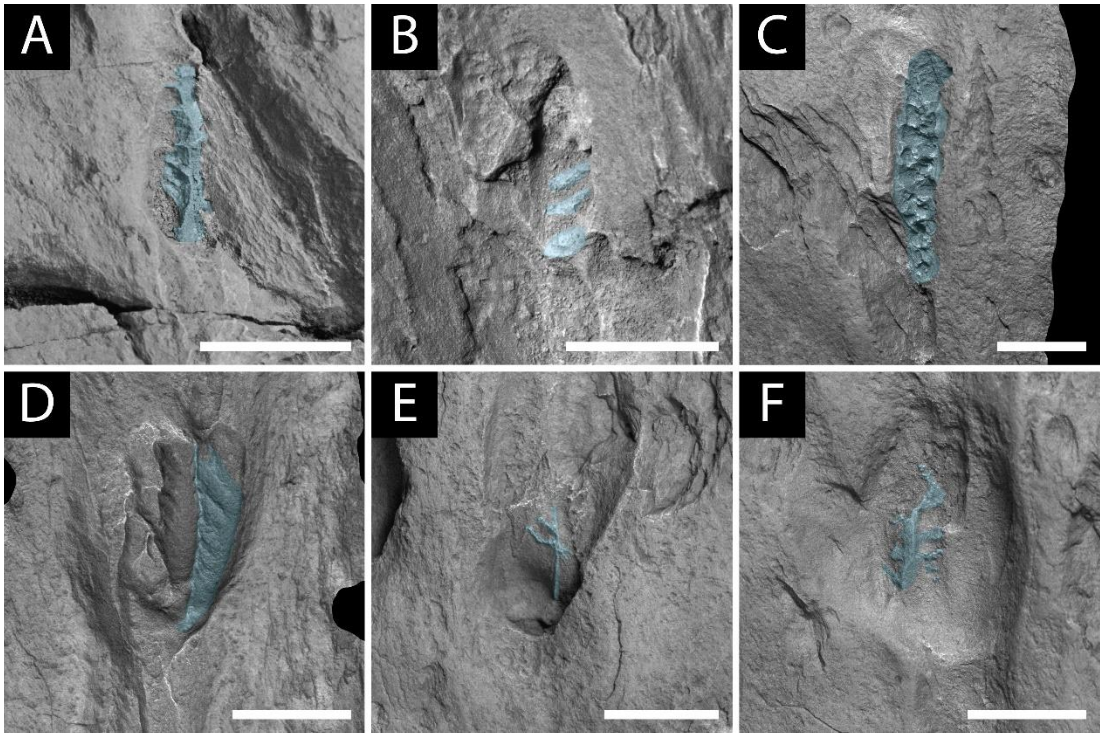


Fig. 3.13 – Insufficiently exhumed frond specimens (light blue) found in obstruction scours, not enough morphological detail is preserved to allow for a taxonomic diagnosis. A, stem/stalk/midline of frondose organism with partial branching (cast SB-2020-001b). B, first-order/primary branching of frondose organism lacking any higher-order detail (cast SB-2020-013iv). C, negative epirelief of a partial organism preserving the lower-side of an unidentifiable rangeomorph frond (cast SB-2020-021i). D, partial branching preserved at a steep angle in negative epirelief (cast SB-2020-028v). E, small remnant of frond preserved close to the holdfast (cast SB-2021-053viii-b). F, stem/stalk/midline of frondose organism with partial branching (cast SB-2022-059viii). (scale bars – 1 cm)

With the acknowledgement of the 'insufficiently exhumed fronds' being preserved in some scours at the site, the suggestion that some of the specimens preserved on the Allison Surface are 'isolated frondlets' (Narbonne 2004) can be readdressed. Due to their small size

(Fig. 3.13) it is possible that the 'insufficiently exhumed fronds' present are the remains of organisms that have been transported with the current as originally suggested in Narbonne (2004). However, the high relief and fine detail that is preserved—and the location of the specimens within the basal to central regions of the scours—suggests that these are not entrained specimens, but organisms that were barely exposed by eddying currents before the site was reburied under the T_c sands and $T_{d/e}$ muds/silts (McKean *et al*. 2023, fig. 11; Fig. 2.11).

The taxonomic affinity of the 'insufficiently exhumed fronds', like the taphomorphs, has proven challenging, with previous studies recognising the specimens as unidentifiable (e.g. Kenchington and Wilby 2014, fig. 4c; McKean *et al*. 2023, fig. 13b-c; Fig. 2.13B-C). The problem arises not from a lack of relief/detail in what is preserved, but a lack of sufficient material in each specimen to give an accurate taxonomic diagnosis with any degree of certainty (Fig. 3.13). For that reason, the partial fronds should be treated the same as the taphomorphs found on the Allison Surface; while of no use taxonomically, they play an important role in understanding the taphonomy and abundance of organisms preserved at the site.

Pneu-structure specimens - Microbially Induced Sedimentary Structure

Three peculiar fossils from the main outcrop of the Allison Surface and one additional specimen from the new outcrop are small structures that preserve a pneu-like body plan (Fig. 3.14). These specimens are devoid of any rangeomorph or arboreomorph branching and are instead composed of rows of pill-like pneu-structures, which are largely constrained by the row they are found in but can divide into smaller units (Fig. 3.14A-B). The best-preserved specimen is located on the new outcrop, measuring 1.1 cm by 0.8 cm; it is composed of roughly three rows of variably-shaped units that are larger towards the up-current portion of the structure (Fig. 3.14A). The specimens located on the main outcrop possess between one to three rows of these pneu-structures (Fig. 3.14B–D). The three specimens from the main outcrop of the Allison Surface are found within obstruction scours in a manner similar to the frondose fossils described herein (Fig. 3.14B-D), however, the specimen found on the new outcrop is not preserved in relation to any scour or other sedimentary structure (Fig. 3.14A). This suggests that it was concurrent with the deposition of the final layer of the T_d deposit, with the rows of pneu-structures being in line with the observed palaeocurrent (Fig. 3.14A).

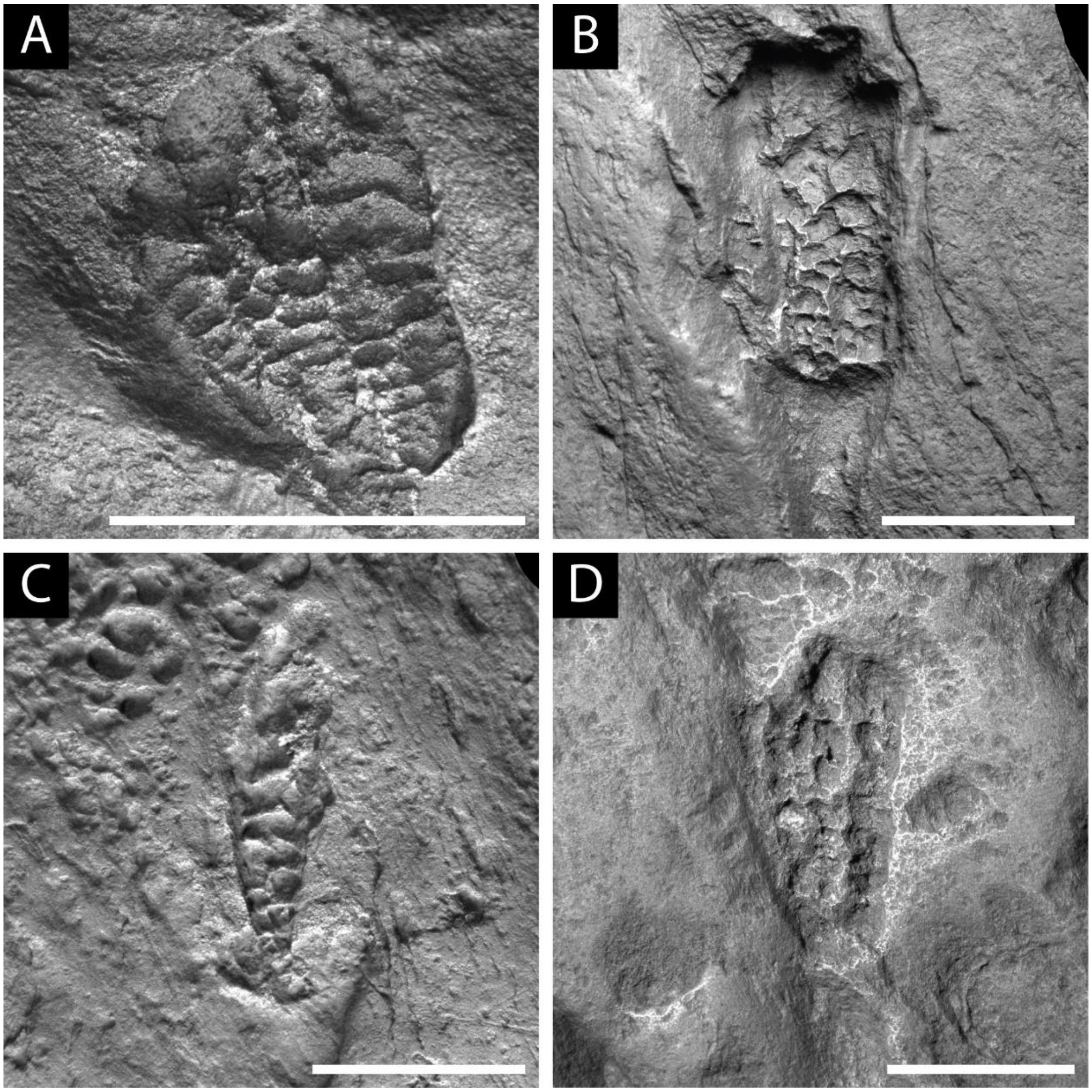


Fig. 3.14 – Pneu-structure specimens. A, best preserved specimen showing three rows of the pill-like structures, note this specimen is not found with an associated obstruction scour (cast SBNO-CM-20-02b). B, specimen preserved at the tip of an obstruction scour preserving at least two rows of the pill-like structures (cast SB-2020-020(b)i). C, small specimen showing the split from a single row (up current) to two rows (down current) of the pill-like structures (cast SB-2020-030i). D, poorly preserved specimen with up to three rows of the pill-like structures preserved (cast SB-2021-038ii). (scale bars – 1 cm)

The lack of systematic growth means that the pneu-specimens are not easily assigned to a pre-existing group or genus within the Ediacaran biota (e.g. Pflüg 1972; Erwin *et al*. 2011). The pill-like structures resemble small allantoid units similar to those of *Gigarimaneta* (Taylor *et al*. 2021), however, they do not share a continuous structure, size or pattern. Instead, these structures are only vaguely arranged in columns (Fig. 3.14) with individual 'units' dividing or joining across the rows (Fig. 3.14A). The shape of these 'units' is not continuous and can be seen to vary from near circular (Fig. 3.14A) to much more elongated and cylindrical (Fig. 3.14C). The most likely explanation for these problematic specimens is that they are a form of microbially induced sedimentary structure (MISS) that has been preserved on the surface (Noffke *et al*. 1996, 2001; Laflamme *et al*. 2011).

Most of these MISS structures appear within obstruction scours (Figs 3.14B-D, 3.15A), with their appearance being broadly reminiscent of the 'bubble trains' found across the surface except that they are elongated in the direction of the scours, not perpendicular to the scours like the 'bubble trains' (Laflamme *et al*. 2011; Brasier *et al*. 2013; McKean *et al*. 2023; Fig. 3.15B). It is possible that these structures are related to a microbial mat buried beneath the Allison Surface, the decay of which may have generated the bubble trains on the top of the T_d siltstone through gas escape (Dornbos *et al*. 2007; Laflamme *et al*. 2011; Homann *et al*. 2015; Fig. 3.15A-B). Other exposures of the microbial mat on the surface have been suggested (Fig. 3.15C), which look different than the pneu-structures presented here. Further work on the bubble trains and these other MISS structures is needed to better understand the microbial activity that was occurring on and in the Allison Surface. The lack of an obstruction scour, or any other sedimentary features, around the best-preserved specimen (Fig. 3.14A) suggest that it was buried just below the T_d silt and easily removed, similar to the organic material in *Bradgatia* sp. A (Fig. 3.6A-C). However, an alternative hypothesis is that the pneu-specimens preserve the impression of a protist growing on top of the T_d silt, similar to the mode of life of *Palaeopascichnus* (Hawco *et al*. 2019).

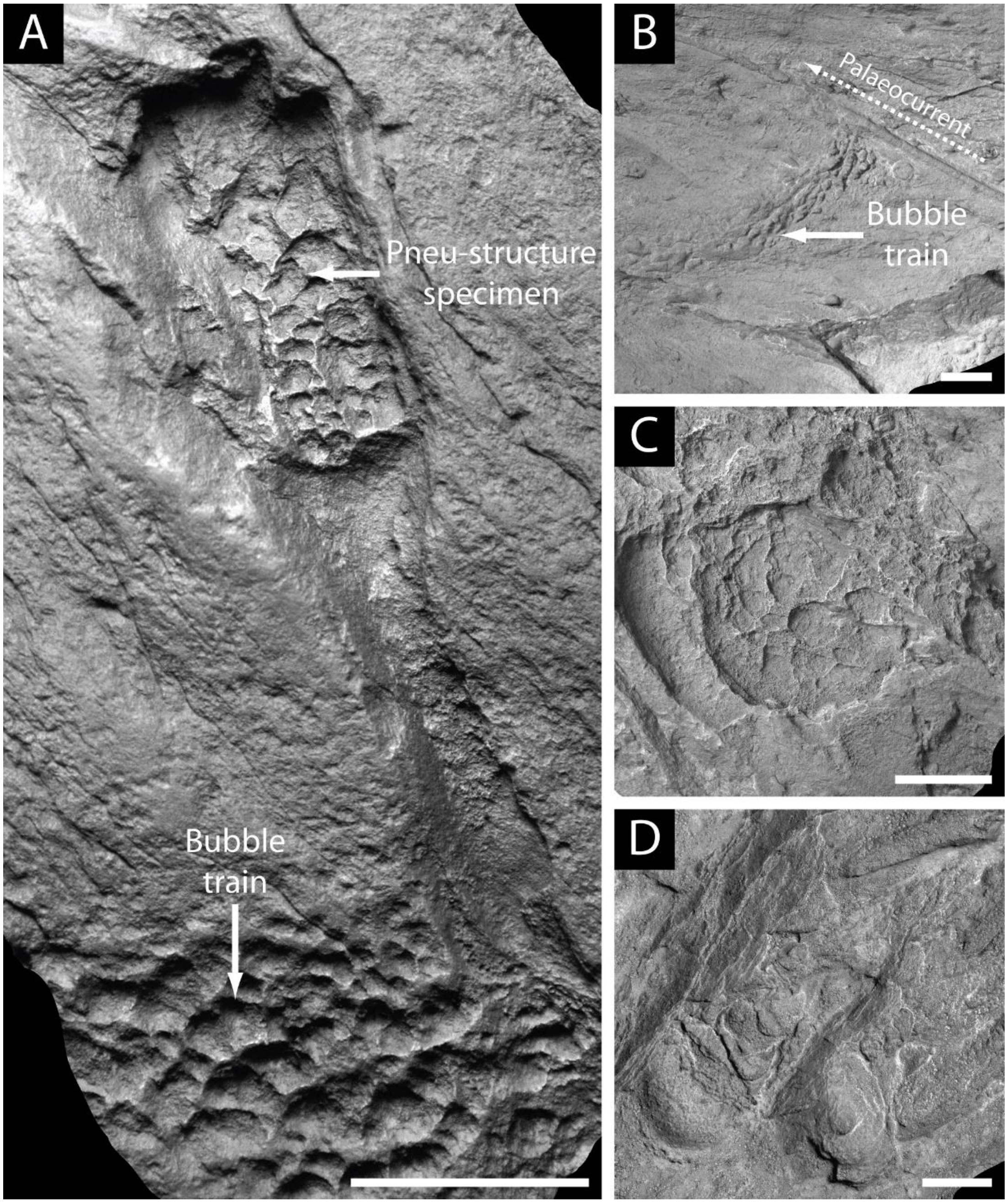


Fig. 3.15 – Potential evidence for preserved microbial mat structures at Upper Island Cove. A, pneu-structure specimen (Fig. 3.14B) preserved in close proximity to bubble train (cast SB-2020-020(b)i). B, bubble train preserved perpendicular to the palaeocurrent, as seen by the orientation of the tool mark (cast SB-2020-010ii). C, possible microbial texture overlying large holdfast (cast SB-2020-

018i). D, possible microbial mat texture exposed within an obstruction scour (SB-2022-065ii). (scale bars – 1 cm)

3.4 CONCLUSION

Recent studies on the taphonomy of the Upper Island Cove assemblage (McKean *et al*. 2023), the discovery of over 150 new specimens (Table B.1) and improved approaches to the systematics of Ediacaran taxonomy (Brasier *et al*. 2012; Dunn *et al*. 2019a) highlighted the need to revisit the taxonomy of the Ediacaran fossils preserved in the Upper Island Cove assemblage. Doing so has allowed us to update the systematic diagnosis of the classic Upper Island Cove organism *Avalofractus* and introduce a new species to the genus (Fig. 3.5), as well as further our understanding of the other classic Ediacaran taxon *Bradgatia* with two new morphotypes and the preservation of differentiated upper and lower surfaces (Fig. 3.6). The different upper and lower surfaces of the Allison Surface *Bradgatia* supports the idea that it might have been an epibenthic recliner that employed chemosymbiosis (Dufour and McIlroy 2017; McIlroy *et al*. 2021), with one surface being adapted for interactions with the water column and the other for interacting with the sediment/porewater system. Differentiated sides are also recognised in *Arborea* sp., a newly described species that shows clear arboreomorph branching on its front side and a backing sheet on its back side, allowing for its generic assignment (Dunn *et al*. 2019a; Pérez-Pinedo *et al*. 2022); however, more complete specimens and a closer comparison to *Pambikalbae* is needed before a formal taxonomic diagnosis can be confidently made.

In addition to *Avalofractus dosomitus*, two further new taxa have been described in this study: *Kannabuchia artkingii* (specimens previously considered to be *Trepassia* sp.; Fig. 3.8) and *Corellia washageuis* (Fig. 3.11). Both taxa preserve differentiated upper and lower surfaces and have been inferred as being epifaunal recliners, like *Bradgatia* and *Fractofusus* (Gehling and Narbonne 2007; Pérez-Pinedo *et al*. 2023; Taylor *et al*. 2023). The only taxon on the Allison Surface noted to preserve similar branching on either side of the frond is the erect rangeomorph *Avalofractus abaculus* (Fig. 3.4), suggesting that the variation in upper and lower surface morphology may be an adaptation in reclined taxa for chemosymbiosis (Dufour and McIlroy 2017; McIlroy *et al*. 2021). Although only preserving a single side of the organism, the rangeomorph *Charnia gracilis* (Wu *et al*. 2022; Fig. 3.7A-C), has been recognised in the Avalonian Assemblage for the first time, increasing its geographical and temporal range.

Other important components of the Upper Island Cove assemblage include the newly described MISS structures referred to herein as 'pneu-specimens' (Fig. 3.14). Alongside the enigmatic bubble train structures found at the site (Laflamme *et al*. 2011; Fig. 3.15A, B), these pneu-specimens give us new evidence for the possibility of a buried matground surface beneath the top of the T_d unit in which the Upper Island Cove assemblage fossils are found.

ACKNOWLEDGEMENTS

D. Pérez-Pinedo, J. Neville and H. Fitzgerald are thanked for their assistance in the field, discussion of the topic and personal insights into Ediacaran taxonomy, with R. Taylor and

G. Pasinetti additionally thanked for their advice, editorial assistance and helpful comments throughout the development of this chapter. Special thanks are given to the community of Upper Island Cove for their hospitality and vigilance and to The Rooms, provincial museum of Newfoundland and Labrador, for access to accessioned material. In accordance with provincial regulations, no fossils were removed from the Upper Island Cove site. This work is based on field photographs and casts which were made under permit from the Province of Newfoundland and Labrador, alongside the study of accessioned specimens housed at The Rooms, St. John's, NL. This project was supported by a NSERC Discovery Grant and Discovery Accelerator Supplement to DM.

REFERENCES

Antcliffe, J.B. and Brasier, M.D. 2008. *Charnia* at 50: Developmental models for Ediacaran fronds. *Palaeontology*, **51**, 11–26, https://doi.org/10.1111/j.1475-4983.2007.00738.x

Antcliffe, J.B., Callow, R.H.T. and Brasier, M.D. 2014. Giving the early fossil record of sponges a squeeze. *Biological Reviews*, **89**, 972–1004, https://doi.org/10.1111/brv.12090

Antcliffe, J.B., Hancy, A.D. and Brasier, M.D. 2015. A new ecological model for the ~565Ma Ediacaran biota of Mistaken Point, Newfoundland. *Precambrian Research*, **268**, 227–242, https://doi.org/10.1016/j.precamres.2015.06.015

Bamforth, E.L., Narbonne, G.M. and Anderson, M.M. 2008. Growth and ecology of a multi-branched Ediacaran rangeomorph from the Mistaken Point assemblage, Newfoundland. *Journal of Paleontology*, **82**, 763–777, https://doi.org/10.1666/07-112.1

Boag, T.H., Darroch, S.A.F. and Laflamme, M. 2016. Ediacaran distributions in space and time: testing assemblage concepts of earliest macroscopic body fossils. *Paleobiology*, **42**, 574–594, https://doi.org/10.1017/pab.2016.20

Boynton, H.E. and Ford, T.D. 1995. Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, **13**, 165–182.

Brasier, M.D. and Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: New insights from laser analysis. *Journal of the Geological Society*, **166**, 363–384, https://doi.org/10.1144/0016-76492008-011

Brasier, M.D., Antcliffe, J.B. and Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124, https://doi.org/10.1111/j.1475-4983.2012.01164.x

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Briggs, D.E.G. 2015. The Cambrian explosion. *Current Biology*, **25**, R864–R868, https://doi.org/10.1016/j.cub.2015.04.047

Butterfield, N.J. 2022. Constructional and functional anatomy of Ediacaran rangeomorphs. *Geological Magazine*, **159**, 1148–1159, https://doi.org/10.1017/S0016756820000734

Clapham, M.E., Narbonne, G.M. and Gehling, J.G. 2003. Paleoecology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland.

Paleobiology, **29**, 527–544, https://doi.org/10.1666/0094-8373(2003)029%3C0527:POTOKA%3E2.0.CO;2

Clarke, A.J.I., Kirkland, C.L., Menon, L.R., Condon, D.J., Cope, J.C.W., Bevins, R.E. and Glorie, S. 2024. U-Pb zircon-rutile dating of the Llangynog Inlier, Wales: Constraints on an Ediacaran shallow-marine fossil assemblage from East Avalonia. *Journal of the Geological Society*, **181**, https://doi.org/10.1144/jgs2023-081

Darroch, S.A.F., Laflamme, M., Schiffbauer, J.D. and Briggs, D.E.G. 2012. Experimental formation of a microbial death mask. *Palaios*, **27**, 293–303, https://doi.org/10.2110/palo.2011.p11-059r

Darroch, S.A.F., Smith, E.F., Laflamme, M. and Erwin, D.H. 2018. Ediacaran extinction and Cambrian explosion. *Trends in Ecology & Evolution*, **33**, 653–663, https://doi.org/10.1016/j.tree.2018.06.003

Darroch, S.A.F., Gutarra, S., Masaki, H., Olaru, A., Gibson, B.M., Dunn, F.S., Mitchell, E.G., Racicot, R.A., Burzynski, G. and Rahman, I.A. 2023. The rangeomorph *Pectinifrons abyssalis*: Hydrodynamic function at the dawn of animal life. *iScience*, **26**, 105989, https://doi.org/10.1016/j.isci.2023.105989

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2017. Relating Ediacaran fronds. *Paleobiology*, **43**, 171–180, https://doi.org/10.1017/pab.2016.54

Dornbos, S.Q., Noffke, N. and Hagadorn, J.W. 2007. Mat-decay features. *In*: Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W. and Catuneau, O. (eds) *Atlas of microbial mat features preserved within the clastic rock record*. Elsevier, 106–110.

Droser, M.L. and Gehling, J.G. 2015. The advent of animals: The view from the Ediacaran. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 4865–4870, https://doi.org/10.1073/pnas.1403669112

Dufour, S.C. and McIlroy, D. 2017. Ediacaran pre-placozoan diploblasts in the Avalonian biota: The role of chemosynthesis in the evolution of early animal life. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 211–219, https://doi.org/10.1144/SP448.5

Dunn, F.S., Liu, A.G. and Gehling, J.G. 2019a. Anatomical and ontogenetic reassessment of the Ediacaran frond *Arborea arborea* and its placement within total group Eumetazoa. *Palaeontology*, **62**, 851–865, https://doi.org/10.1111/pala.12431

Dunn, F.S., Wilby, P.R., Kenchington, C.G., Grazhdankin, D.V., Donoghue, P.C.J. and Liu, A.G. 2019b. Anatomy of the Ediacaran rangeomorph *Charnia masoni*. *Papers in Palaeontology*, **5**, 157–176, https://doi.org/10.5061/dryad.fg14s2r

Dunn, F.S., Liu, A.G., Grazhdankin, D.V., Vixseboxse, P., Flannery-Sutherland, J., Green, E., Harris, S., Wilby, P.R. and Donoghue, P.C.J. 2021. The developmental biology of *Charnia* and the eumetazoan affinity of the Ediacaran rangeomorphs. *Science Advances*, **7**, eabe0291, https://doi.org/10.1126/sciadv.abe0291

Erwin, D.H., Laflamme, M., Tweedt, S.M., Sperling, E.A., Pisani, D. and Peterson, K.J. 2011. The Cambrian conundrum: Early divergence and later ecological success in the early history of animals. *Science*, **334**, 1091–1097, https://doi.org/10.1126/science.1206375

Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. and Vickers-Rich, P. 2007. *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press.

Flude, L.I. and Narbonne, G.M. 2008. Taphonomy and ontogeny of a multibranched Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland. *Canadian Journal of Earth Sciences*, **45**, 1095–1109, https://doi.org/10.1139/E08-057

Ford, T.D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 211–217, https://doi.org/10.1144/pygs.31.3.211

Gehling, J.G. 1999. Microbial mats in terminal Proterozoic siliciclastics: Ediacaran death masks. *Palaios*, **14**, 40–57, https://doi.org/10.2307/3515360

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Ghisalberti, M., Gold, D.A., Laflamme, M., Clapham, M.E., Narbonne, G.M., Summons, R.E., Johnston, D.T. and Jacobs, D.K. Canopy flow analysis reveals the advantage of size in the oldest communities of multicellular eukaryotes. *Current Biology*, **24**, 305–309, https://doi.org/10.1016/j.cub.2013.12.017

Glaessner, M.F. and Daily, B. 1959. The geology and late Precambrian fauna of the Ediacara fossil reserve. *Records of the South Australia Museum*, **13**, 369–401.

Glaessner, M.F. and Wade, M. 1966. The Late Precambrian fossils from Ediacara, South Australia. *Palaeontology*, **9**, 599–628.

Grazhdankin, D. 2004. Patterns of distribution in the Ediacaran biotas: Facies versus biogeography and evolution. *Paleobiology*, **30**, 203–221, https://doi.org/10.1666/0094-8373(2004)030%3C0203:PODITE%3E2.0.CO;2

Grazhdankin, D. and Seilacher, A. 2005. A re-examination of the Nama-type Vendian organism *Rangea schneiderhoehni*. *Geological Magazine*, **142**, 571–582, https://doi.org/10.1017/S0016756805000920

Grazhdankin, D.V., Balthasar, U., Nagovitsin, K.E. and Kochnev, B.B. 2008. Carbonate-hosted Avalon-type fossils in arctic Siberia. *Geology*, **36**, 803–806, https://doi.org/10.1130/G24946A.1

Grimes, K.F., Narbonne, G.M., Gehling, J.G., Trusler, P.W. and Dececchi, T.A. 2023. Elongate Ediacaran fronds from the Flinders Ranges, South Australia. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2023.45

Hancy, A.D. and Antcliffe, J.B. 2020. Anoxia can increase the rate of decay for cnidarian tissue: Using *Actinia equina* to understand the early fossil record. *Geobiology*, **18**, 167–184, https://doi.org/10.1111/gbi.12370

Hawco, J.B., Kenchington, C.G. and McIlroy, D. 2019. A quantitative and statistical discrimination of morphotaxa within the Ediacaran genus *Palaeopascichnus*. *Papers in Palaeontology*, **7**, 657–673, https://doi.org/10.5061/dryad.jq7460s

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Hofmann, H.J. and Mountjoy, E.W. 2010. Ediacaran body and trace fossils in Miette Group (Windermere Supergroup) near Salient Mountain, British Columbia, Canada.

Canadian Journal of Earth Sciences, **47**, 1305–1325, https://doi.org/10.1139/E10-070

Hofmann, H.J., O'Brien, S.J. and King, A.F. 2008. Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36, https://doi.org/10.1666/06-087.1

Homann, M., Heubeck, C., Airo, A. and Tice, M.M. 2015. Morphological adaptations of 3.22 Ga-old tufted microbial mats to Archean coastal habitats (Moodies Group, Barberton Greenstone Belt, South Africa). *Precambrian Research*, **266**, 47–64, https://doi.org/10.1016/j.precamres.2015.04.018

Hoyal Cuthill, J.F. and Conway Morris, S. 2014. Fractal branching organizations of Ediacaran rangeomorph fronds reveal a lost Proterozoic body plan. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 13122–13126, https://doi.org/10.1073/pnas.1408542111

Hoyal Cuthill, J.F. and Conway Morris, S. 2017. Nutrient-dependent growth underpinned the Ediacaran transition to large body size. *Nature Ecology & Evolution*, **1**, 1201–1204, https://doi.org/10.1038/s41559-017-0222-7

Huang, T., Chen, D., Ding, Y., Zhou, X. and Zhang, G. 2020. SIMS U-Pb zircon geochronological and carbon isotope chemostratigraphic constraints on the Ediacaran-Cambrian boundary succession in the Three Gorges Area, South China. *Journal of Earth Science*, **31**, 69–78, https://doi.org/10.1007/s12583-019-1233-x

Ichaso, A.A., Dalrymple, R.W. and Narbonne, G.M. 2007. Paleoenvironmental and basin analysis of the late Neoproterozoic (Ediacaran) upper Conception and St. John's groups, west Conception Bay, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 25–41, https://doi.org/10.1139/e06-098

Jenkins, R.J.F. 1985. The enigmatic Ediacaran (late Precambrian) genus *Rangea* and related forms. *Paleobiology*, **11**, 336–355, https://doi.org/10.1017/S0094837300011635

Jenkins, R.J.F. and Gehling, J.G. 1978. A review of the frond-like fossils of the Ediacara assemblage. *Records of the South Australia Museum*, **17**, 347–359.

Jenkins, R.J.F. and Nedin, C. 2007. The provenance and palaeobiology of a new multi-vaned, chambered frondose organism from the Ediacaran (later Neoproterozoic) of South Australia. *In*: Vickers-Rich, P. and Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, Special Publications, **286**, 195–222, https://doi.org/10.1144/sp286.15

Keller, B.M. and Fedonkin, M.A. 1977. New organic fossil finds in the Precambrian Valday series along the Syuz'ma River. *International Geology Review*, **19**, 924–930, https://doi.org/10.1080/00206817709471091

Kenchington, C.G. and Wilby, P.R. 2014. Of time and taphonomy: Preservation in the Ediacaran. *The Paleontological Society Papers*, **20**, 101–122, https://doi.org/10.1017/S1089332600002825

Kenchington, C.G. and Wilby, P.R. 2017. Rangeomorph classification schemes and intra-specific variation: Are all characters created equal? *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 221–250, https://doi.org/10.1144/SP448.19

Laflamme, M. 2014. Modeling morphological diversity in the oldest large multicellular organisms. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 12962–12963, https://doi.org/10.1073/pnas.1412523111

Laflamme, M. and Narbonne, G.M. 2008a. Ediacaran fronds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 162–179, https://doi.org/10.1016/j.palaeo.2007.05.020

Laflamme, M. and Narbonne, G.M. 2008b. Competition in a Precambrian world: Palaeoecology of Ediacaran fronds. *Geology Today*, **24**, 182–187, https://doi.org/10.1111/j.1365-2451.2008.00685.x

Laflamme, M., Narbonne, G.M. and Anderson, M.M. 2004. Morphometric analysis of the Ediacaran frond *Charniodiscus* from the Mistaken Point Formation, Newfoundland. *Journal of Paleontology*, **78**, 827–837, https://doi.org/10.1666/0022-3360(2004)078%3C0827:MAOTEF%3E2.0.CO;2

Laflamme, M., Narbonne, G.M., Greentree, C. and Anderson, M.M. 2007. Morphology and taphonomy of an Ediacaran frond: *Charnia* from the Avalon Peninsula of Newfoundland. *In*: Vickers-Rich, P. and Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, Special Publications, **286**, 237–257, https://doi.org/10.1144/SP286.17

Laflamme, M., Xiao, S. and Kowaleski, M. 2009. Osmotrophy in modular Ediacara organisms. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 14438–14443, https://doi.org/10.1073/pnas.0904836106

Laflamme, M., Schiffbauer, J.D. and Narbonne, G.M. 2011. Deep-water microbially induced sedimentary structures (MISS) in deep time: The Ediacaran fossil *Iveshedia*.

In: Noffke, N. and Chafetz, H. (eds) *Microbial Mats in Siliciclastic Depositional Systems Through Time*. Society for Sedimentary Geology SEPM Special Publications, **101**, 111–123, https://doi.org/10.2110/sepmsp.101.111

Laflamme, M., Darroch, S.A.F., Tweedt, S.M., Peterson, K.J. and Erwin, D.H. 2013. The end of the Ediacara biota: Extinction, biotic replacement, or Cheshire Cat? *Gondwana Research*, **23**, 558–573, https://doi.org/10.1016/j.gr.2012.11.004

Laflamme, M., Gehling, J.G. and Droser, M.L. 2018. Deconstructing an Ediacaran frond: Three-dimensional preservation of *Arborea* from Ediacara, South Australia. *Journal of Paleontology*, **92**, 323–335, https://doi.org/10.1017/jpa.2017.128

Landing, E., Antcliffe, J.B., Geyer, G., Kouchinsky, A., Bowser, S.S. and Andreas, A. 2018. Early evolution of colonial animals (Ediacaran Evolutionary Radiation–Cambrian Evolutionary Radiation–Great Ordovician Biodiversification Interval). *Earth-Science Reviews*, **178**, 105–135, https://doi.org/10.1016/j.earscirev.2018.01.013

Legwold, G. 1996. *The Last Word on Lutefisk: True Tales of Cod and Tradition*. Conrad Henry Press.

Liu, A.G. and Conliffe, J. 2015. *2015 Fall Field Trip, The Ediacaran fossils of the Avalon Peninsula*. Geological Association of Canada, Newfoundland and Labrador Section.

Liu, A.G., McIlroy, D., Antcliffe, J.B. and Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630, https://doi.org/10.1111/j.1475-4983.2010.01024.x

Liu, A.G., Matthews, J.J., Menon, L.R., McIlroy, D. and Brasier, M.D. 2014. *Haootia quadriformis* n. gen., n. sp., interpreted as a muscular cnidarian impression from the

Late Ediacaran period (approx. 560 Ma). *Proceedings of the Royal Society B*, **281**, 20141202, https://doi.org/10.1098/rspb.2014.1202

Liu, A.G., Kenchington, C.G. and Mitchell, E.G. 2015. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380, https://doi.org/10.1016/j.gr.2014.11.002

Liu, A.G., Matthews, J.J. and McIlroy, D. 2016. The *Beothukis*/*Culmofrons* problem and its bearing on Ediacaran macrofossil taxonomy: Evidence from an exceptional new fossil locality. *Palaeontology*, **59**, 45–58, https://doi.org/10.1111/pala.12206

Liu, A.G., Matthews, J.J. and McIlroy, D. 2017. *Field Trip 3, Late Ediacaran Geology and Palaeobiology of the Bonavista Peninsula, Newfoundland*. International Symposium on the Ediacaran–Cambrian Transition 2017.

Magnus, O. 1555. *Historia de gentibus septentrionalibus (The history of the Nordic people)*. Rome.

Mason, S.J. and Narbonne, G.M. 2016. Two new Ediacaran small fronds from Mistaken Point, Newfoundland. *Journal of Paleontology*, **90**, 183–194, https://doi.org/10.1017/jpa.2016.14

Matthews, J.J., Liu, A.G. and McIlroy, D. 2017. Post-fossilization processes and their implications for understanding Ediacaran macrofossil assemblages. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 251–269, https://doi.org/10.1144/SP448.20

Matthews, J.J., Liu, A.G., Yang, C., McIlroy, D., Levell, B. and Condon, D.J. 2020. A chronostratigraphic framework for the rise of the Ediacaran macrobiota: New constraints from Mistaken Point Ecological Reserve, Newfoundland. *GSA Bulletin*, **133**, 612–624, https://doi.org/10.1130/B35646.1

McIlroy, D. and Horák, J.M. 2006. Neoproterozoic: The late Precambrian terranes that formed Eastern Avalonia. *In*: Brenchley, P.J. and Rawson, P.F. (eds) *The Geology of England and Wales, Second Edition*. The Geological Society, London, 9–23, https://doi.org/10.1144/GOEWP

McIlroy, D. and Logan, G.A. 1999. The impact of bioturbation on infaunal ecology and evolution during the Proterozoic-Cambrian transition. *Palaios*, **14**, 58–72, https://doi.org/10.2307/3515361

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Pérez-Pinedo, D., Pasinetti, G., McKean, C., Taylor, R.S. and Hiscott, R.N. 2022a. Rheotropic epifaunal growth, not felling by density currents, is responsible for many Ediacaran fossil orientations at Mistaken Point. *Frontiers in Earth Science*, **10**, 849194, https://doi.org/10.3389/feart.2022.849194

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022b. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

McKean, C., Taylor, R.S. and McIlroy, D. 2023. New taphonomic and sedimentological insights into the preservation of high-relief Ediacaran fossils at Upper Island Cove, Newfoundland. *Lethaia*, **56**, 1–17, https://doi.org/10.18261/let.56.4.2

McKean, C., Matthews, J.J., Rideout, B.W.T., Taylor, R.S. and McIlroy, D. 2024. Protecting Newfoundland's palaeontological geoheritage: mitigating anthropic and environmental damage to the Ediacaran fossils of Upper Island Cove. *Geoheritage*, **16**, 1–19, http://doi.org/10.1007/s12371-024-00959-5

Mitchell, E.G. and Butterfield, N.J. 2018. Spatial analyses of Ediacaran communities at Mistaken Point. *Paleobiology*, **44**, 40–57, https://doi.org/10.1017/pab.2017.35

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M. 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442, https://doi.org/10.1146/annurev.earth.33.092203.122519

Narbonne, G.M. and Gehling, J.G. 2003. Life after snowball: The oldest complex Ediacaran fossils. *Geobiology*, **31**, 27–30, https://doi.org/10.1130/0091-7613(2003)031%3C0027:LASTOC%3E2.0.CO;2

Narbonne, GM., Gehling, J.G. and Vickers-Rich, P. 2007. The Misty Coasts of Newfoundland. *In*: Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. Vickers-Rich, P. (eds) *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press, 49–68.

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 505–523, https://doi.org/10.1666/08-072R1.1

Nedin, C. and Jenkins, R.J.F. 1998. First occurrence of the Ediacaran fossil *Charnia* from the southern hemisphere. *Alcheringa: An Australasian Journal of Palaeontology*, **22**, 315–316, https://doi.org/10.1080/03115519808619329

Noble, S.R., Condon, D.J., Carney., J.N., Wilby, P.R., Pharaoh, T.C. and Ford, T.D. 2015. U-Pb geochronology and global context of the Charnian Supergroup, UK: Constraints on the age of key Ediacaran fossil assemblages. *Geological Society of America Bulletin*, **127**, 250–265, https://doi.org/10.1130/B31013.1

Noffke, N., Gerdes, G., Klenke, T. and Krumbein, W.E. 1996. Microbially induced sedimentary structures—Examples from modern sediments of siliciclastic tidal flats. *Zentralblatt für Geologie und Paläontologie Teil I*, 307–316.

Noffke, N., Gerdes, G., Klenke, T. and Krumbein, W.E. 2001. Microbially induced sedimentary structures—A new category within the classification of primary sedimentary structures. *Journal of Sedimentary Research*, **71**, 649–656, https://doi.org/10.1306/2DC4095D-0E47-11D7-8643000102C1865D

Pasinetti, G. and McIlroy, D. 2023. Paleobiology and taphonomy of the rangeomorph *Culmofrons plumosa*. *Palaeontology*, **66**, e12671, https://doi.org/10.1111/pala.12671

Pérez-Pinedo, D., McKean, C., Taylor, R.S. and McIlroy, D. 2022. *Charniodiscus* and *Arborea* are separate genera within the Arboreomorpha: Using the holotype of *C. concentricus* to resolve a taxonomic tangle. *Frontiers in Earth Science*, **9**, 785929, https://doi.org/10.3389/feart.2021.785929

Pérez-Pinedo, D., Neville, J.M., Pasinetti, G., McKean, C., Taylor, R. and McIlroy, D. 2023. Frond orientations with independent current indicators demonstrate the reclining rheotropic mode of life of several Ediacaran rangeomorph taxa. *Paleobiology*, **49**, 471–492, https://doi.org/10.1017/pab.2023.2

Pérez-Pinedo, D., Nicholls, R., Neville, J. and McIlroy, D. 2024. Hydrodynamic insights into the palaeobiology of the Ediacaran rangeomorph *Fractofusus misrai*. *iScience*, **27**, 110107, https://doi.org/10.1016/j.isci.2024.110107

Pflüg, H.D. 1972. Systematik der jung-präkambrischen Petalonamae. *Paläontologische Zeitschrift*, **46**, 56–67, https://doi.org/10.1007/BF02989552

Seilacher, A. 1992. Vendobionta and Psammocorallia: Lost constructions of Precambrian evolution. *Journal of the Geological Society*, **149**, 607–613, https://doi.org/10.1144/gsjgs.149.4.0607

Singer, A., Plotnick, R. and Laflamme, M. 2012. Experimental fluid mechanics of an Ediacaran frond. *Palaeontologia Electronica*, **15**, 19A, https://doi.org/10.26879/297

Taylor, R.S., Matthews, J.J., Nicholls, R. and McIlroy, D. 2021. A re-assessment of the taxonomy, palaeobiology and taphonomy of the rangeomorph organism *Hapsidophyllas flexibilis* from the Ediacaran of Newfoundland, Canada. *Paläontologische Zeitschrift*, **95**, 187–207, https://doi.org/10.1007/s12542-020-00537-4

Taylor, R.S., Nicholls, R., Neville, J.M. and McIlroy, D. 2023. Morphological variation in the rangeomorph organism *Fractofusus misrai* from the Ediacaran of Newfoundland, Canada. *Geological Magazine*, **160**, 146–166, https://doi.org/10.1017/S0016756822000723

Wang, X., Pang, K., Chen, Z., Wan, B., Xiao, S., Zhou, C. and Yuan, X. 2020. The Ediacaran frondose fossil *Arborea* from the Shibantan limestone of South China. *Journal of Paleontology*, **94**, 1034–1050, https://doi.org/10.1017/jpa.2020.43

Williams, G.C., Hoeksema, B.W. and van Ofwegen, L. 2012. A fifth morphological polyp in pennatulacean octocorals, with a review of polyp polymorphism in the genera *Pennatula* and *Pteroeides* (Anthozoa: Pennatulidae). *Zoological Studies*, **51**, 1006–1017.

Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, J.G. and Clapham, M.E. 2003. Paleoenvironmental analysis of the late Neoproterozoic Mistaken Point and Trepassey formations, southeastern Newfoundland. *Canadian Journal of Earth Sciences*, **40**, 1375–1391, https://doi.org/10.1139/e03-048

Wu, C., Pang, K., Chen, Z., Wang, X., Zhou, C., Wan, B., Yuan, X. and Xiao, S. 2022. The rangeomorph fossil *Charnia* from the Ediacaran Shibantan biota in the Yangtze Gorges area, South China. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2022.97

Xiao, S., Narbonne, G.M., Zhou, C., Laflamme, M., Grazhdankin, D.V., Moczydlowska-Vidal, M. and Cui, H. 2016. Towards an Ediacaran time scale: Problems, protocols, and prospects. *Episodes*, **39**, 540–555, https://doi.org/10.18814/epiiugs/2016/v39i4/103886

Xiao, S., Chen, Z., Pang, K., Zhou, C. and Yuan, X. 2020. The Shibantan Lagerstätte: Insights into the Proterozoic-Phanerozoic transition. *Journal of the Geological Society*, **178**, jgs2020-135, https://doi.org/10.1144/jgs2020-135

Yang, C., Rooney, A.D., Condon D.J., Li, X., Grazhdankin, D.V., Bowyer, F.T., Hu, C., Macdonald, F.A. and Zhu, M. 2021. The tempo of Ediacaran evolution. *Science Advances*, **7**, eabi9643, http://doi.org/10.1126/sciadv.abi9643

CHAPTER 4

Protecting Newfoundland's palaeontological geoheritage: Mitigating anthropic and environmental damage to the Ediacaran fossils of Upper Island Cove

CHRISTOPHER MCKEAN[1*], JACK J. MATTHEWS[2], BENJAMIN W.T. RIDEOUT[3], ROD S. TAYLOR[1,4] AND DUNCAN MCILROY[1]

[1]*Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5, Canada*

[2]*Oxford University Museum of Natural History, Parks Road, Oxford, OX1 3PW, UK*

[3]*Unaffiliated, Spaniard's Bay, NL, Canada*

[4]*Johnson Geo Centre, Memorial University of Newfoundland, St. John's, NL, A1A 1B2, Canada*

[*]*Corresponding author (cmckean@mun.ca)*

PREFACE

This chapter has been *published* with the international journal *Geoheritage* (doi: 10.1007/s12371-024-00959-5) and has been formatted for thesis submission herein. The scientific content of this chapter is identical to the research publication, with the copyright and publishing rights for this thesis chapter being retained by the authors (see pages iv–vi). The research conducted within this chapter was exempt from a Research Ethics Board review as outlined in *Article 2.3* in the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans – TCPS 2 (2022)*. This chapter was devised by Christopher McKean, Jack J. Matthews and Duncan McIlroy. Christopher McKean, as lead author, wrote this chapter, with editorial input from Jack J. Matthews, Rod S. Taylor and Duncan McIlroy. Collection and analysis of data was conducted by Christopher McKean, based off of a method originally developed by Jack J. Matthews. Interpretation of results and discussion of mitigation techniques was conducted by Christopher McKean and refined through feedback from Jack J. Matthews and Duncan McIlroy. Casting of the Allison Surface as outlined in this chapter was led by Christopher McKean. All figures were constructed by Christopher McKean. The data used for Fig. 4.11 was collected by Benjamin W.T. Rideout who provided support in discovering the accessory sites in Conception Bay North, for which he has been acknowledged as an author in this chapter and the published paper. Additional support from those not listed as authors can be found in the acknowledgements at the end of this chapter.

ABSTRACT

Over 250 fossils belonging to the Ediacaran biota have been recognised from a single site in the town of Upper Island Cove, Newfoundland. These fossils preserve high-relief, sub-mm morphological detail providing an opportunity to further our understanding of some of the earliest Ediacaran organisms. Unlike many other Ediacaran localities, the geoheritage of this site is at risk to both high impact anthropic and environmental events due to its location within the town and close proximity to the ocean. As part of a year-long study, cameras were set up to record potentially deleterious events impacting the fossiliferous surface. Rare high impact anthropic events such as debris falling onto the surface have been noted at the site, alongside the potential for inadvertent damage caused by misuse through poor footwear and inappropriate activities. Environmental events are more common and present a high risk of damage to the fossils through high-energy waves covering the surface and the formation of sheets of ice during the winter that engulf the fossils on numerous occasions. Work is now underway to implement geoconservation methods that will mitigate the challenges that the site faces and minimise any future damage. Some of these methods may be pertinent to other at-risk fossil localities found across the world.

KEYWORDS

Ediacaran biota, Palaeontology, Geoconservation, Geoheritage, Newfoundland

4.1 INTRODUCTION

The town of Upper Island Cove, on the west of Conception Bay, Newfoundland (Fig. 4.1), hosts some of the best-preserved Ediacaran macroorganisms in the world (Narbonne 2004; Brasier *et al*. 2013). The fossils are contemporaries of the well-studied fossiliferous localities at Mistaken Point Ecological Reserve (Anderson and Misra 1968; Matthews *et al*. 2020), the Discovery UNESCO Global Geopark on the Bonavista Peninsula (Hofmann *et al*. 2008; Liu *et al*. 2016; McIlroy *et al*. 2021), and Charnwood Forest in Central England (Ford 1958; Wilby *et al*. 2011; Pérez-Pinedo *et al*. 2022). Unlike the other Ediacaran fossil sites in Newfoundland, which are found in relatively remote locations, the fossil site in Upper Island Cove is located within the town and is a popular site for recreational activities.

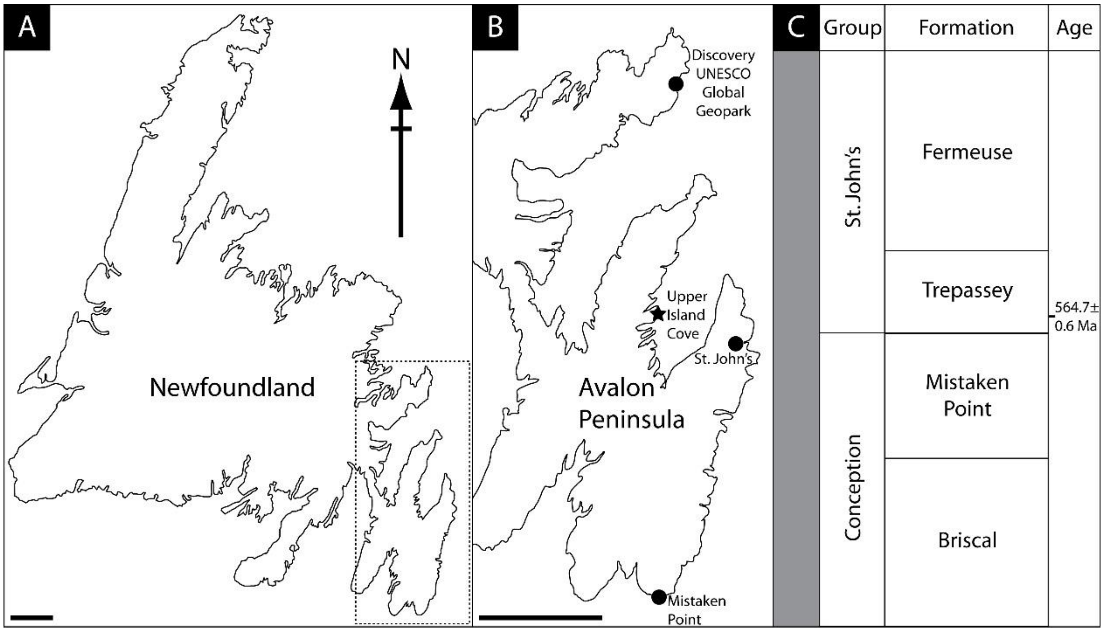


Fig. 4.1 – Location of the Upper Island Cove fossil locality. A, map of Newfoundland highlighting the southeastern section of the island where Ediacaran fossils have been discovered. B, the Avalon and Bonavista Peninsulas indicating the key fossil localities of Mistaken Point and the Discovery

UNESCO Global Geopark in relation to Upper Island Cove and the city of St. John's. C, stratigraphic column highlighting the formation and lithostratigraphically-correlated age of the fossils discovered in Upper Island Cove (following Matthews *et al*. 2020). (scale bars – 50 km)

Fossils of Ediacaran age have been known from western Conception Bay since the 1980s (King 1988). Despite the popularity of the site, the fossil bed in Upper Island Cove proper, a ~130 m^2 locality known as the Allison Surface (Province of Newfoundland and Labrador 2011; Brasier *et al*. 2013), was not recognised until 2004 (Narbonne 2004). The fossils were noted to exhibit sub-mm, three-dimensional preservation of Ediacaran fronds belonging to the clade Rangeomorpha (Narbonne 2004; Narbonne *et al*. 2009; Fig. 4.2). This type of three-dimensional preservation is not known from elsewhere in the Avalonian Assemblage (Narbonne *et al*. 2009; Brasier *et al*. 2013). Recently it has been observed that some of the fossils found at Upper Island Cove preserve both the upper and lower surface of the organisms, alongside "full" relief preservation (Brasier *et al*. 2013; McKean *et al*. 2023). "Full" relief preservation is known from later Ediacaran assemblages (e.g. Butterfield 2022), with the only other examples of upper surface preservation of Ediacaran organisms in Newfoundland being the disturbed/tousled *Fractofusus* from Mistaken Point Ecological Reserve (Gehling and Narbonne, 2007; Taylor *et al*. 2023), and the "full" relief preservation of the arboreomorph *Charniodiscus* sp. (Pérez-Pinedo *et al*. 2022; McKean *et al*. 2023). As such, the Upper Island Cove lagerstätte provides a valuable opportunity to further our understanding of the morphology of some of the earliest Ediacaran organisms, making it a geoheritage site of international significance.

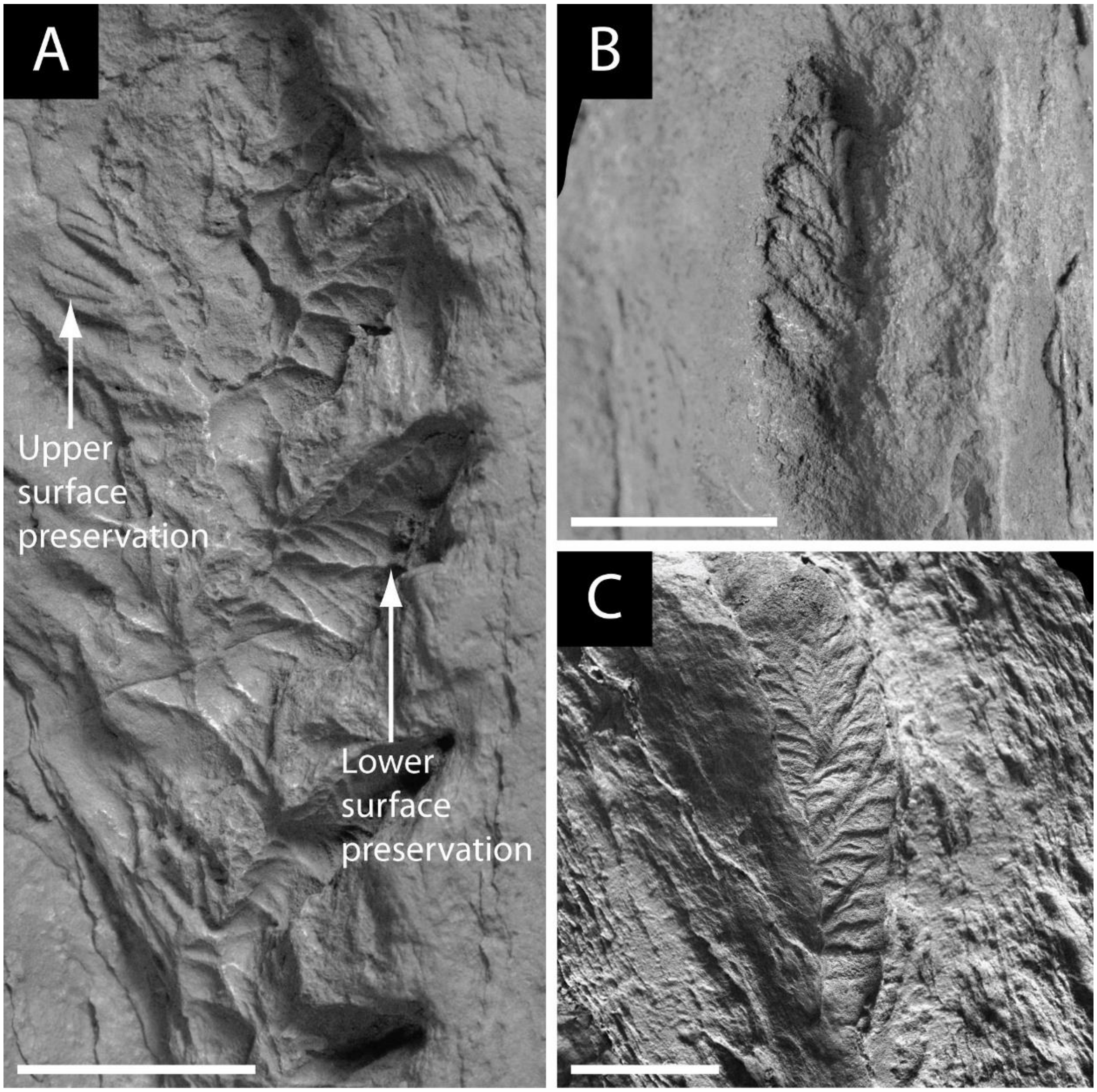


Fig 4.2 – High relief, sub-mm 3D preservation of Ediacaran fronds from Upper Island Cove. A, *Bradgatia* sp. preserving the upper and lower surface of the organism (cast SB-2021-052i). B, *Avalofractus abaculus* (cast SB-2022-062v). C, cf. *Trepassia* sp. (cast SB-2021-034). (scale bars – 1 cm)

In the Province of Newfoundland and Labrador, Ediacaran fossils within Ecological Reserves were first protected by the '*Fossils Ecological Reserve Regulations* under the *Wilderness and Ecological Reserves Act*' at Fortune Head, Mistaken Point and Table Point.

These regulations prohibit the destruction, damage or removal of fossil material and ban the use of mechanical and electrical rock cutting/removal tools within the reserves (Province of Newfoundland and Labrador 1997, 2009). Ediacaran fossils outside of reserves were not protected until 2011 under the '*Palaeontological Resource Regulations* under the *Historic Resources Act*' which designated all known Ediacaran fossil sites, including the Allison Surface at Upper Island Cove, as 'Significant Palaeontological Sites'. The vast majority of fossils belonging to the Ediacaran biota received additional protection as 'Significant Fossils', granting immediate protection regardless of where they are discovered in the province (Province of Newfoundland and Labrador 2011). Under the designation of 'Significant Palaeontological Sites' conservation status is maintained by controlling activities such as sampling and development, with scientific research only allowed under permit from the provincial government (Province of Newfoundland and Labrador 2011).

Even with the provincial legislation that protects fossils from collection, the Allison Surface at Upper Island Cove is still at risk from environmental and anthropic damage, risking the loss of the exquisite detail preserved in these fossils or even their complete destruction. Previous studies conducted in relation to the Mistaken Point Ecological Reserve in Newfoundland have shown that footfall on fossiliferous surfaces is potentially a highly significant agent of erosion (Matthews and McIlroy 2019). Other sites that are not within ecological reserves do not have policies to protect against damage by visitation, and the number of visitors is not controlled or monitored. Anecdotal accounts of the usage of the Upper Island Cove site by the local community (pers. comm. Town of Upper Island Cove

2021) highlight that the fossil surface itself has experienced a wide variety of activities such as: wedding and "prom" group photography; BBQs; picnics and a variety of other recreational activities.

It is likely that the relatively flat nature of the fossiliferous surface, with bedding planes that are near horizontal and in close proximity to the ocean, is what makes the Allison Surface an attractive location to the general public. This is enhanced by the ease of access to the site, which is just a few metres from the main road, with steps taking people from street-level to the beach. This surface is also subject to erosion by wave action as evinced by the physical smoothing of the bed close to the shingle beach (Fig. 4.3). Due to the harsh climatic conditions characteristic of the Newfoundland winter (e.g. Hosek *et al*. 2011; O'Brien 2020), we had only previously witnessed the environmental conditions at the site from late-Spring to early-Autumn. To fully understand the factors—both environmental and anthropic—that impact the site it was considered that year-round observation was needed. Understanding the full range of stresses experienced by the site is integral to determining the best ways to try to mitigate and/or minimize damage.

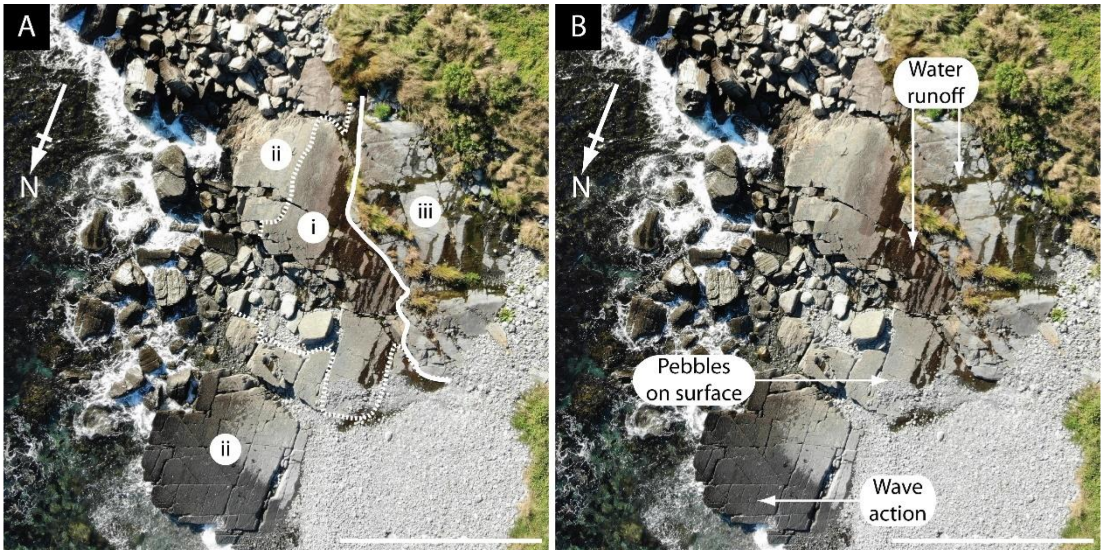


Fig. 4.3 – Overview of the Upper Island Cove fossil site using drone photography. A, key portions of the site: i) fossil bearing portion of the surface, ii) heavily weathered sections of the surface, iii) overlying strata. B, initial observations of potential environmental risks to the site including terrestrial runoff and wave action in the intertidal and supratidal. (scale bars – approx. 10 m)

This paper reports the current risks the Allison Surface is subject to, as observed between the 1st November 2021 to the 31st October 2022, and documents the historical damage that had already impacted the fossiliferous locality. We address the significant geoconservation challenges that the site faces and suggest measures that can be put into place to minimize future damage. These range from simple initiatives aimed at mitigating human impact on the site, to the more advanced and costly attempts to remove the risk of damage caused by environmental factors. If implemented, these measures should help preserve the site, conserve geoheritage of scientific value and lead to potential economic benefit to the local community through geotourism. These methods could also be applied to the geoconservation of other Ediacaran fossil sites in Newfoundland, and other large, low-dip bedding planes of significant geoheritage value across the world.

4.2 METHODS

The use of timelapse cameras to monitor environmental and anthropic risks is an increasingly used technique in geoconservation research (e.g. Hoblea *et al*. 2014; Edgar *et al*. 2023). To remotely record year-long environmental and anthropic activities, permission was obtained from the Government of Newfoundland and Labrador (Department of Tourism, Culture, Industry and Innovation) and Upper Island Cove Town Council to set up three Brinno TLC 200 Pro timelapse cameras at the fossil site. This was necessary due to the Significant Palaeontological Site status of the Allison Surface at Upper Island Cove. The cameras were set up to take a photo every minute during daylight hours, with the cameras automatically stitching the photographs together at the end of each day to create a timelapse video, which could be viewed as such or frame-by-frame using the Brinno Video Software. The weatherproof cameras were able to function during the harsh conditions typical of Newfoundland winters and required minimal maintenance, only needing to have the batteries and memory cards replaced every one to two months. The cameras were mounted onto the cliffs, boulders and concrete walls surrounding the Alison Surface using metal brackets (Fig. 4.4). Having three cameras set up allowed us to monitor the Allison Surface from multiple angles, and make sure that activities and events were fully documented. To monitor for potential tampering, each camera was set up to be visible from at least one other camera.

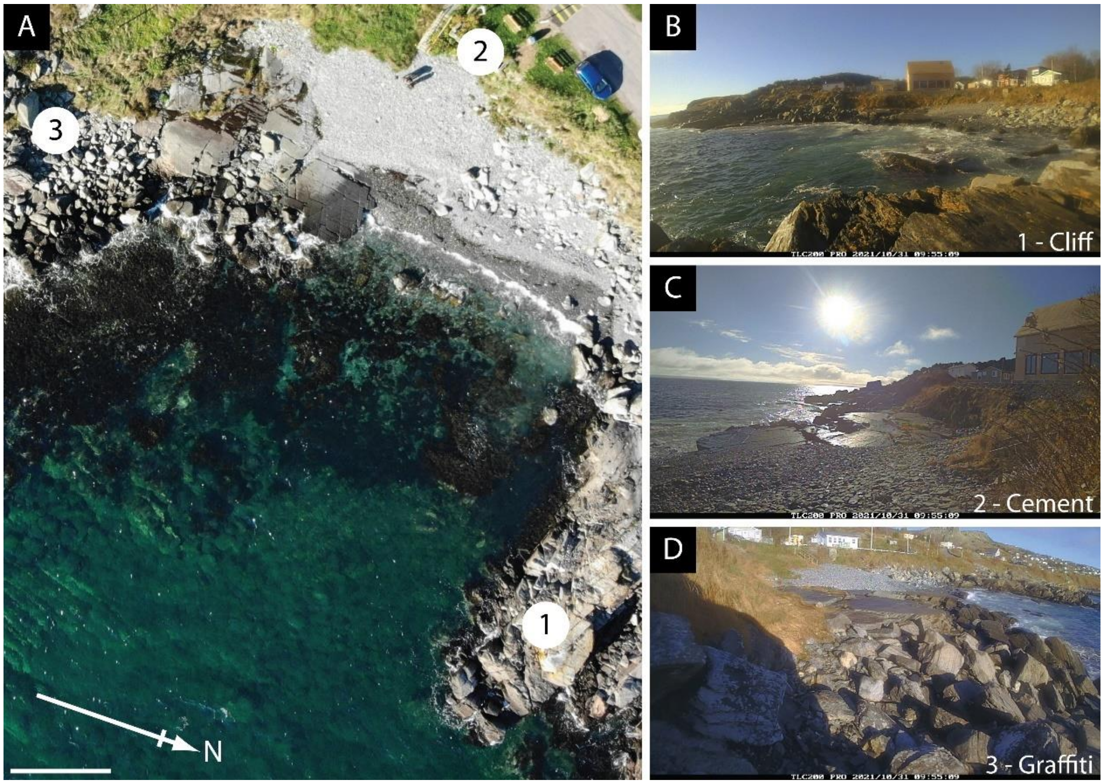


Fig. 4.4 – Positioning of Brinno TLC 200 Pro cameras and their field of view of the fossil surface. A, drone photo of the Allison Surface showing the location of each Brinno TLC 200 Pro camera in relation to the Upper Island Cove fossil site and the other cameras. B, Camera 1 – "Cliff", named for its location on a small cliff. C, Camera 2 – "Cement", named for being drilled into a concrete pillar supporting the above vegetation. D, Camera 3 – "Graffiti", named for the graffiti that appears on the same large boulder on which the camera is mounted. Photos all taken at 09:55 am (UTC-3:30) 31st October 2021 (first full day of recording). (scale bar – approx. 10 m)

Over the course of the study it became clear that each camera was best positioned for recording certain activities: Camera 1 (Fig. 4.4B) overlooked the whole site and the surrounding area and was best suited to recording daily weather conditions; Camera 2 (Fig. 4.4C) overlooked the site from the road and was well suited to documenting the frequency of anthropic activity and the extent of wave and ice action on the surface; and Camera 3

(Fig. 4.4D) allowed for clear recording of footfall and ice development on the portion of the surface that contains the most fossils.

In total the cameras at Upper Island Cove recorded 375 days of footage, equating to 1,026 individual videos in the study period (Table C.1). For each day of the study, the video which best captured the day's activities was viewed frame-by-frame using the Brinno Video Software to record visitation and weather data. If the video was incomplete or obscured in any way (e.g. due to weather conditions or tampering), a second video from the day was also reviewed frame-by-frame to ensure that data appropriately encompassed the activities (see Table C.1). Daily weather conditions were recorded to show the changing conditions over the course of one to multiple days. This helped to inform temporal changes in visitation as a function of weather conditions through a day (e.g. overcast to cloudy to clear) or varying conditions (e.g. rain to overcast, and back to rain). Significant weather events that might have a direct impact on the site were noted and their duration recorded (e.g. intense wave action, shore ice/rime development caused by supercooled water freezing on a surface; ballycater in Newfoundland English). Both wave action and freeze-thaw are significant agents of physical erosion (Sunamura 1976; Matsuoka and Murton 2008; Stephenson *et al*. 2013; García-Ortiz *et al*. 2014; Deprez *et al*. 2020) and are likely to impact the fossils over time. Photographic evidence of environmental conditions was supplemented with local weather data sourced from the Government of Canada's Environment and Natural Resources website (Environment and Natural Resources Canada 2023). Data were used from two weather stations located within 100 km of Upper Island Cove: St. John's International Airport (33.77 km) and Grates Cove (62.59 km). St. John's

International Airport weather station collected the largest amount of data and is geographically closer to the Upper Island Cove fossil site, however, it is situated on the opposite arm of Conception Bay (Fig. 4.1B), which may have caused differences in localised rainfall and other weather patterns. To account for this, the Grates Cove weather station was used to support the data from St. John's International Airport. Both weather stations had periods of missing data during the study period (St. John's International airport – 24 partially missing days and 1 fully missing day; Grates Cove – 11 partially missing days and 67 fully missing days), however when the two datasets were combined there was no days with zero weather data recorded for the region.

Visitation to the site was recorded as the number of individuals who walked on the surface in a single day. The surface at Upper Island Cove can be split into two sections; the heavily eroded section where fossil evidence is scarce, and the less eroded section where the high-quality fossils are abundant (Figs 4.2, 4.3). Because of the non-continuous nature of the data collection (photographs only once a minute), visitation data were combined from both the eroded and non-eroded sections of the site since many people spent time on both portions of the surface. Footfall duration was estimated by assigning 1 minute of visitation time per frame of footage that people were observed on the surface (e.g. if two people were on the surface at the same time for 1 hour, the duration would be recorded as 1 hour not 2 hours). This also allowed us to determine the relative importance of the various activities that were being conducted on the surface. In cases where multiple cameras were used to view a day, the highest visitation number and duration was recorded, unless otherwise stated (see Table C.1).

The camera monitoring approach developed for this study has the potential to be broadly applied to other geoheritage sites across the globe, although consideration into the duration, cost and implications of such a study should be considered first. The duration of the timelapse videos ranged from 24 to 36 seconds, depending on daylight hours (Table C.1), with frame-by-frame viewing taking upwards of 10 minutes per video as this was subject to the anthropic and environmental events being observed. As such, future users of this methodology should allow one to two hours to observe and record information for each week of footage.

For similar studies it would be beneficial to use multiple cameras over the course of a year as cameras can become damaged, tampered with or have their fields of vision obscured (see Table C.1; Fig. C.1). Since the study was conducted Brinno have developed the updated TLC300 time lapse camera that retails at around \$300 CAD (~£180/\$225 USD). This is significantly cheaper than the typical timelapse camera used for geoscience research (e.g. Walter *et al*. 2019) and therefore provides a cost-effective method for monitoring sites, even in areas with inclement weather.

In this study the cameras were positioned at varying distances from the site (Fig. 4.4). Despite this, individuals on the surface were only visible in low resolution and as such were not identifiable, posing no associated safety/data protection concerns with this study. After permission to set up the cameras was obtained from the town council and provincial government, the cameras were positioned in public areas that were in full view of anyone visiting the site. As a result, close-up images of individuals inspecting or interacting with the cameras were captured. These images have not been made publicly available unless the express permission of the individual was received (e.g. the authors of this study) or the image was altered to anonymise individuals (e.g. Fig. C.1).

4.3 RESULTS/SITE VULNERABILITIES

Careful review of all data between the 1st November 2021 and the 31st October 2022 allowed us to identify the most significant risks impacting the Upper Island Cove surface over the course of a single year (Fig. 4.5). These can be divided into environmental (Fig. 4.5B-C) and anthropic events (Fig. 4.5D).

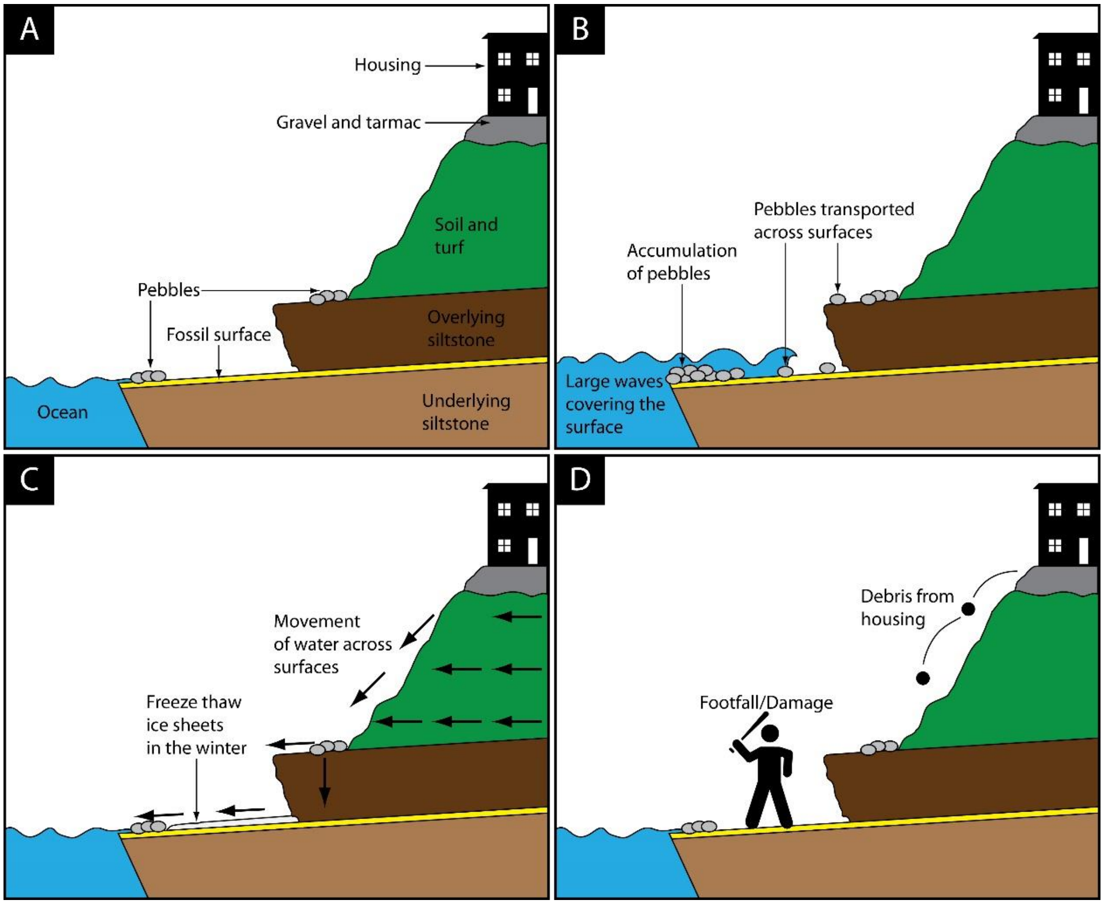


Fig. 4.5 – Schematic cross section of the Upper Island Cove fossil surface and the associated risks to the site. A, schematic cross section of the fossiliferous surface (yellow) and the associated strata and features that make up the rest of the site. B, significant wave action covering the fossiliferous surface can drag large pebbles and other abrasive material across the surface. C, water runoff from land moving through the soil and across the surface continuously, note that this freezes into large ice sheets in the winter months. D, anthropic impacts on the site falling into one of the two categories; general footfall and man-made damage; debris (littering and building material) from the house above the surface has also been found at the site.

4.3.1 Environmental Erosion

Erosion caused by natural environmental events was noted to occur across the entirety of the study period (Table 4.1) with two of the likeliest contributors to erosion being identified as ice formation directly on top of the fossils during the winter and large waves covering the entirety of the fossiliferous surface on numerous occasions across the entire study period (Fig. 4.6; Table C.1). Ice formation (Fig. 4.6C-D) was caused by the freezing of freshwater that runs continuously across the surface throughout the year from the glacial-till that forms the adjacent embankment (Fig. 4.6A). Ice was formed on the surface intermittently during the coldest months of the study period starting in December 2021 and ending in April 2022. The other major class of erosional event to occur at the site—large surface-covering waves (Fig. 4.6B, E-F)—was noted to occur across the entirety of the study period and recorded on 90 separate days over the course of the year (Table 4.1), or 24.7% of the study period, only being completely absent during the month of February 2022 when the fossiliferous surface was largely covered in ice sheets.

Table 4.1 – Overview of environmental events impacting the Upper Island Cove fossil site over the study period.

Month	Ice coverage (days)	Waves on surface (days)	Waves on fossils (days)
November '21	0/30	10/30	5/30
December '21	18/31	11/31	9/31
January '22	26/31	2/31	2/31
February '22	24/28	0/28	0/28

March '22	24/31	4/31	0/31
April '22	0/30	6/30	2/30
May '22	0/31	10/31	0/31
June '22	0/30	9/30	0/30
July '22	0/31	1/31	0/31
August '22	0/31	7/31	0/31
September '22	0/30	16/30	4/30
October '22	0/31	14/31	0/31
Total	92/365 (25.2%)	90/365 (24.7%)	22/365 (6.0%)

Fig. 4.6 – Environmental events on the fossiliferous surface over the study period. A, freshwater runoff, running continuously across the fossiliferous surface and the overlying strata. B. large waves breaking on and covering the entire surface during the winter. C, ice covering the fossiliferous and weathered sections of the surface. D, ice covering the fossiliferous surface, the fossil abundant section of the surface is that most affected by ice formation E, large waves caused by post-tropical storm Earl

covering the entire fossiliferous surface. F, large waves from post-tropical storm Earl covering both the fossiliferous surface and overlying strata. Precise dates and times are in the timestamps on the photographs (time zone UTC-3:30).

Formation of ice across the surface is the most temporally common environmental impact occurring at the site (25.2% of the study period, Table 4.1; Fig. 4.5C-D) and is a potential cause of physical erosion due to freeze-thaw action (Nicholson and Nicholson 2000; Dewanckele *et al*. 2013; García-Ortiz *et al*. 2014; Deprez *et al*. 2020). During the winter months the weather in the Upper Island Cove area remained below freezing for a total of 40 recorded days (Environment and Natural Resources Canada 2023), but outside of this there were periods where temperatures were above freezing long enough to allow for some thawing of the ice. This led to a total of 17 unique ice growth events across the study period (Table C.2). These events could range from a single day, where freezing and thawing occurred within a few hours of each other, up to periods several weeks long. In the case of protracted freezing events the ice was not static, instead it was noted that the ice would recede and grow on a day-to-day basis (Table C.1). The partial melt and regrowth of ice is the basis for freeze-thaw erosion and is inferred to be the cause of the breakup of the overlying strata due to the continuous movement of water through fractures (e.g. García-Ortiz *et al*. 2014; Figs 4.3B, 4.5C, 4.6A). Freeze-thaw action recently exposed a new part of the fossiliferous surface, revealing new fossils, and as such has added to the palaeontological significance of the surface. For the fossils at Upper Island Cove to be adequately protected from this potential threat, a method for mitigating the formation of ice on the surface must be found.

Freshwater runoff from the overlying soil and glacial-till at the Allison Surface (Figs 4.5C, 4.6A) runs across the site throughout the year, even during the summer months. This freshwater covers the middle section of the highly fossiliferous portion of the surface (Figs 4.3Ai, 4.6A), which has not only caused challenges in the observation and recording of data from the fossils but has also led to the formation of a microbial film on top of the surface and the specimens. The layer of algae overlying the fossils may help prevent the worst of the erosive action on the specimens found directly below, but for field based scientific study of the fossils it must be removed. After removing this microbial film, several completely new and previously unrecorded specimens have been observed. The surface does not remain free of the microbial film for long, however, as the microbial layers quickly grow back, obscuring the fossils once again.

Most of the large waves that broke onto the fossil surface over the course of the study only covered the already heavily weathered sections (Fig. 4.3A), explaining the lack of fossil evidence in these areas. Waves that covered the highly fossiliferous portion were less common, but still occurred on 22 separate days (6% of the study period, Table 4.1). Large waves across the fossiliferous portion of the surface (Fig. 4.6E-F) were most common in the early morning and evening (Table C.1) except during protracted stormy periods (e.g. post-tropical storm Earl; Fig. 4.6E-F; Table C.3). A few of the large waves brought coarse-grained material into contact with the surface (Fig. 4.5A-B). Through abrasion of the surface by coarse sedimentary grains (Sunamura 1976; Whipple *et al*. 2000) and the scraping and impact of fossils from pebbles across the beach (Fig. 4.5B), it is likely that significant damage will occur to the fossils over time. Impact marks damaging Ediacaran sites in Newfoundland are reported from other sites in the province (e.g. Murphy's Cove in Discovery UNESCO Global Geopark and Pigeon Cove at the Mistaken Point Ecological Reserve) and are shown to greatly impact the fidelity of the fossils preserved there (Matthews *et al*. 2017). An impact from a pebble could easily remove the sub-mm detail seen in the Upper Island Cove fossils (Fig. 4.2) and could even entirely destroy fragile specimens. The intertidal portion of the fossil surface, which is exposed to constant wave action in association with mobile shingle, is notably polished smooth and completely devoid of any surface detail. While this has occurred over a prolonged period, there is the possibility of this occurring over wider parts of the surface, especially as extreme weather conditions become more common and sea level rises by ~3 mm/y over the next few decades due to climate change (Leatherman *et al*. 2000; Zhang *et al*. 2004; Batterson and Liverman 2010; Overeem *et al*. 2011; Shadrick *et al*. 2022) and the subsidence of eastern Newfoundland due to glacial isostatic adjustment (Liverman 1994; Batterson and Liverman 2010; MacDougall *et al*. 2020), resulting in the complete loss of fossils if left unchecked.

The rate of mechanical erosion on the fossiliferous surface greatly outstrips the rate at which new portions of the surface are exposed. This is a common threat to fossiliferous sites in areas with low rates of coastal retreat and with rare fossiliferous horizons (e.g. Clark *et al*. 2004; Santos *et al*. 2013; Matthews *et al*. 2017; Matthews and McIlroy 2019). At sites that are at high risk of environmental erosive damage, such as Upper Island Cove, it is imperative that action is taken to preserve the fossils and data present before they are permanently lost.

4.3.2 Anthropic Erosion

During the period of study 234 days (64.1%) saw footfall on the surface, totalling up to almost 1,800 visitors, and a total footfall duration on the surface of 136 hours and 7 minutes (Table 4.2). Summer visitation peaked in June and July of 2022, with a significant drop-off in August 2022 probably due to the relatively poor weather (Environment and Natural Resources Canada 2023; Table C.1). December 2021 and January 2022 had the lowest visitation and total footfall duration on the surface, totalling less than 2 hours of the overall footfall duration (Fig. 4.6B-D; Table 4.1; Table C.1). January 2022 saw 26 days where the surface was covered in an ice sheet (Table C.2), which would have made the surface hazardous to walk on and likely accounts for the low footfall; during that period most people exclusively visited the pebble beach next to the site (Fig. 4.3).

Table 4.2 – Overview of the total visitation and duration on the Upper Island Cove fossil site over the period of study; approximation (~) for visitation given where number of individuals was too high to give accurate number (see Table C.1 in the Appendices).

Month	Total days	Total visitation	Total duration
November '21	14/30 (46.7%)	48	02hr 27min
December '21	4/31 (12.9%)	14	01hr 24min
January '22	7/31 (22.6%)	15	00hr 27min
February '22	12/28 (42.9%)	44	04hr 41min
March '22	17/31 (54.9%)	82	04hr 22min
April '22	21/30 (70%)	130	06hr 58min

May '22	25/31 (80.6%)	172	08hr 35min
June '22	23/30 (76.7%)	~233	30hr 11min
July '22	31/31 (100%)	~510	41hr 55min
August '22	31/31 (100%)	284	15hr 10min
September '22	22/30 (73.3%)	126	10hr 34min
October '22	27/31 (87.1%)	130	09hr 23min
Total	234/365 (64.1%)	~1788	136hr 07min

A range of human activities were noted to occur at the site (Fig. 4.7), ranging from common low impact actions such as dog walking and picnics, to more rare but high impact activities such as fieldwork and large group photoshoots.

Fig. 4.7 – High impact anthropic activities at the Upper Island Cove fossil site. A, large group taking photos across the entire surface; the greater likelihood of high heels on the surface might have an increased adverse effect on the fossils. B, moderately sized group taking photos on top of the fossiliferous section of the surface; footwear choice is likely to have an adverse effect on the fossils. C, multiple activities occurring on the site simultaneously, on the left a group of researchers cast the

fossils and to the right a small group of individuals take photos on the weathered part of the surface. D, debris, in the form of wooden planks, from the construction of a new house (top right, just out of field of view), being dragged across the surface and removed after having fallen onto the site on the 3rd December 2021. E, inappropriate use of the surface, with potential for inadvertent damage, with individuals performing scooter tricks on top of the fossiliferous section of the surface. F, potential damage caused by a group smashing blocks of ice on the fossils. This group tried obscuring Camera 3 so that this would not be recorded (see Fig. C.1 in the Appendices). Precise dates and times are in the timestamps on the photographs (time zone UTC-3:30).

Because of the ease of access from the main road, the Allison Surface is popular for both scenic and group photography. During the study this was most commonly formal group photography (Fig. 4.7A-B) and, less commonly, more adult themed photography sessions. The formal groups usually included many individuals wearing dress shoes and high heels (Fig. 4.7A; Table C.1). Previous studies on the impact of different footwear on Newfoundland's fossil surfaces revealed that the ability of a shoe type to carry abrasive sediment (three-body abrasion) was the primary control on footwear abrasion (Matthews and McIlroy 2019). While high heels, with their reduced sole-to-surface contact area, would cause less three-body abrasion, the high localized pressure of a high-heel may lead to an increased risk of two-body abrasion, where direct degradation of the surface is caused by the footwear itself.

The longest periods of continuous time spent on the surface were by research teams working on the fossils (Fig. 4.7C), with at least three separate groups being identified as visiting the surface (see Table C.1). Activities conducted by research groups range from low impact observation and photography of fossil specimens to higher intensity activities involving the fossils directly such as casting and placing heavy equipment on the surface.

When conducted properly, casting has little impact on the fossils. There is a long history of successful casting to support research across multiple localities in southeastern Newfoundland, including Mistaken Point Ecological Reserve (e.g. Hawco *et al*. 2020; McIlroy *et al*. 2022, fig. 4) and Discovery UNESCO Global Geopark (e.g. Liu *et al*. 2016, fig. 2b; Pasinetti and McIlroy 2023). It must, however, be acknowledged that the associated footfall and interaction with the surface during the casting period is higher than the average amount of time usually spent by individuals at these sites. Furthermore, the deleterious effect of casting is greatly increased when carried out poorly. Examples of substandard research casting practice can include:

- Non-cured medium remaining on the surface due to spillage, improper measurement, poor mixing, or casting in poor weather conditions.
- Use of abrasive substances on the surfaces in a misguided attempt to remove overlying strata.
- ‘Strings’ of casting medium being blown onto the surface by the wind during pouring of the silicone, which if not removed immediately are difficult to remove after a winter of curing on the rock surface.

One of the threats of greatest concern is the risk posed by accidental or intentional anthropic damage (Fig. 4.7E-F). Similar threats have already been recorded at the Ediacaran fossil surfaces of Charnwood Forest (Boynton and Ford 1995; Farooq 2013) and are known from elsewhere in the world (e.g. Wimbledon and Smith-Meyer 2012; Newsome and Johnson 2013; Antić *et al*. 2020). On the Allison Surface, graffiti is common on the edges of the outcrop as well as on the surrounding boulders. No graffiti is currently found on the fossils themselves, however small amounts of tar from the construction of the nearby road have previously been noted close to the fossils by the authors. The risk of anthropic damage extends beyond graffiti to also include intentional and unintentional physical damage to the fossils. During the camera setup on the 30th October 2021 (outside the period of study), an individual was observed walking across the surface with a baseball bat and hitting rocks over the surface into the ocean (Figs 4.5D, C.1); although no rocks were seen to come into contact with the surface during our observations, the risk of accidental damage by individuals was noted. Potential anthropic damage of note includes a group smashing blocks of ice directly on top of the fossils during the study period (Fig. 4.7F), these individuals also attempted to obscure this activity from being recorded by blocking the field of view of Camera 3 (Fig. C.1). Confirmed anthropic damage to the site is known from looting in 2004 which used a rock saw, hammers and chisels and led to irreversible damage to the site. There is also evidence for unintentional anthropic damage to the fossils, a prime example of this being a group practising scooter tricks on top of the surface during the summer months (Fig. 4.7E). It is likely that this group were unaware of the importance of the site and were using it due to its relatively flat surface and distance from any traffic, however, the wheels of the scooter are likely to be abrasive and lead to high erosion of the surface.

This study coincided with the construction of a new house on the hill that overlooks the site (Figs 4.4B-C, 4.5). The construction of the house involved improved site drainage which now routes a significant portion of the freshwater flow away from the fossil site (Figs 4.5C, 4.6A). Flow across the surface is however still present and has not mitigated the presence of ice during winter months (Fig. 4.6C-D). The construction of the house had a negative effect on the site in the form of debris falling onto the upper fossiliferous surface (Figs 4.5D, 4.7D, C.1), which preserves large examples of *Aspidella* sp. (Gehling *et al*. 2000). Additionally, wooden planks were dragged across the surface when removing the debris (Fig. 4.7D). Although a rare event, this demonstrates a shortfall in site management that could be rectified within the community if fossil sites were better identified to them.

4.4 BEST PRACTICE OF SITE-WIDE CASTING

The recognition of environmental and anthropic risks to the Allison Surface at Upper Island Cove clearly highlights the need to conserve the site prior to any further damage to the high-relief fossils found there. Mitigation of the highlighted risks to the site will take time to implement effectively, and a method is needed to accurately preserve the information in a shorter amount of time. Previous studies have recorded the fossils present at Upper Island Cove by taking laser scans of the surface for palaeoecological studies (Mitchell *et al*. 2020) or by casting specific specimens for use in taxonomic and taphonomic studies (Narbonne *et al*. 2009; Brasier *et al*. 2013; Hawco *et al*. 2020; McIlroy *et al*. 2022; McKean *et al*. 2023). To fully capture the sub-mm details of all of the specimens and to record the abundant sedimentological structures present at the site, casting of the surface was conducted from August 2020 to July 2022. This project cast the entirety of the fossiliferous surface at Upper Island Cove (Figs 4.3, 4.8) recording data on the fossils and sedimentary structures (McKean *et al*. 2023), alongside documenting prior damage. The extensive clean-up and casting operation recognized approximately 250 specimens from the Upper Island Cove fossil site, while previous studies had recognised less than 100 (Narbonne *et al*. 2009).

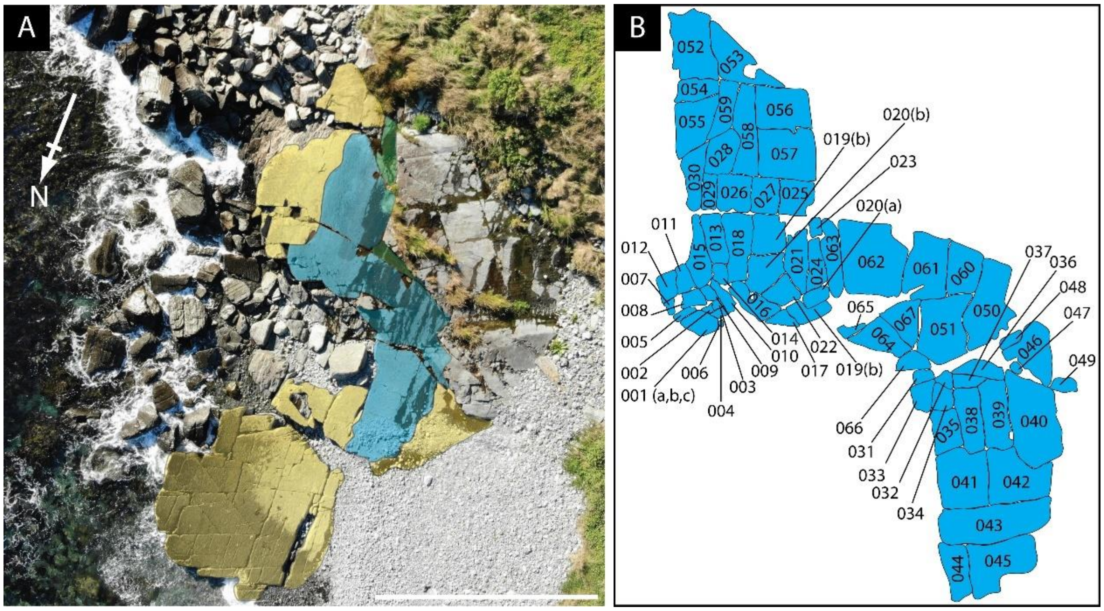


Fig. 4.8 – Drone photo showing the Allison Surface and the area cast during the period of August 2020 to July 2022. A, colour coded breakdown of the cast area (yellow = heavily weathered regions of the surface not cast, blue = fossiliferous regions of the surface that were cast, green = fossiliferous regions of the surface that were not cast due to continuous water flow). B, close-up of the casts with their designated number, note that casts fit together largely following the natural fractures that run across the surface. (scale bar – approx. 10 m)

Various casting media are available, however, when working in the field it is important to use material that will not leave a permanent mark or damage the site, while also successfully capture the high-relief detail of the specimens. Researchers must select a casting material that leaves the site in the same condition as it was prior to casting. To this end a translucent food-grade silicone, Smooth-On Mold Star 20T, was chosen for the casting work at Upper Island Cove. This food-grade silicone entails no risk to the environment or local food chain. Smooth-On Mold Star 20T is easy to apply onto the rock surface in the field, as it begins curing once its two components are evenly mixed, with silicone casts becoming fully cured within hours (if the site is above 15°C). Once the casts have been lifted and removed from the site a minor oily residue is left behind, which is easily removed by washing the surface with biodegradable dish soap. Any discolouration caused by the oil disappears in less than a week. This protocol, which was developed by the Palaeobiology Research Group at Memorial University of Newfoundland, is now required by the Mistaken Point Ecological Reserve to permit work on the Ediacaran fossils in the reserve. Best practice includes photography before and after casting to demonstrate any potential impact of the process. These silicone molds can be used to make accurate replicas of the fossils present at the site out of Jesmonite AC100 (e.g. Fig. 4.2) or Plaster of Paris (Taylor *et al*. 2023, figs 7d, 10c).

During the casting process (Fig. 4.9) small pieces of cured silicone can become trapped within fractures and cracks in the surface. If left on the surface this material, alongside discarded silicone ‘strings’, will harden over the cold winter months and become difficult to remove from the surface. It is thus imperative that all waste material is identified and removed from the surface once casting is complete. Casting should not be attempted on windy days to reduce the production of ‘strings’ via the blowing of silicone around the site. The same clean-up principle is applied to the plasticine ‘walls’ that are constructed prior to casting, to stop the silicone from running across the surface during the curing period (Fig. 4.9). Plasticine is easiest to remove at low temperatures and can be removed by hand, with any residue easily cleared away with biodegradable dish soap.

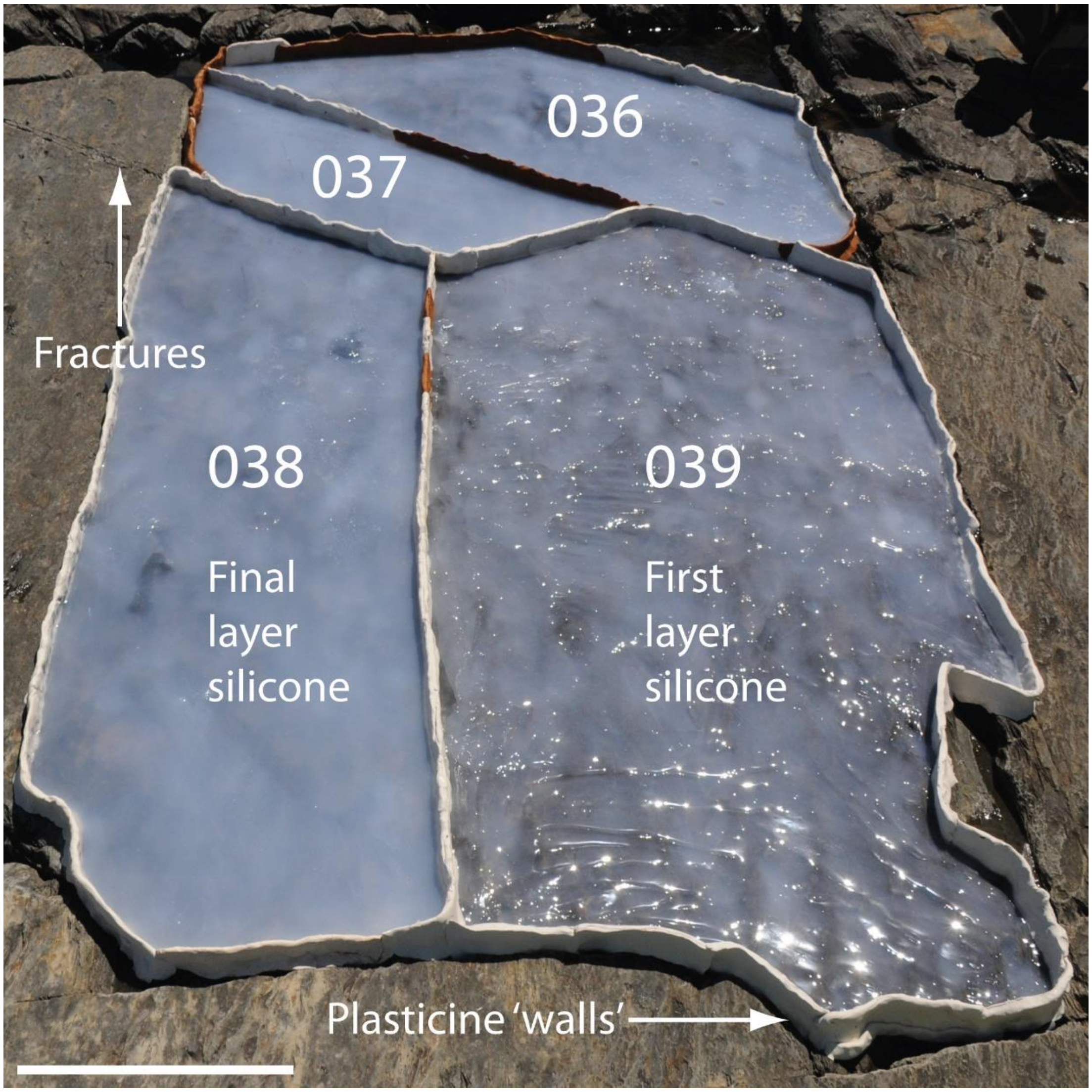


Fig. 4.9 – Example of best-practice casting at Upper Island Cove, showing the construction of casts 036, 037, 038 and 039. (scale bar – 50 cm)

While we are confident that, when done carefully, the casting process does not damage the rock, we have decided to accession the research-quality silicone molds created during this study to The Rooms, provincial museum of Newfoundland and Labrador, in St. John's, Newfoundland, so that other researchers can make replicas from our molds, thereby reducing the intense field activity at the site. The replication of fossils from quality molds as a method of geoconservation has been implemented elsewhere in the world, such as the Cabeço da Ladeira fossil site in Portugal (Machado *et al*. 2021).

4.5 HISTORICAL FOSSIL DAMAGE AND LOOTING

The frondose Ediacaran fossils that comprise a large portion of the Avalonian Assemblage (Liu *et al*. 2015) are predominantly preserved as negative epirelief impressions within the sediment (Narbonne 2005), with a few examples of positive epirelief impressions known from the Allison Surface at Upper Island Cove (Brasier *et al*. 2013; McKean *et al*. 2023). The position of the fossils in the middle of a large flat bedding plane with few natural fractures, and the highly indurated nature of the rock means that removal of material from the Ediacaran sites of Newfoundland is not possible without risking permanent damage to the site. Casting and laser scanning are the two most common methods for documenting Avalonian Ediacaran fossils (e.g. Brasier and Antcliffe 2009; Mitchell *et al*. 2019; McIlroy *et al*. 2022; Figs 4.8, 4.9). While provincial law protects all sites with significant fossils, and all Ediacaran fronds, in Newfoundland as soon as they are discovered from tampering with the threat of a fine and imprisonment (Province of Newfoundland and Labrador 2011), this has not stopped looting and attempted looting from some Ediacaran sites.

When fossils of the Ediacaran biota were first discovered in Newfoundland at Mistaken Point (Anderson and Misra 1968), specimens were removed from the site for both research and to be housed in university, museum and, most probably, private collections. In recent years, researchers have become more aware of the need for geoconservation and the decolonisation of research practices, such as ensuring that important specimens remain for study in the territory of discovery (Guerrero-Arenas *et al*. 2020; Cisneros *et al*. 2022). Ediacaran fossil sites across Avalonia are often highly indurated and cleaved/jointed, such that attempts to remove specimens are usually unsuccessful, resulting in destruction of the fossil as it breaks apart along existing planes of weakness. In 2012 it was discovered that the attempted removal of a *Charnia masoni* from the Discovery UNESCO Global Geopark had led to the total destruction of the specimen. Upper Island Cove was subject to the removal of fossils in 2004 (prior to the 2011 legislation), with at least five specimens being removed with a rock saw (Fig. 4.10): the holotype and paratype of *Avalofractus abaculus* (Narbonne *et al*. 2009), two *Beothukis*/beothukid specimens (Narbonne *et al*. 2009) and an I-shaped *Bradgatia*, a form only known from Upper Island Cove (Flude and Narbonne 2008).

Fig. 4.10 – Removed specimens and site damage from Upper Island Cove. Specimens now repatriated and housed at The Rooms, provincial museum of Newfoundland and Labrador. A, holotype of *Avalofractus abaculus* (NFM F-756) showing distinct cracks across its surface due to removal. B, side profile of the holotype of *Avalofractus abaculus* (NFM F-756) showing rock saw marks. C, close-up of the holotype of *Avalofractus abaculus* (NFM F-756) showing fractures running through the specimen caused by removal from the site; note the glue just below the frond where the specimen was repaired and, critically, the missing portion of the fossil. D, paratype of *Avalofractus abaculus* (NFM F-754) showing how the rock fractured perilously close to the specimen. E, side profile of the paratype of *Avalofractus abaculus* (NFM F-754) showing how precariously thin the specimen is after its

removal from Upper Island Cove. F, example of one of the holes cut into the Allison Surface during removal of fossils. Note the hammer percussion marks left behind on the top and bottom left of the hole still looking fresh after 20 years. (scale bars – 1 cm (A-E), 5 cm (F))

Specimens removed from Upper Island Cove were damaged during the process of removal, as can be clearly seen from the large cracks (Fig. 4.10C) and rock saw marks (Fig. 4.10B) on the specimens. In some cases, where the specimens broke into pieces, the repair work is clearly visible. This is most obvious in the holotype of *Avalofractus,* where glue holding the specimen together is visible and a portion of the specimen is missing just below the lower-left section of the frond (Fig. 4.10A, C). Comparing the current condition of the holotype to field photos taken prior to its removal (cf. Narbonne *et al*. 2009, fig 2.4) clearly shows that details and features have been permanently lost. While appearing in better condition, damage to the paratype of *Avalofractus* (Fig. 4.10D-E) is clear. During removal the rock fractured parallel to the bedding plane (Fig. 4.10D); the side view clearly shows how thin the specimen is (Fig. 4.10E). The only way to photograph the paratype is to mount it on a plasticine stand. The delicate nature of this exceptional specimen means that any further analysis beyond simple photography carries a risk of damaging or destroying it.

The Allison Surface has been irreparably damaged by the practice of removing fossils (Fig. 4.10F). Holes are apparent across the surface, with marks left behind by the rock saws and hammers clearly visible almost two decades later. When the specimens were removed, much of the surrounding surface was damaged and destroyed, and apparently not retained/accessioned. The specimens accessioned into public collections, as such, are much smaller than the holes left at the site. It is impossible to determine which specimen came from which hole, rendering the removed specimens useless in quantitative palaeoecological studies that use methods such as spatial analysis (cf. Clapham *et al*. 2003; Mitchell *et al*. 2015). With the destruction of the surface surrounding the specimens, there is also the plausible possibility that surrounding specimens, not yet recorded in any studies, were destroyed. The repatriation of the Upper Island Cove material to The Rooms, the provincial museum of Newfoundland and Labrador, coincides with the larger movement of decolonisation in palaeontology (Das and Lowe 2018; Guerrero-Arenas *et al*. 2020; Cisneros *et al*. 2022; Raja *et al*. 2022). Geological discoveries can act as the basis for sustainable development through well-managed geological tourism, but this is only possible when specimens remain in the territory where they were discovered. With the return of the Upper Island Cove specimens to Newfoundland, communities now have the opportunity to benefit from their own geoheritage.

4.6 ACCESSIONING OF MATERIAL AND OPEN ACCESS

This study is part of a larger ongoing palaeobiologic and taphonomic project on the Upper Island Cove lagerstätte (McKean *et al*. 2023). The 71 research-quality silicone molds are to be accessioned to The Rooms upon completion of current research and will be made open access for use by visiting researchers. With the material being open access, scientists will be able to study the site without repeated intense field activity that may degrade the fossils (Fig. 4.7C; Table C.1). Projects replicating entire, or potions of, fossiliferous surfaces and placing them in the public domain (e.g. Machado *et al*. 2021) also provide insurance against the permanent loss of palaeontological resources caused by catastrophic destruction of entire sites.

4.7 FUTURE GEOCONSERVATION OF THE UPPER ISLAND COVE FOSSIL SITE

The risk of anthropic damage to the Allison Surface is likely the easiest challenge to control and mitigate. The clearest human-related risks are from large groups with unsuitable footwear (Fig. 4.7A-B), direct damage to the fossils (Fig. 4.7E-F) and the looting of fossils from the site (Fig. 4.10). Controlling the footwear used at a public space such as Upper Island Cove is not realistic, nor is limiting access to the site as has been done for other geoheritage sites in Newfoundland and elsewhere in the world (e.g. Matthews and McIlroy 2019; Machado *et al*. 2021). Instead, designating areas suitable for unrestricted public use, such as the heavily weathered parts of the surface (Figs 4.3, 4.8), may reduce the amount of footfall on top of the specimens. The most effective potential means of protecting the surface from all risks would be the construction of an interpretation centre around it—the engineering for which would be non-trivial and likely very expensive.

Much of the inappropriate use of the fossiliferous surface is likely because of insufficiently effective communication of the geological significance of the site and how to respect it. The profile of the site has increased within the past few years with both articles in the media and public talks being given on the significance of the Upper Island Cove fossils, however, more could be done to actively engage the community in general. Outreach has been conducted to great success elsewhere in Newfoundland within the Discovery UNESCO

Global Geopark, where our geoconservation training is implementing a sense of community pride in local sites, effectively making people the custodians of their own geological heritage (Foss 2021). Education and better communication of the significance of the site might bring an end to anthropic damage (Fig. 4.7E-F). Much of the use of the site by groups and individuals is likely without sufficient knowledge of the significance of the locality. The best way to reduce the risks of looting and attempted looting is the creation of a network of engaged and diligent community guardians.

The recorded 'adult themed photography' highlights the use of the site for exhibitionist purposes, though the distance of the cameras from the surface means that images don't pose a safety/data protection concern to the individuals involved. While the activities pose little risk of damaging the site, they do highlight the implications of what can be captured when cameras are used to record publicly accessible sites. Therefore, future users of this monitoring methodology at other sites should be aware of this risk.

Environmental impacts on the Upper Island Cove fossil site (Fig. 4.6) occur throughout the year and are far more common than the anthropic hazards (see Tables 4.1, 4.2). With climate change there are likely to be increases in potentially damaging events (Hanson and Lindh 1993; Zhang *et al*. 2004; Shadrick *et al*. 2022), and as we adapt to climate change it is paramount to find a way to mitigate these natural hazards (Gordon *et al*. 2022). Ice formation from the freezing of the freshwater that is running continuously across the surface (Figs 4.5C, 4.6A) is causing mechanical weathering (Nicholson and Nicholson 2000; Dewanckele *et al*. 2013; Deprez *et al*. 2020). This same freshwater leads to algal growth across the surface which covers the fossils, obscuring much of their morphology. In the Summer 2022, a pressure washer was used to clean the algae off many of the fossils beneath the freshwater, however, it was observed that by Autumn much of the surface was already overgrown with algae. The best way to deal with both the ice and algal cover of the surface would be to stop or redirect the water flow from the surface. The water flow across the surface has already been altered through the construction of the outlet pipe for the new building, however other mitigation techniques such as draining or damming the source of the water could avert all freshwater related damage. Although, this would require that heavy equipment was brought onto the surface, which would likely increase the risk of anthropic damage to the fossils (i.e. through debris; Fig. 4.7D). As such, any effort to mitigate the environmental threats to the Allison Surface should be reviewed and assessed prior to any work being conducted.

The position and low dip of the surface means that parts of the surface are highly weathered (Fig. 4.3Aii) and do not preserve any fossils or sedimentary features. The areas closest to sea level are commonly subject to intense wave action throughout the year (Table 4.1), with sections closer to the shoreline being worst affected. The fossiliferous portion of the surface is covered by large, high-energy waves only during significant weather events, encompassing 6% of the study period. Waves large enough to reach the fossiliferous sections of the surface are also capable of transporting pebbles and other abrasive material (e.g. sand and gravel) creating significant risk of mechanical erosion (e.g. Whipple *et al.* 2000). The construction of a seawall would likely negate much of the current risk to the Allison Surface from wave-related damage. However, as with the suggested draining/damming of the fresh water that runs across the surface, it is noted that the construction of a sea wall would necessitate the need to bring heavy equipment onto the surface and risk accidental anthropic damage to the fossils. With the anticipated sea level change in the coming decades, and the potential for more frequent and powerful hurricanes, wave-related damage is likely to become a major risk to site's integrity that will need addressing.

4.8 GEOHERITAGE AND GEOCONSERVATION IN CONCEPTION BAY NORTH

Ediacaran studies in the Conception Bay North area have largely focused on the site at Upper Island Cove (Narbonne 2004; Narbonne *et al*. 2009; Brasier *et al*. 2013), along with a couple of other sites (Flude and Narbonne 2008). Recently there have been numerous new sites located within the region (Fig. 4.11), with some preserving well-known Ediacaran taxa such as *Charnia* (cf. Ford 1958; Wu *et al*. 2022) and *Arborea* (Pérez-Pinedo *et al*. 2022; Fig. 4.12). These new localities are within and around small communities, meaning there is potential for the development of sustainable geotourism offerings alongside community-based geoconservation (cf. Ghosh *et al*. 2021). The Province of Newfoundland and Labrador has a growing geotourism sector, including internationally significant geological sites such as the Mistaken Point UNESCO World Heritage Site, Discovery UNESCO Global Geopark, Fortune Head Ecological Reserve and Gros Morne National Park (also a UNESCO World Heritage Site). Aside from these prominent sites there is potential for strings of spatially—and thematically—related small geosites, such as the fossil localities in Conception Bay North (Fig. 4.12), to contribute to provincial geotourism, but these small sites come with unique challenges to ensure the ongoing conservation of their geoheritage. Many of these sites are coastal, like the Allison Surface, and as such could benefit from wave mitigation. Also, their public accessibility— especially as they become more widely known—means that they could benefit from the same local community engagement and custodianship as suggested for the town of Upper Island Cove given that they are not in provincial or federal parks or reserves.

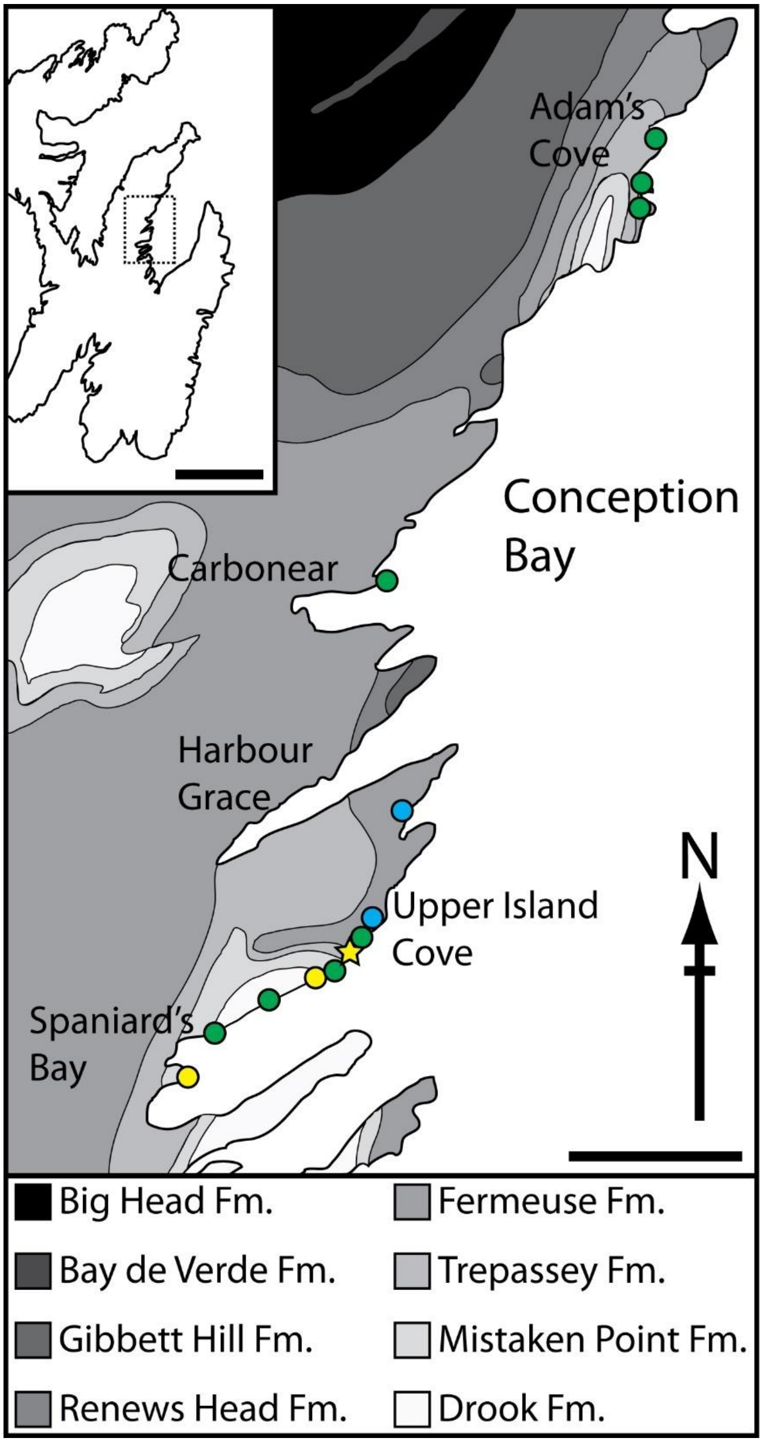


Fig. 4.11 – Ediacaran fossil localities in Conception Bay North, geological formations from King (1988) (key – yellow = sites previously discovered, green = recent discoveries by an author of this

study (B.W.T. Rideout), blue = recent discoveries by members of the local communities). (scale bars – 5 km (main), 50 km (inset))

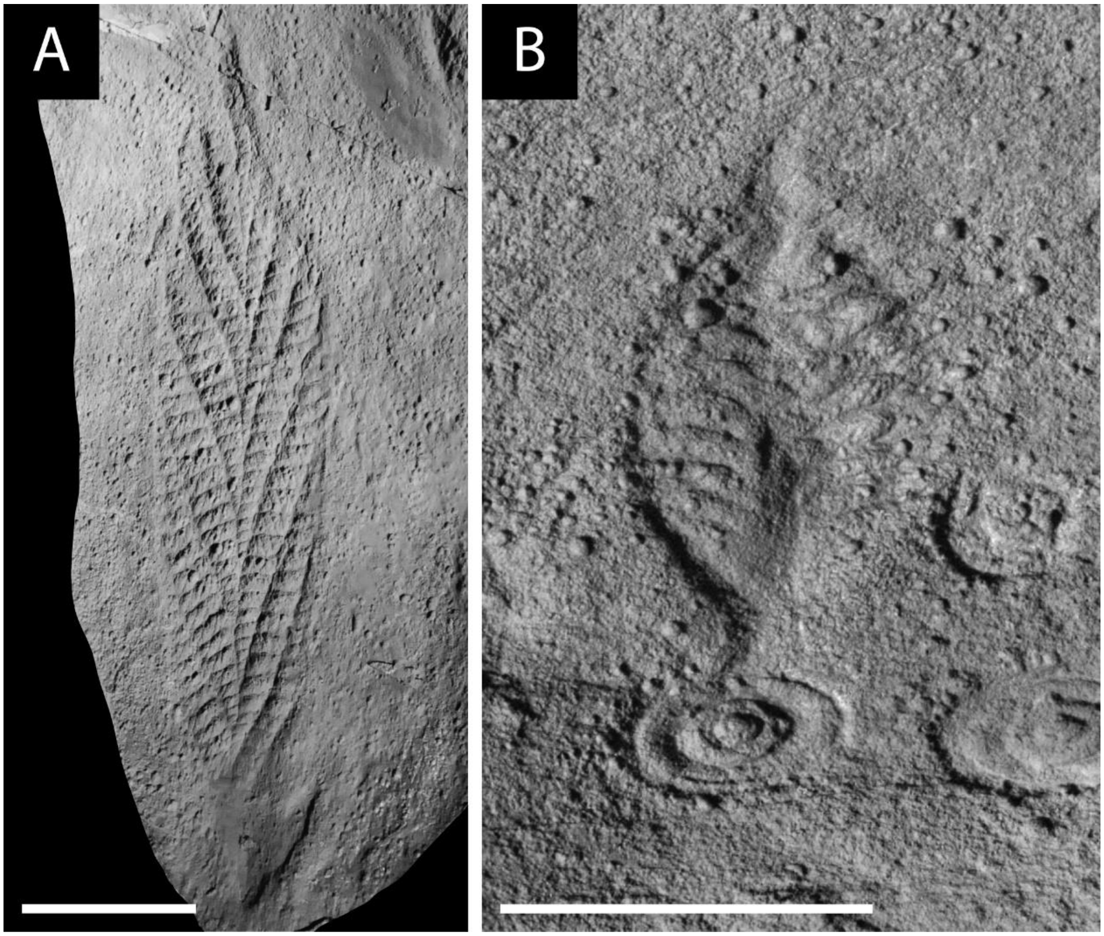


Fig. 4.12 – Examples of Ediacaran fossils from the new EM Coombs Surface in Upper Island Cove. A, *Charnia* cf. *gracilis* (cast). B, *Arborea spinosus* (cast). (scale bars – 5 cm)

4.9 CONCLUSION

The fossils found on the Allison Surface at Upper Island Cove record a unique high-relief, three-dimensional preservational style not seen elsewhere in the Avalonian Assemblage. They are currently at risk of damage from both anthropic and environmental threats that, if left unchecked, could lead to irreversible damage to the fossil site. Removal of specimens from the site has already led to significant damage, and improvements to the culture of field research are needed to prevent examples of this practice happening again. To assist in the conservation of the palaeontological geoheritage at Upper Island Cove much of the Allison Surface has been preserved as silicone casts, accessioned to The Rooms' natural history collections.

Many of the risks highlighted in this study are not unique to Upper Island Cove and are present at localities elsewhere in Newfoundland and worldwide. Through informing the general population of Upper Island Cove and the surrounding communities on the significance of their local geoheritage, as well as educating younger groups from an early age, the anthropic impact on the site can be greatly reduced through having a community that takes pride in the palaeontology on their doorsteps. Mitigation of environmental events at the site will take longer to deal with, but due to the severity of these events and the conditions they present, finding a way to reduce their occurrence will be beneficial to the long-term preservation of the site. It is hoped that methods of mitigating the risk of damage to the exceptional fossils found in Upper Island Cove can be implemented, and that the site will be used as an example of effective geoconservation methods to protect a natural heritage using a community-engaged approach.

ACKNOWLEDGEMENTS

G. Pasinetti, D. Pérez-Pinedo, J. Neville, H. Fitzgerald, C. Deal, J. Weddell and M. Swain are thanked for their assistance and support in casting the Allison Surface at Upper Island

Cove, and T. Colvin is thanked for his help in setting up the cameras across the site. Special thanks are given to the town council of Upper Island Cove and the Department of Tourism, Culture, Industry and Innovation, Government of Newfoundland and Labrador, for permission to set up the cameras at the site and additional support when required, and to The Rooms, St. John’s, NL, for access to accessioned specimens. Finally, we thank the reviewer for their feedback and constructive comments. In accordance with provincial regulations, no fossils were removed from the Upper Island Cove site. This research was supported by funding from a NSERC Discovery Grant and Discovery Accelerator Supplement to DM.

REFERENCES

Anderson, M.M. and Misra, S.B. 1968. Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland. *Nature*, **220**, 680–681, https://doi.org/10.1038/220680a0

Antić, A., Peppoloni, S. and Di Capua, G. 2020. Applying the values of geoethics for sustainable speleotourism development. *Geoheritage*, **12**, 73, https://doi.org/10.1007/s12371-020-00504-0

Batterson, M. and Liverman, D. 2010. Past and future sea-level change in Newfoundland and Labrador: Guidelines for policy and planning. *Current Research, Newfoundland and Labrador Department of Natural Resources—Geological Survey*, **10-1**, 129–141.

Boynton, H.E. and Ford, T.D. 1995. Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, **13**, 165–182.

Brasier, M.D. and Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: New insights from laser analysis. *Journal of the Geological Society*, **166**, 363–384, https://doi.org/10.1144/0016-76492008-011

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Butterfield, N.J. 2022. Constructional and functional anatomy of Ediacaran rangeomorphs. *Geological Magazine*, **159**, 1148–1159, https://doi.org/10.1017/S0016756820000734

Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, and Social Sciences and Humanities Research Council of Canada. 2022. *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*. Government of Canada.

Cisneros, J.C., Raja, N.B., Ghilardi, A.M., Dunne, E.M., Pinheiro, F.L., Fernández, O.R.R., Sales, M.A.F., Rodríguez-de la Rosa, R.A., Miranda-Martínez, A.Y., González-Mora, S., Bantim, R.A.M., de Lima, F.J. and Pardo, J.D. 2022. Digging deeper into colonial palaeontological practices in modern day Mexico and Brazil. *Royal Society Open Science*, **9**, 210898, https://doi.org/10.1098/rsos.210898

Clapham, M.E., Narbonne, G.M. and Gehling, J.G. 2003. Paleoecology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland. *Paleobiology*, **29**, 527–544, https://doi.org/10.1666/0094-8373(2003)029%3C0527:POTOKA%3E2.0.CO;2

Clark, N.D.L., Booth, P., Booth, C. and Ross, D.A. 2004. Dinosaur footprints from the Duntulm Formation (Bathonian, Jurassic) of the Isle of Skye. *Scottish Journal of Geology*, **40**, 13–21, https://doi.org/10.1144/sjg40010013

Das, S. and Lowe, M. 2018. Nature read in black and white: decolonial approaches to interpreting natural history collections. *Journal of Natural Science Collections*, **6**, 4–14.

Deprez, M., de Kock, T., de Schutter, G. and Cnudde, V. 2020. A review on freeze-thaw action and weathering of rocks. *Earth-Science Reviews*, **203**, 103143, https://doi.org/10.1016/j.earscirev.2020.103143

Dewanckele, J., Boone, M.A., de Kock, T., de Boever, W., Brabant, L., Boone, M.N., Fronteau, G., Dils, J., van Hoorebeke, L., Jacobs, P. and Cnudde, V. 2013. Holistic approach of pre-existing flaws on the decay of two limestones. *Science of The Total Environment*, **447**, 403–414, https://doi.org/10.1016/j.scitotenv.2012.12.094

Edgar, K.M., Meade, L.E., Jones, H.T., Haller, L., Scriven, S., Reedman, C. and Butler, R.J. 2023. The condition, use and future of the UK's largest accessible dinosaur tracksite at Spyway Quarry, Dorset. *Proceedings of the Geologists' Association*, **134**, 125–138, https://doi.org/10.1016/j.pgeola.2023.01.001

Environment and Natural Resources Canada 2023. Historical Climate Data, Government of Canada, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Accessed 21 March 2023.

Farooq, K. 2013. British fossils being lost to vandalism, The Guardian, https://www.theguardian.com/science/lost-worlds/2013/oct/11/british-fossils-vandalism-charnwood-forest. Accessed 22 June 2023.

Flude, L.I. and Narbonne, G.M. 2008. Taphonomy and ontogeny of a multibranched Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland. *Canadian Journal of Earth Sciences*, **45**, 1095–1109, https://doi.org/10.1139/E08-057

Ford, T.D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 211–217, https://doi.org/10.1144/pygs.31.3.211

Foss, K. 2021. Half a billion years in the making, Gazette, https://gazette.mun.ca/public-engagement/half-a-billion-years-in-the-making/. Accessed 23 June 2023.

García-Ortiz, E., Fuertes-Gutiérrez, I. and Fernández-Martínez, E. 2014. Concepts and terminology for the risk of degradation of geological heritage sites: Fragility and natural vulnerability, a case study. *Proceedings of the Geologists' Association*, **125**, 463–479, https://doi.org/10.1016/j.pgeola.2014.06.003

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Gehling, J.G., Narbonne, G.M. and Anderson, M.M. 2000. The first named Ediacaran body fossil, *Aspidella Terranovica*. *Palaeontology*, **43**, 427–456, https://doi.org/10.1111/j.0031-0239.2000.00134.x

Ghosh, A., Mukhopadhyay, S. and Chatterjee, S. 2021. Assessment of geoheritage and prospects of geotourism: An approach to geoconservation of important geological and geomorphological sites of Puruliya district, West Bengal, India. *International*

Journal of Geoheritage and Parks, **9**, 264–283, https://doi.org/10.1016/j.ijgeop.2021.03.001

Gordon, J.E., Bailey, J.J. and Larwood, J.G. 2022. Conserving nature's stage provides a foundation for safeguarding both geodiversity and biodiversity in protected and conserved areas. *Parks Steward Forum*, **38**, 39–45, https://doi.org/10.5070/P538156118

Guerrero-Arenas, R., Aguilar Arellano, F.J., Alvarado Mendoza, L. and Jiménez-Hidalgo, E. 2020. How is the paleontological heritage of Mexico and other Latin American countries protected? *Paleontología Mexicana*, **9**, 83–90.

Hanson, H. and Lindh, G. 1993. Coastal erosion: an escalating environmental threat. *Ambio*, **22**, 188–195.

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Hoblea, F., Delannoy, J.J., Jaillet, S., Ployon, E. and Sadier, B. 2014. Digital tools for managing and promoting karst geosites in southeast France. *Geoheritage*, **6**, 113–127, https://doi.org/10.1007/s12371-014-0112-1

Hofmann, H.J., O'Brien, S.J. and King, A.F. 2008. Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36, https://doi.org/10.1666/06-087.1

Hosek, J., Musilek, P., Lozowski, E. and Pytlak, P. 2011. Forecasting severe ice storms using numerical weather prediction: The March 2010 Newfoundland event. *Natural*

Hazards and Earth System Sciences, **11**, 587–595, https://doi.org/10.5194/nhess-11-587-2011

King, A.F. 1988. *Geology of the Avalon Peninsula, Newfoundland (parts of 1K, 1L, 1M, 1N and 2C)*. Newfoundland Department of Mines and Energy Map **88-01**.

Leatherman, S.P., Zhang, K. and Douglas, B.C. 2000. Sea level rise shown to drive coastal erosion. *Eos, Transactions American Geophysical Union*, **81**, 55–57, https://doi.org/10.1029/00EO00034

Liu, A.G., Kenchington, C.G. and Mitchell, E.G. 2015. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380, https://doi.org/10.1016/j.gr.2014.11.002

Liu, A.G., Matthews, J.J. and McIlroy, D. 2016. The *Beothukis*/*Culmofrons* problem and its bearing on Ediacaran macrofossil taxonomy: Evidence from an exceptional new fossil locality. *Palaeontology*, **59**, 45–58, https://doi.org/10.1111/pala.12206

Liverman, D.G.E. 1994. Relative sea-level history and isostatic rebound in Newfoundland, Canada. *Boreas*, **23**, 217–230, https://doi.org/10.1111/j.1502-3885.1994.tb00944.x

MacDougall, M.D.J., Braun, A. and Fotopoulos, G. 2020. Implications of glacial isostatic adjustment on petroleum reservoirs in the Grand Banks of Newfoundland. *Journal of Geodynamics*, **140**, 101781, https://doi.org/10.1016/j.jog.2020.101781

Machado, S., Mergulhão, L., Pereira, B.C., Pereira, P., Carvalho, J., Anacleto, J.A., Neto de Carvalho, C., Belo, J., Paredes, R. and Baucon, A. 2021. Geoconservation in the Cabeço da Ladeira Paleontological Site (Serras de Aire e Candeeiros Nature Park, Portugal): Exquisite Preservation of Animals and Their Behavioral Activities in a

Middle Jurassic Carbonate Tidal Flat. *Geosciences*, 11, 366, https://doi.org/10.3390/geosciences11090366

Matsuoka, N. and Murton, J. 2008. Frost weathering: Recent advances and future directions. *Permafrost and Periglacial Processes*, **19**, 195–210, https://doi.org/10.1002/ppp.620

Matthews, J.J. and McIlroy, D. 2019. On the adhesion of sediment to footwear and the implications for geoconservation. *Geoheritage*, **11**, 1749–1756, https://doi.org/10.1007/s12371-019-00380-3

Matthews, J.J., Liu, A.G. and McIlroy, D. 2017. Post-fossilization processes and their implications for understanding Ediacaran macrofossil assemblages. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 251–269, https://doi.org/10.1144/SP448.20

Matthews, J.J., Liu, A.G., Yang, C., McIlroy, D., Levell, B. and Condon, D.J. 2020. A chronostratigraphic framework for the rise of the Ediacaran macrobiota: New constraints from Mistaken Point Ecological Reserve, Newfoundland. *GSA Bulletin*, **133**, 612–624, https://doi.org/10.1130/B35646.1

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken

Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

McKean, C., Taylor, R.S. and McIlroy, D. 2023. New taphonomic and sedimentological insights into the preservation of high relief Ediacaran fossils at Upper Island Cove, Newfoundland. *Lethaia*, **56**, 1–17, https://doi.org/10.18261/let.56.4.2

Mitchell, E.G., Kenchington, C.G., Liu, A.G., Matthews, J.J. and Butterfield, N.J. 2015. Reconstructing the reproductive mode of an Ediacaran macro-organism. *Nature*, **524**, 343–346, https://doi.org/10.1038/nature14646

Mitchell, E.G., Harris, S., Kenchington, C.G., Vixseboxse, P., Roberts, L., Clark, C., Dennis, A., Liu, A.G. and Wilby, P.R. 2019. The importance of neutral over niche processes in structuring Ediacaran early animal communities. *Ecology Letters*, **22**, 2028–2038, https://doi.org/10.1111/ele.13383

Mitchell, E.G., Bobkov, N., Bykova, N., Dhungana, A., Kolesnikov, A.V., Hogarth, I.R.P., Liu, A.G., Mustill, T.M.R., Sozonov, N., Rogov, V.I., Xiao, S. and Grazhdankin, D.V. 2020. The influence of environmental setting on the community ecology of Ediacaran organisms. *Interface Focus*, **10**, 20190109, http://doi.org/10.1098/rsfs.2019.0109

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M. 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442, https://doi.org/10.1146/annurev.earth.33.092203.122519

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 503–523, https://doi.org/10.1666/08-072R1.1

Newsome, D. and Johnson, C.P. 2013. Potential geotourism and the prospect of raising awareness about geoheritage and the environment on Mauritius. *Geoheritage*, **5**, 1–9, https://doi.org/10.1007/s12371-012-0070-4

Nicholson, D.T. and Nicholson, F.H. 2000. Physical deterioration of sedimentary rocks subjected to experimental freeze-thaw weathering. *Earth Surface Processes and Landforms*, **25**, 1295–1307, https://doi.org/10.1002/1096-9837(200011)25:12%3C1295::AID-ESP138%3E3.0.CO;2-E

Overeem, I., Anderson, R.S., Wobus, C.W., Clow, G.D., Urban, F.E. and Matell, N. 2011. Sea ice loss enhances wave action at the Arctic coast. *Geophysical Research Letters*, **38**, L17503, https://doi.org/10.1029/2011GL048681

O'Brien, C. 2020. Winter weather escalates across Canada as army sent to help Newfoundland, CTV News, https://www.ctvnews.ca/canada/winter-weather-escalates-across-canada-as-army-sent-to-help-newfoundland-1.4773937. Accessed 21 June 2023.

Pasinetti, G. and McIlroy, D. 2023. Paleobiology and taphonomy of the rangeomorph *Culmofrons plumosa*. *Palaeontology*, **66**, e12671, https://doi.org/10.1111/pala.12671

Pérez-Pinedo, D., McKean, C., Taylor, R.S. and McIlroy, D. 2022. *Charniodiscus* and *Arborea* are separate genera within the Arboreomorpha: Using the holotype of *C. concentricus* to resolve a taxonomic tangle. *Frontiers in Earth Science*, **9**, 785929, https://doi.org/10.3389/feart.2021.785929

Province of Newfoundland and Labrador 1997. Fossil Ecological Reserve Regulations 63/97 under the Wilderness and Ecological Reserves Act 1990, https://faolex.fao.org/docs/pdf/nf53903.pdf. Accessed 18 July 2023.

Province of Newfoundland and Labrador 2009. Fossil Ecological Reserve Regulations 13/09 under the Wilderness and Ecological Reserves Act 1990, https://www.assembly.nl.ca/legislation/sr/regulations/rc090013.htm. Accessed 23 June 2023.

Province of Newfoundland and Labrador 2011. Palaeontological Resource Regulations 67/11 under the Historic Resources Act 1990, https://www.assembly.nl.ca/legislation/sr/regulations/rc110067.htm#5_. Accessed 23 June 2023.

Raja, N.B., Dunne, E.M., Matiwane, A., Ming Khan, T., Nätscher, P.S., Ghilardi, A.M. and Chattopadhyay, D. 2022. Colonial history and global economics distort our understanding of deep-time biodiversity. *Nature Ecology & Evolution*, **6**, 145–154, https://doi.org/10.1038/s41559-021-01608-8

Santos, V.F., Callapez, P.M. and Rodrigues, N.P.C. 2013. Dinosaur footprints from the Lower Cretaceous of the Algarve Basin (Portugal): New data on the ornithopod palaeoecology and palaeobiogeography of the Iberian Peninsula. *Cretaceous Research*, **40**, 158–169, https://doi.org/10.1016/j.cretres.2012.07.001

Shadrick, J.R., Rood, D.H., Hurst, M.D., Piggott, M.D., Hebditch, B.G., Seal, A.J. and Wilcken, K.M. 2022. Sea-level rise will likely accelerate rock coast cliff retreat rates. *Nature Communications*, **13**, 7005, https://doi.org/10.1038/s41467-022-34386-3

Stephenson, W.J., Dickson, M.E. and Trenhaile, A.S. 2013. 10.11 Rock Coasts. *In*: Shroder, J.F. (ed) *Treatise on Geomorphology, Volume 10: Coastal Geomorphology*. Academic Press, 289–307.

Sunamura, T. 1976. Feedback relationship in wave erosion of laboratory rocky coast. *The Journal of Geology*, **84**, 427–437, https://doi.org/10.1086/628209

Taylor, R.S., Nicholls, R., Neville, J.M. and McIlroy, D. 2023. Morphological variation in the rangeomorph organism *Fractofusus misrai* from the Ediacaran of Newfoundland, Canada. *Geological Magazine*, **160**, 146–166, https://doi.org/10.1017/S0016756822000723

Walter, T.R., Harnett, C.E., Varley, N., Vargas Bracamontes, D., Salzer, J., Zorn, E.U., Bretón, M., Arámbula, R. and Thomas, M.E. 2019. Imaging the 2013 explosive crater excavation and new dome formation at Volcán de Colima with TerraSAR-X, time-lapse cameras and modelling. *Journal of Volcanology and Geothermal Research*, **369**, 224–237, https://doi.org/10.1016/j.jvolgeores.2018.11.016

Whipple, K.X., Hancock, G.S. and Anderson, R.S. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. *GSA Bulletin*, **112**, 490–503, https://doi.org/10.1130/0016-7606(2000)112%3C490:RIIBMA%3E2.0.CO;2

Wilby, P.R., Carney, J.N. and Howe, M.P.A. 2011. A rich Ediacaran assemblage from eastern Avalonia: Evidence of early widespread diversity in the deep ocean. *Geology*, **39**, 655–658, https://doi.org/10.1130/G31890.1

Wimbledon, W.A. and Smith-Meyer, S. 2012. *Geoheritage in Europe and its conservation*. ProGEO.

Wu, C., Pang, K., Chen, Z., Wang, X., Zhou, C., Wan, B., Yuan, X. and Xiao, S. 2022. The rangeomorph fossil *Charnia* from the Ediacaran Shibantan biota in the Yangtze Gorges area, South China. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2022.97

Zhang, K., Douglas, B.C. and Leatherman, S.P. 2004. Global warming and coastal erosion. *Climatic Change*, **64**, 41–58, https://doi.org/10.1023/B:CLIM.0000024690.32682.48

CHAPTER 5

Conclusions

The aim of this PhD project, as detailed herein, has been to further our understanding of the Allison Surface, an Ediacaran fossiliferous locality in Upper Island Cove, Conception Bay North. Through detailed site observation, the collection of new taphonomic and sedimentological data, updated systematics in Ediacaran taxonomy and a novel approach to observing site-specific anthropic and environmental risks, it has been possible to improve our understanding of this exceptional locality. In Chapter 2, newly collected taphonomic and sedimentological data has been used to develop an updated taphonomic model for the three-dimensional, high relief fossil preservation present at Upper Island Cove. While also presenting clear evidence for community succession, the preservation of both sides of certain taxa and the partial/damaged nature of many of the specimens at the site. In Chapter 3 a reassessment of the taxonomy of the fossils at the site has led to an emended generic diagnosis for *Avalofractus*, the description of three new species; *Avalofractus dosomitus* sp. nov., *Kannabuchia artkingii* gen. et sp. nov. and *Corellia washageuis* gen. et sp. nov., as well as new insights into classic Ediacaran taxa such as *Arborea*, *Bradgatia* and *Charnia*. Finally, in Chapter 4, in light of the unique taphonomic processes and taxa at the site, a novel approach to site observation is detailed which highlights key anthropic and environmental risks to the Allison Surface and the mitigation techniques that can be implemented for future site protection.

5.1 TAPHONOMY OF THE UPPER ISLAND COVE LAGERSTÄTTE

The new taphonomic model for high-relief, three-dimensional preservation of Ediacaran fronds at Upper Island Cove developed in Chapter 2 builds upon the two previously suggested taphonomic models by incorporating new taphonomic and sedimentological observations from the fossiliferous surface (Narbonne 2004; Brasier *et al*. 2013; Fig. 2.11). New evidence from the site includes the realisation that many of the previously inferred 'stems' of frondose organisms preserved at the site are actually obstruction scours (Narbonne *et al*. 2009; Hawco *et al*. 2020; McIlroy *et al*. 2022; Fig. 2.3F), a clear dissociation in the orientation of obstruction scours and fronds (Figs 2.3, 2.4; Supp. Material 2.1), the partial exposure of the fronds within the obstruction scours due to burial and subsequent exhumation (Fig. 2.6) and the presence of separate rangeomorph-dominated communities at the site (Brasier *et al*. 2013, fig. 3; Fig. 2.5; Supp. Material 2.2).

This new model shows that both erect and reclined Ediacaran fronds were encased within the top centimetre of a T_d silt, before being subsequently exhumed by a current that eroded the seafloor in the lee of a community of erect organisms (Fig. 2.11). Approximately 75% of the obstruction scours at the site contain no evidence for a frond (Figs 2.3H, 2.9C; Supp. Material 2.1), with those that do exposing decayed or decaying organic remains that would have been comparable to lutefisk (see Magnus 1555; Figs 2.11, 3.12). Where tissue was removed by the current the lower surface of the organism was exposed and preserved as a negative epirelief impression in the partly lithified T_d siltstone, when erosion was insufficient to remove the top of the organism this was cast in positive epirelief by the overlying pyritic, fine-grained T_c sandstone (Figs 2.11, 2.12). This has allowed for both the upper and lower surfaces of the same taxon to be preserved on the same fossiliferous horizon (e.g. Figs 2.8, 3.4, 3.6, 3.8, 3.9, 3.11, 4.2).

Key implications from this study into the taphonomy of the Allison Surface at Upper Island Cove include evidence that suggests there are at least three successive communities preserved at the site, making the surface one of a few Ediacaran localities in the Avalonian Assemblage to show community succession (Liu *et al*. 2011, 2013; Mitchell and Butterfield 2018). The presence of a tiered community, as evinced by the epifaunal recliners and erect stemmed fronds on the surface, and the realisation that the specimens preserved in the T_d siltstone are the partially exhumed remains of buried organisms, with both the upper and lower surfaces of select taxa present, which has significant implications for the taxonomic revisions in Chapter 3.

5.2 TAXONOMIC REASSESSMENT OF THE UPPER ISLAND COVE LAGERSTÄTTE

Improved systematic descriptions of Ediacaran fossils—especially the Rangeomorpha—since the discovery of the Allison Surface (Brasier *et al*. 2012; Dunn *et al*. 2019), and the discovery of over 150 additional specimens at the site (Supp. Material 3.1), has allowed for the taxonomic reassessment of the Ediacaran fossils at Upper Island Cove presented in Chapter 3. By applying an up-to-date systematic approach, which was developed after the last taxonomic assessment of the site (cf. Brasier *et al*. 2012), to the 258 specimens now recognised from the surface, three new species are described:

1) *Avalofractus dosomitus* sp. nov. an erect rangeomorph with acicular first-order branches emanating from a central stalk (Fig. 3.5).
2) *Kannabuchia artkingii* gen. et sp. nov. an epifaunal rangeomorph with a distinct pronounced midline (Fig. 3.8).
3) *Corellia washageuis* gen. et sp. nov. the first fully reclined arboreomorph which has a distinctive U-shaped bedding-parallel stem (Fig. 3.11).

Alongside the new species, new morphotypes of the classic Ediacaran taxa *Arborea*, *Bradgatia* and *Charnia* have been described for the first time, giving us new insights into their morphologies and palaeobiology. With the *Arborea* sp. found on the surface being most comparable to the Australian frondose taxon *Pambikalbae* (Jenkins and Nedin 2007), the *Bradgatia* morphotypes showing further evidence that support an epibenthic reclined mode of life for the genus (Pérez-Pinedo *et al*. 2023) and *Charnia gracilis* being seen for the first time outside of the Shibantan biota of China increasing the spatiotemporal range of the taxon (Wu *et al*. 2022; Fig. 3.7A-C).

Of the genera present at the site, *Arborea*, *Bradgatia*, *Corellia* and *Kannabuchia* show differentiation on their upper and lower surfaces. For the reclined taxa it is likely that this is an adaptation for chemosymbiosis (Dufour and McIlroy 2017; McIlroy *et al*. 2021). Other components of the Allison Surface have been described for the first time with taphomorphs and insufficiently exhumed fronds making up a high percentage of the fossils present (Figs 3.12, 3.13; Supp. Material 3.1). Enigmatic MISS structures referred to as 'pneu-specimens' have also been recognised from the site (Fig. 3.14), which, alongside the already reported bubble train structures (Laflamme *et al*. 2011; Fig. 3.15A-B), present new evidence for the possibility of a buried microbial matground at the site.

This taxonomic reassessment gives further evidence for the initial community preserved at Upper Island Cove to be tiered, as both reclined and erect taxa are preserved within the scours present on the top of the T_d siltstone. Of the reclined taxa *Corellia* is the first fully reclined arboreomorph, expanding the known modes of life for the clade. Chapter 3 also presents the first reported differentiated upper surface of *Bradgatia* (Fig. 3.6C). This suggests that other rangeomorph taxa in which only a single side is known for may also have different upper and lower surfaces, challenging the traditional view that Ediacaran taxa have the same morphology on both their upper and lower surfaces (Gehling and Narbonne 2007). Furthermore, the pronounced midline present only on the upper surface of *Kannabuchia* suggests it is possible that similar connecting structures may have been present in other rangeomorph taxa in which only the lower surface is currently known (Fig. 3.8).

5.3 GEOCONSERVATION OF THE UPPER ISLAND COVE LAGERSTÄTTE

With the unique taphonomic processes that led to the exquisite preservation of Ediacaran fossil at Upper Island Cove detailed in Chapter 2 and the presence of two endemic species (*A. abaculus* and *K. artkingii* gen. et sp. nov.) and several unique morphotypes of Ediacaran taxa detailed in Chapter 3, the significance of the Allison Surface has been shown across this thesis. A novel technique described in Chapter 4 for site observation was implemented at the Allison Surface from the 1st November 2021 to the 31st October 2022, and shows that the fossils of Upper Island Cove are at risk to both anthropic and environmental factors.

High impact anthropic events, such as large groups congregating at the site, have been noted at the Allison Surface (Fig. 4.7F). Although rare these events present a risk of site-wide damage over a short period of time. More common is inadvertent damage caused by inappropriate footwear and activities being conducted on top of the fossils (Fig. 4.7A-E). Environmental events that present a risk to the Ediacaran fossils preserved at the site are more common, with high-energy waves covering the fossils and the transportation of abrasive material onto the surface being the most consistent risk (Fig. 4.6A-B, E-F; Supp. Material 4.2). Sheets of ice forming across the surface were also noted to occur on 17 different occasions over the winter months (Fig. 4.7C-E; Supp. Material 4.2), by engulfing the fossils these ice-forming events risk damaging the fossils through physical erosion by freeze-thaw action (Nicholson and Nicholson 2000; Deprez *et al*. 2020). If left unchecked, these risks could lead to irreversible damage to the Allison Surface. The site has also been subject to historical damage in the form of the removal of several fossils shortly after the site was discovered, including the holotypes of *Avalofractus abaculus* and, as described in Chapter 3, *Avalofractus dosomitus* (Fig. 4.10), leaving clear anthropic damage, which is still visible at the site in the present day (Fig. 4.10F).

To address the anthropic risks to the fossils at Upper Island Cove communication of the importance of the site to the local community is essential. By informing the general population of the town about the international significance of the Allison Surface the anthropic risks can be reduced through collaborative measures and community custodianship. Mitigation of environmental events will take more time to process, but due to the high risks these present to the integrity of the site it is paramount that work is conducted alongside the local community and town council to address these.

Prior to suggested mitigation techniques at the Allison Surface being implemented the main fossiliferous outcrop is still at risk to irreparable damage. As such the fossil bearing portion of Allison Surface has been cast in a non-evasive material, with the casts to be made open access at The Rooms, provincial museum of Newfoundland and Labrador (Figs 4.8, 4.9), preserving a copy of the surface and fossils in perpetuity for future studies if the site were to be damaged. Many of the risks highlighted in this study are not unique to the Allison Surface and are present at localities elsewhere in Newfoundland and worldwide. With the discovery of new fossiliferous surfaces across the Conception Bay North region the approach to site monitoring and geoconservation laid out in this chapter can be implemented at those sites (Figs 4.11, 4.12), leading to their long-term protection and the preservation of Newfoundland’s palaeontological geoheritage.

5.4 FUTURE IMPLICATIONS

Through the focused study of the taphonomy and taxonomy of the fossils preserved at the Allison Surface of Upper Island Cove this project has further developed our understanding of this unique site and the organisms present. Previous models of taphonomy and the species composition at the site have been assessed and built upon with up-to-date research and approaches to give a more comprehensive understanding of the surface. Furthermore, the geoconservation study conducted in Upper Island Cove has led to the development of a novel approach to site observation that can be implemented at other at-risk fossil localities worldwide.

This project also shows what can be achieved through site-specific studies of Ediacaran fossil sites, and how these can further our understanding of the Ediacaran biota. For a site to be used in broader studies, such as palaeoecology, palaeobiogeography and phylogenetics, the taphonomy and taxonomy must be fully understood. This project can be used as a framework for future studies focussing on site-specific Ediacaran research. The region of Conception Bay North is only now being recognised as an important area for Ediacaran research, with the number of known sites increasing year on year (Fig. 4.11). By implementing site-specific research to these sites, as well as implementing geoconservation monitoring and risk mitigation, Conception Bay North—like Mistaken Point Ecological Reserve and the Discovery UNESCO Global Geopark—can become a location of international importance for research into the Ediacaran biota.

REFERENCES

Brasier, M.D., Antcliffe, J.B. and Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124, https://doi.org/10.1111/j.1475-4983.2012.01164.x

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard’s Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Deprez, M., de Kock, T., de Schutter, G. and Cnudde, V. 2020. A review on freeze-thaw action and weathering of rocks. *Earth-Science Reviews*, **203**, 103143, https://doi.org/10.1016/j.earscirev.2020.103143

Dufour, S.C. and McIlroy, D. 2017. Ediacaran pre-placozoan diploblasts in the Avalonian biota: The role of chemosynthesis in the evolution of early animal life. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 211–219, https://doi.org/10.1144/SP448.5

Dunn, F.S., Liu, A.G. and Gehling, J.G. 2019. Anatomical and ontogenetic reassessment of the Ediacaran frond *Arborea arborea* and its placement within total group Eumetazoa. *Palaeontology*, **62**, 851–865, https://doi.org/10.1111/pala.12431

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Jenkins, R.J.F. and Nedin, C. 2007. The provenance and palaeobiology of a new multi-vaned, chambered frondose organism from the Ediacaran (later Neoproterozoic) of South Australia. *In*: Vickers-Rich, P. and Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, Special Publications, **286**, 195–222, https://doi.org/10.1144/sp286.15

Laflamme, M., Schiffbauer, J.D. and Narbonne, G.M. 2011. Deep-water microbially induced sedimentary structures (MISS) in deep time: The Ediacaran fossil *Iveshedia*. *In*: Noffke, N. and Chafetz, H. (eds) *Microbial Mats in Siliciclastic Depositional Systems Through Time*. Society for Sedimentary Geology SEPM Special Publications, **101**, 111–123, https://doi.org/10.2110/sepmsp.101.111

Liu, A.G., McIlroy, D., Antcliffe, J.B. and Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630, https://doi.org/10.1111/j.1475-4983.2010.01024.x

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2013. Exploring an Ediacaran 'nursery': Growth, ecology and evolution in a rangeomorph palaeocommunity. *Geology Today*, **29**, 23–26, https://doi.org/10.1111/j.1365-2451.2013.00860.x

Magnus, O. 1555. *Historia de gentibus septentrionalibus (The history of the Nordic people)*. Rome.

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

Mitchell, E.G. and Butterfield, N.J. 2018. Spatial analyses of Ediacaran communities at Mistaken Point. *Paleobiology*, **44**, 40–57, https://doi.org/10.1017/pab.2017.35

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 505–523, https://doi.org/10.1666/08-072R1.1

Nicholson, D.T. and Nicholson, F.H. 2000. Physical deterioration of sedimentary rocks subjected to experimental freeze-thaw weathering. *Earth Surface Processes and Landforms*, **25**, 1295–1307, https://doi.org/10.1002/1096-9837(200011)25:12%3C1295::AID-ESP138%3E3.0.CO;2-E

Pérez-Pinedo, D., Neville, J.M., Pasinetti, G., McKean, C., Taylor, R. and McIlroy, D. 2023. Frond orientations with independent current indicators demonstrate the reclining rheotropic mode of life of several Ediacaran rangeomorph taxa. *Paleobiology*, **49**, 471–492, https://doi.org/10.1017/pab.2023.2

Wu, C., Pang, K., Chen, Z., Wang, X., Zhou, C., Wan, B., Yuan, X. and Xiao, S. 2022. The rangeomorph fossil *Charnia* from the Ediacaran Shibantan biota in the Yangtze Gorges area, South China. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2022.97

BIBLIOGRAPHY

Anderson, M.M. and Misra, S.B. 1968. Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland. *Nature*, **220**, 680–681, https://doi.org/10.1038/220680a0

Antcliffe, J.B. and Brasier, M.D. 2007. *Charnia* and sea pens are poles apart. *Journal of the Geological Society*, **164**, 49–51, https://doi.org/10.1144/0016-76492006-080

Antcliffe, J.B. and Brasier, M.D. 2008. *Charnia* at 50: Developmental models for Ediacaran fronds. *Palaeontology*, **51**, 11–26, https://doi.org/10.1111/j.1475-4983.2007.00738.x

Antcliffe, J.B., Callow, R.H.T. and Brasier, M.D. 2014. Giving the early fossil record of sponges a squeeze. *Biological Reviews*, **89**, 972–1004, https://doi.org/10.1111/brv.12090

Antcliffe, J.B., Hancy, A.D. and Brasier, M.D. 2015. A new ecological model for the ~565Ma Ediacaran biota of Mistaken Point, Newfoundland. *Precambrian Research*, **268**, 227–242, https://doi.org/10.1016/j.precamres.2015.06.015

Antić, A., Peppoloni, S. and Di Capua, G. 2020. Applying the values of geoethics for sustainable speleotourism development. *Geoheritage*, **12**, 73, https://doi.org/10.1007/s12371-020-00504-0

Bamforth, E.L., Narbonne, G.M. and Anderson, M.M. 2008. Growth and ecology of a multi-branched Ediacaran rangeomorph from the Mistaken Point assemblage, Newfoundland. *Journal of Paleontology*, **82**, 763–777, https://doi.org/10.1666/07-112.1

Batterson, M. and Liverman, D. 2010. Past and future sea-level change in Newfoundland and Labrador: Guidelines for policy and planning. *Current Research, Newfoundland and Labrador Department of Natural Resources—Geological Survey*, **10-1**, 129–141.

Becker-Kerber, B., El Albani, A., Konhauser, K., Abd Elmola, A., Fontaine, C., Paim, P.S.G., Mazurier, A., Prado, G.M.E.M., Galante, D., Kerber, P.B., da Rosa, A.L.Z., Fairchild. T.R., Meunier, A. and Pacheco, M.L.A.F. 2021. The role of volcanic-derived clays in the preservation of Ediacaran biota from the Itajaí Basin (ca. 563 Ma, Brazil). *Scientific Reports*, **11**, 5013, https://doi.org/10.1038/s41598-021-84433-0

Billings, E. 1872. On some fossils from the primordial rocks of Newfoundland. *Canadian Naturalist and Quarterly Journal of Science*, **6**, 465–479.

Boag, T.H., Darroch, S.A.F. and Laflamme, M. 2016. Ediacaran distributions in space and time: testing assemblage concepts of earliest macroscopic body fossils. *Paleobiology*, **42**, 574–594, https://doi.org/10.1017/pab.2016.20

Boag, T.H., Busch, J.F., Gooley, J.T., Strauss, J.V. and Sperling, E.A. 2024. Deep-water first occurrences of Ediacara biota prior to the Shuram carbon isotope excursion in the Wernecke Mountains, Yukon, Canada. *Geobiology*, **22**, e12597, https://doi.org/10.1111/gbi.12597

Bobrovskiy, I., Krasnova, A., Ivantsov, A., Luzhnaya (Serezhnikova), E. and Brocks, J.J. 2019. Simple sediment rheology explains the Ediacara biota preservation. *Nature Ecology & Evolution*, **3**, 582–589, https://doi.org/10.1038/s41559-019-0820-7

Borchvardt, D.V. and Nessov, L.A. 1999. New records of metaphytes from the Vendian (Precambrian) of Zimnii Bereg of the White Sea. *Trudy Zoologicheskogo Instituta Rossiĭskoĭ Akademii Nauk*, **277**, 50–57.

Bottjer, D.J. and Clapham, M.E. 2006. Evolutionary palaeoecology of Ediacaran benthic marine animals. *In*: Xiao, S. and Kaufman, A.J. (eds) *Neoproterozoic Geobiology and Paleobiology*. Topics in Geobiology, **27**, 91–114, https://doi.org/10.1007/1-4020-5202-2_4

Boyce, W.D. and Reynolds, K. 2008. The Ediacaran fossil *Aspidella terranovica* Billings, 1872 from St. John's Convention Centre test pit CjAe-33. *Current Research, Newfoundland and Labrador Department of Natural Resources—Geological Survey*, **08-1**, 55–61.

Boynton, H.E. and Ford, T.D. 1995. Ediacaran fossils from the Precambrian (Charnian Supergroup) of Charnwood Forest, Leicestershire, England. *Mercian Geologist*, **13**, 165–182.

Brasier, M.D. and Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: New insights from laser analysis. *Journal of the Geological Society*, **166**, 363–384, https://doi.org/10.1144/0016-76492008-011

Brasier, M.D., Callow, R.H.T., Menon, L.R. and Liu, A.G. 2010: Osmotrophic biofilms: From modern to ancient. *In*: Seckbach, J. and Oren, A. (eds) *Microbial Mats: Modern and Ancient Microorganisms in Stratified Systems*. Springer, Cellular Origin, Life in Extreme Habitats and Astrobiology series, **14**, 131–148, https://doi.org/10.1007/978-90-481-3799-2_7

Brasier, M.D., Antcliffe, J.B. and Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124, https://doi.org/10.1111/j.1475-4983.2012.01164.x

Brasier, M.D., Liu, A.G., Menon, L., Matthews, J.J., McIlroy, D. and Wacey, D. 2013. Explaining the exceptional preservation of Ediacaran rangeomorphs from Spaniard's

Bay, Newfoundland: A hydraulic model. *Precambrian Research*, **231**, 122–135, https://doi.org/10.1016/j.precamres.2013.03.013

Brett, C.E., Zambito, J.J., Hunda, B.R. and Schindler, E. 2012. Mid-Paleozoic trilobite lagerstätten: Models of diagenetically enhanced obrution deposits. *Palaios*, **27**, 326–345, https://doi.org/10.2110/palo.2011.p11-040r

Briggs, D.E.G. 2015. The Cambrian explosion. *Current Biology*, **25**, R864–R868, https://doi.org/10.1016/j.cub.2015.04.047

Budd, G.E. and Jensen, S. 2017. The origin of the animals and a 'Savannah' hypothesis for early bilaterian evolution. *Biological Reviews*, **92**, 446–473, https://doi.org/10.1111/brv.12239

Butterfield, N.J. 2022. Constructional and functional anatomy of Ediacaran rangeomorphs. *Geological Magazine*, **159**, 1148–1159, https://doi.org/10.1017/S0016756820000734

Callow, R.H.T. and Brasier, M.D. 2009. Remarkable preservation of microbial mats in Neoproterozoic siliciclastic settings: Implications for Ediacaran taphonomic models. *Earth Science Reviews*, **96**, 207–219, https://doi.org/10.1016/j.earscirev.2009.07.002

Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, and Social Sciences and Humanities Research Council of Canada. 2022. *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*. Government of Canada.

Canfield, D.E., Poulton, S.W. and Narbonne, G.M. 2007. Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life. *Science*, **315**, 92–95, https://doi.org/10.1126/science.1135013

Canfield, D.E., Knoll, A.H., Poulton, S.W., Narbonne, G.M. and Dunning, G.R. 2020. Carbon isotopes in clastic rocks and the Neoproterozoic carbon cycle. *American Journal of Science*, **320**, 97–124, https://doi.org/10.2475/02.2020.01

Cisneros, J.C., Raja, N.B., Ghilardi, A.M., Dunne, E.M., Pinheiro, F.L., Fernández, O.R.R., Sales, M.A.F., Rodríguez-de la Rosa, R.A., Miranda-Martínez, A.Y., González-Mora, S., Bantim, R.A.M., de Lima, F.J. and Pardo, J.D. 2022. Digging deeper into colonial palaeontological practices in modern day Mexico and Brazil. *Royal Society Open Science*, **9**, 210898, https://doi.org/10.1098/rsos.210898

Clapham, M.E. and Narbonne, G.M. 2002. Ediacaran epifaunal tiering. *Geology*, **30**, 627–630, https://doi.org/10.1130/0091-7613(2002)030%3C0627:EET%3E2.0.CO;2

Clapham, M.E., Narbonne, G.M. and Gehling, J.G. 2003. Paleoecology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland. *Paleobiology*, **29**, 527–544, https://doi.org/10.1666/0094-8373(2003)029%3C0527:POTOKA%3E2.0.CO;2

Clark, T.H. 1923. New fossils from the vicinity of Boston. *Proceedings of the Boston Society of Natural History*, **36**, 473–485.

Clark, N.D.L., Booth, P., Booth, C. and Ross, D.A. 2004. Dinosaur footprints from the Duntulm Formation (Bathonian, Jurassic) of the Isle of Skye. *Scottish Journal of Geology*, **40**, 13–21, https://doi.org/10.1144/sjg40010013

Clarke, A.J.I., Kirkland, C.L., Menon, L.R., Condon, D.J., Cope, J.C.W., Bevins, R.E. and Glorie, S. 2024. U-Pb zircon-rutile dating of the Llangynog Inlier, Wales: Constraints on an Ediacaran shallow-marine fossil assemblage from East Avalonia. *Journal of the Geological Society*, **181**, https://doi.org/10.1144/jgs2023-081

Clements, T., Purnell, M. and Gabbott, S. 2019. The Mazon Creek Lagerstätte: A diverse late Paleozoic ecosystem entombed within siderite concretions. *Journal of the Geological Society*, **176**, 1–11, https://doi.org/10.1144/jgs2018-088

Cocks, L.R.M., McKerrow, W.S. and van Staal, C.R. 1997. The margins of Avalonia. *Geological Magazine*, **134**, 627–636, https://doi.org/10.1017/S0016756897007425

Cribb, A.T., Kenchington, C.G., Koester, B., Gibson, B.M., Boag, T.H., Racicot, R.A., Mocke, H., Laflamme, M. and Darroch, S.A.F. 2019. Increase in metazoan ecosystem engineering prior to the Ediacaran-Cambrian boundary in the Nama Group, Namibia. *Royal Society Open Science*, **6**, 190548, https://doi.org/10.1098/rsos.190548

Crimes, T.P. and Fedonkin, M.A. 1996. Biotic changes in platform communities across the precambrian Phanerozoic boundary. *Rivista Italiana di Paleontologia e Stratigrafia*, **102**, 317–332, https://doi.org/10.13130/2039-4942/5266

Darroch, S.A.F., Laflamme, M., Schiffbauer, J.D. and Briggs, D.E.G. 2012. Experimental formation of a microbial death mask. *Palaios*, **27**, 293–303, https://doi.org/10.2110/palo.2011.p11-059r

Darroch, S.A.F., Laflamme, M. and Clapham, M.E. 2013. Population structure of the oldest known macroscopic communities from Mistaken Point, Newfoundland. *Paleobiology*, **39**, 591–608, https://doi.org/10.1666/12051

Darroch, S.A.F., Smith, E.F., Laflamme, M. and Erwin, D.H. 2018. Ediacaran extinction and Cambrian explosion. *Trends in Ecology & Evolution*, **33**, 653–663, https://doi.org/10.1016/j.tree.2018.06.003

Darroch, S.A.F., Cribb, A.T., Buatois, L.A., Germs, G.J.B., Kenchington, C.G., Smith, E.F., Mocke, H., O'Neil, G.R., Schiffbauer, J.D., Maloney, K.M., Racicot, R.A., Turk, K.A., Gibson, B.M., Almond, J., Koestar, B., Boag, T.H., Tweedt, S.M. and Laflamme, M. 2021. The trace fossil record of the Nama Group, Namibia: Exploring the terminal Ediacaran roots of the Cambrian Explosion. *Earth-Science Reviews*, **212**, 103435, https://doi.org/10.1016/j.earscirev.2020.103435

Darroch, S.A.F., Gutarra, S., Masaki, H., Olaru, A., Gibson, B.M., Dunn, F.S., Mitchell, E.G., Racicot, R.A., Burzynski, G. and Rahman, I.A. 2023. The rangeomorph *Pectinifrons abyssalis*: Hydrodynamic function at the dawn of animal life. *iScience*, **26**, 105989, https://doi.org/10.1016/j.isci.2023.105989

Darwin, C. 1859. *The Origin of Species (Collins Classics)*. HarperCollins.

Das, S. and Lowe, M. 2018. Nature read in black and white: decolonial approaches to interpreting natural history collections. *Journal of Natural Science Collections*, **6**, 4–14.

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2017. Relating Ediacaran fronds. *Paleobiology*, **43**, 171–180, https://doi.org/10.1017/pab.2016.54

Dececchi, T.A., Narbonne, G.M., Greentree, C. and Laflamme, M. 2018. Phylogenetic relationships among the Rangeomorpha: The importance of outgroup selection and implications for their diversification. *Canadian Journal of Earth Sciences*, **55**, 1223–1239, https://doi.org/10.1139/cjes-2018-0022

Deprez, M., de Kock, T., de Schutter, G. and Cnudde, V. 2020. A review on freeze-thaw action and weathering of rocks. *Earth-Science Reviews*, **203**, 103143, https://doi.org/10.1016/j.earscirev.2020.103143

Dewanckele, J., Boone, M.A., de Kock, T., de Boever, W., Brabant, L., Boone, M.N., Fronteau, G., Dils, J., van Hoorebeke, L., Jacobs, P. and Cnudde, V. 2013. Holistic approach of pre-existing flaws on the decay of two limestones. *Science of The Total Environment*, **447**, 403–414, https://doi.org/10.1016/j.scitotenv.2012.12.094

Dornbos, S.Q., Noffke, N. and Hagadorn, J.W. 2007. Mat-decay features. *In*: Schieber, J., Bose, P.K., Eriksson, P.G., Banerjee, S., Sarkar, S., Altermann, W. and Catuneau, O. (eds) *Atlas of microbial mat features preserved within the clastic rock record*. Elsevier, 106–110.

Droser, M.L. and Gehling, J.G. 2015. The advent of animals: The view from the Ediacaran. *Proceedings of the National Academy of Sciences of the United States of America*, **112**, 4865–4870, https://doi.org/10.1073/pnas.1403669112

Dufour, S.C. and McIlroy, D. 2017. Ediacaran pre-placozoan diploblasts in the Avalonian biota: The role of chemosynthesis in the evolution of early animal life. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 211–219, https://doi.org/10.1144/SP448.5

Dunn, F.S., Liu, A.G. and Donoghue, P.C.J. 2018. Ediacaran developmental biology. *Biological Reviews*, **93**, 914–932, https://doi.org/10.1111/brv.12379

Dunn, F.S., Liu, A.G. and Gehling, J.G. 2019a. Anatomical and ontogenetic reassessment of the Ediacaran frond *Arborea arborea* and its placement within total group Eumetazoa. *Palaeontology*, **62**, 851–865, https://doi.org/10.1111/pala.12431

Dunn, F.S., Wilby, P.R., Kenchington, C.G., Grazhdankin, D.V., Donoghue, P.C.J. and Liu, A.G. 2019b. Anatomy of the Ediacaran rangeomorph *Charnia masoni*. *Papers in Palaeontology*, **5**, 157–176, https://doi.org/10.5061/dryad.fg14s2r

Dunn, F.S., Liu, A.G., Grazhdankin, D.V., Vixseboxse, P., Flannery-Sutherland, J., Green, E., Harris, S., Wilby, P.R. and Donoghue, P.C.J. 2021. The developmental biology of *Charnia* and the eumetazoan affinity of the Ediacaran rangeomorphs. *Science Advances*, **7**, eabe0291, https://doi.org/10.1126/sciadv.abe0291

Dunn, F.S., Kenchington, C.G., Parry, L.A., Clark, J.W., Kendall, R.S. and Wilby, P.R. 2022. A crown-group cnidarian from the Ediacaran of Charnwood Forest, UK. *Nature Ecology & Evolution*, **6**, 1095–1104, https://doi.org/10.1038/s41559-022-01807-x

Dzik, J. 2002. Possible ctenophoran affinities of the Precambrian "Sea-Pen" *Rangea*. *Journal of Morphology*, **252**, 315–334, https://doi.org/10.1002/jmor.1108

Dżułyński, S. and Walton, E.K. 1965. *Sedimentary Features of Flysch and Greywackes*. Elsevier.

Eden, R., Manica, A. and Mitchell, E.G. 2022. Metacommunity analyses show an increase in ecological specialisation throughout the Ediacaran period. *PLoS Biology*, **20**, e3001289, https://doi.org/10.1371/journal.pbio.3001289

Edgar, K.M., Meade, L.E., Jones, H.T., Haller, L., Scriven, S., Reedman, C. and Butler, R.J. 2023. The condition, use and future of the UK's largest accessible dinosaur tracksite at Spyway Quarry, Dorset. *Proceedings of the Geologists' Association*, **134**, 125–138, https://doi.org/10.1016/j.pgeola.2023.01.001

Environment and Natural Resources Canada 2023. Historical Climate Data, Government of Canada, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html. Accessed 21 March 2023.

Erwin, D.H., Laflamme, M., Tweedt, S.M., Sperling, E.A., Pisani, D. and Peterson, K.J. 2011. The Cambrian conundrum: Early divergence and later ecological success in the early history of animals. *Science*, **334**, 1091–1097, https://doi.org/10.1126/science.1206375

Evans, S.D., Droser, M.L. and Erwin, D.H. 2021. Developmental processes in Ediacara macrofossils. *Proceedings of the Royal Society B*, **288**, 20203055, https://doi.org/10.1098/rspb.2020.3055

Farooq, K. 2013. British fossils being lost to vandalism, The Guardian, https://www.theguardian.com/science/lost-worlds/2013/oct/11/british-fossils-vandalism-charnwood-forest. Accessed 22 June 2023.

Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. and Vickers-Rich, P. 2007. *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press.

Flude, L.I. and Narbonne, G.M. 2008. Taphonomy and ontogeny of a multibranched Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland. *Canadian Journal of Earth Sciences*, **45**, 1095–1109, https://doi.org/10.1139/E08-057

Ford, T.D. 1958. Pre-Cambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 211–217, https://doi.org/10.1144/pygs.31.3.211

Foss, K. 2021. Half a billion years in the making, Gazette, https://gazette.mun.ca/public-engagement/half-a-billion-years-in-the-making/. Accessed 23 June 2023.

García-Ortiz, E., Fuertes-Gutiérrez, I. and Fernández-Martínez, E. 2014. Concepts and terminology for the risk of degradation of geological heritage sites: Fragility and natural vulnerability, a case study. *Proceedings of the Geologists' Association*, **125**, 463–479, https://doi.org/10.1016/j.pgeola.2014.06.003

Gehling, J.G. 1999. Microbial mats in terminal Proterozoic siliciclastics: Ediacaran death masks. *Palaios*, **14**, 40–57, https://doi.org/10.2307/3515360

Gehling, J.G. and Droser, M.L. 2018. Ediacaran scavenging as a prelude to predation. *Emerging Topics in Life Sciences*, **2**, 213–222, https://doi.org/10.1042/etls20170166

Gehling, J.G. and Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387, https://doi.org/10.1139/e07-003

Gehling, J.G., Narbonne, G.M. and Anderson, M.M. 2000. The first named Ediacaran body fossil, *Aspidella Terranovica*. *Palaeontology*, **43**, 427–456, https://doi.org/10.1111/j.0031-0239.2000.00134.x

Germs, G.J.B. 1972. New shelly fossils from the Nama Group, South West Africa. *American Journal of Science*, **272**, 752–761, https://doi.org/10.2475/ajs.272.8.752

Geyer, G. and Landing, E. 1995. The Cambrian of the Moroccan Atlas regions. *In*: Geyer, G. and Landing, E. (eds) *Morocco '95—the Lower-Middle Cambrian standard of western Gondwana*. Beringeria, Special Issue, **2**, 7–46.

Geyer, G. and Landing, E. 2006. Morocco field excursion 2006. Ediacaran-Cambrian depositional environments and stratigraphy of the western Atlas regions. *In*: Geyer, G. and Landing, E. (eds) *Morocco 2006. Ediacaran-Cambrian depositional environments and stratigraphy of the western Atlas regions. Explanatory description and field excursion guide*. Beringeria, Special Issue, **6**, 47–112.

Ghisalberti, M., Gold, D.A., Laflamme, M., Clapham, M.E., Narbonne, G.M., Summons, R.E., Johnston, D.T. and Jacobs, D.K. Canopy flow analysis reveals the advantage of size in the oldest communities of multicellular eukaryotes. *Current Biology*, **24**, 305–309, https://doi.org/10.1016/j.cub.2013.12.017

Ghosh, A., Mukhopadhyay, S. and Chatterjee, S. 2021. Assessment of geoheritage and prospects of geotourism: An approach to geoconservation of important geological and geomorphological sites of Puruliya district, West Bengal, India. *International Journal of Geoheritage and Parks*, **9**, 264–283, https://doi.org/10.1016/j.ijgeop.2021.03.001

Gibson, B.M., Schiffbauer, J.D., Wallace, A.F. and Darroch, S.A.F. 2023. The role of iron in the formation of Ediacaran 'death masks'. *Geobiology*, **21**, 421–434, https://doi.org/10.1111/gbi.12551

Glaessner, M.F. 1959. Precambrian Coelenterata from Australia, Africa and England. *Nature*, **183**, 1472–1473, https://doi.org/10.1038/1831472b0

Glaessner, M.F. 1984. *The Dawn of Animal Life: A biohistorical Study*. Cambridge University Press.

Glaessner, M.F. and Daily, B. 1959. The geology and late Precambrian fauna of the Ediacara fossil reserve. *Records of the South Australia Museum*, **13**, 369–401.

Glaessner, M.F. and Wade, M. 1966. The Late Precambrian fossils from Ediacara, South Australia. *Palaeontology*, **9**, 599–628.

Gordon, J.E., Bailey, J.J. and Larwood, J.G. 2022. Conserving nature's stage provides a foundation for safeguarding both geodiversity and biodiversity in protected and conserved areas. *Parks Steward Forum*, **38**, 39–45, https://doi.org/10.5070/P538156118

Grazhdankin, D. 2004. Patterns of distribution in the Ediacaran biotas: Facies versus biogeography and evolution. *Paleobiology*, **30**, 203–221, https://doi.org/10.1666/0094-8373(2004)030%3C0203:PODITE%3E2.0.CO;2

Grazhdankin, D. 2014. Patterns of evolution of the Ediacaran soft-bodied biota. *Journal of Paleontology*, **88**, 269–283, https://doi.org/10.1666/13-072

Grazhdankin, D. 2016. Forbidden fruits in the Garden of Ediacara. *Paläontologische Zeitschrift*, **90**, 649–657, https://doi.org/10.1007/s12542-016-0327-3

Grazhdankin, D. and Seilacher, A. 2005. A re-examination of the Nama-type Vendian organism *Rangea schneiderhoehni*. *Geological Magazine*, **142**, 571–582, https://doi.org/10.1017/S0016756805000920

Grazhdankin, D.V., Balthasar, U., Nagovitsin, K.E. and Kochnev, B.B. 2008. Carbonate-hosted Avalon-type fossils in arctic Siberia. *Geology*, **36**, 803–806, https://doi.org/10.1130/G24946A.1

Grimes, K.F., Narbonne, G.M., Gehling, J.G., Trusler, P.W. and Dececchi, T.A. 2023. Elongate Ediacaran fronds from the Flinders Ranges, South Australia. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2023.45

Guerrero-Arenas, R., Aguilar Arellano, F.J., Alvarado Mendoza, L. and Jiménez-Hidalgo, E. 2020. How is the paleontological heritage of Mexico and other Latin American countries protected? *Paleontología Mexicana*, **9**, 83–90.

Gürich, G. 1930. Die bislang ältesten Spuren von Organismen in Südafrika. *International Geological Congress (XV), Pretoria, Union of South Africa, Die altesten Fossilien Sud-Afrikas*, **2**, 670–680.

Gürich, G. 1933. Die Kuibis-Fossilien der Nama-Formation von Südwestafrika. *Paläontologische Zeitschrift*, **15**, 137–154, https://doi.org/10.1007/BF03041648

Hahn, G. and Pflüg, H.D. 1985. Die Cloudinidae n. fam., Kalk-Röhren aus dem Vendium and Unter-Kambrium. *Senckenbergiana Lethaea*, **65**, 413–431.

Hancy, A.D. and Antcliffe, J.B. 2020. Anoxia can increase the rate of decay for cnidarian tissue: Using *Actinia equina* to understand the early fossil record. *Geobiology*, **18**, 167–184, https://doi.org/10.1111/gbi.12370

Hanson, H. and Lindh, G. 1993. Coastal erosion: an escalating environmental threat. *Ambio*, **22**, 188–195.

Hawco, J.B., Kenchington, C.G. and McIlroy, D. 2019. A quantitative and statistical discrimination of morphotaxa within the Ediacaran genus *Palaeopascichnus*. *Papers in Palaeontology*, **7**, 657–673, https://doi.org/10.5061/dryad.jq7460s

Hawco, J.B., Kenchington, C.G., Taylor, R.S. and McIlroy, D. 2020. A multivariate statistical analysis of the Ediacaran rangeomorph taxa *Beothukis* and *Culmofrons*. *Palaios*, **35**, 495–511, https://doi.org/10.2110/palo.2020.049

Hoblea, F., Delannoy, J.J., Jaillet, S., Ployon, E. and Sadier, B. 2014. Digital tools for managing and promoting karst geosites in southeast France. *Geoheritage*, **6**, 113–127, https://doi.org/10.1007/s12371-014-0112-1

Hofmann, H.J. and Mountjoy, E.W. 2010. Ediacaran body and trace fossils in Miette Group (Windermere Supergroup) near Salient Mountain, British Columbia, Canada.

Canadian Journal of Earth Sciences, **47**, 1305–1325, https://doi.org/10.1139/E10-070

Hofmann, H.J., O'Brien, S.J. and King, A.F. 2008. Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36, https://doi.org/10.1666/06-087.1

Homann, M., Heubeck, C., Airo, A. and Tice, M.M. 2015. Morphological adaptations of 3.22 Ga-old tufted microbial mats to Archean coastal habitats (Moodies Group, Barberton Greenstone Belt, South Africa). *Precambrian Research*, **266**, 47–64, https://doi.org/10.1016/j.precamres.2015.04.018

Hosek, J., Musilek, P., Lozowski, E. and Pytlak, P. 2011. Forecasting severe ice storms using numerical weather prediction: The March 2010 Newfoundland event. *Natural Hazards and Earth System Sciences*, **11**, 587–595, https://doi.org/10.5194/nhess-11-587-2011

Hoyal Cuthill, J.F. and Conway Morris, S. 2014. Fractal branching organizations of Ediacaran rangeomorph fronds reveal a lost Proterozoic body plan. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 13122–13126, https://doi.org/10.1073/pnas.1408542111

Hoyal Cuthill, J.F. and Conway Morris, S. 2017. Nutrient-dependent growth underpinned the Ediacaran transition to large body size. *Nature Ecology & Evolution*, **1**, 1201–1204, https://doi.org/10.1038/s41559-017-0222-7

Huang, T., Chen, D., Ding, Y., Zhou, X. and Zhang, G. 2020. SIMS U-Pb zircon geochronological and carbon isotope chemostratigraphic constraints on the

Ediacaran-Cambrian boundary succession in the Three Gorges Area, South China. *Journal of Earth Science*, **31**, 69–78, https://doi.org/10.1007/s12583-019-1233-x

Ichaso, A.A., Dalrymple, R.W. and Narbonne, G.M. 2007. Paleoenvironmental and basin analysis of the late Neoproterozoic (Ediacaran) upper Conception and St. John's groups, west Conception Bay, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 25–41, https://doi.org/10.1139/e06-098

Jenkins, R.J.F. 1985. The enigmatic Ediacaran (late Precambrian) genus *Rangea* and related forms. *Paleobiology*, **11**, 336–355, https://doi.org/10.1017/S0094837300011635

Jenkins, R.J.F. and Gehling, J.G. 1978. A review of the frond-like fossils of the Ediacara assemblage. *Records of the South Australia Museum*, **17**, 347–359.

Jenkins, R.J.F. and Nedin, C. 2007. The provenance and palaeobiology of a new multi-vaned, chambered frondose organism from the Ediacaran (later Neoproterozoic) of South Australia. *In*: Vickers-Rich, P. and Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, Special Publications, **286**, 195–222, https://doi.org/10.1144/sp286.15

Keller, B.M. and Fedonkin, M.A. 1977. New organic fossil finds in the Precambrian Valday series along the Syuz'ma River. *International Geology Review*, **19**, 924–930, https://doi.org/10.1080/00206817709471091

Kenchington, C.G. and Wilby, P.R. 2014. Of time and taphonomy: Preservation in the Ediacaran. *The Paleontological Society Papers*, **20**, 101–122, https://doi.org/10.1017/S1089332600002825

Kenchington, C.G. and Wilby, P.R. 2017. Rangeomorph classification schemes and intra-specific variation: Are all characters created equal? *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 221–250, https://doi.org/10.1144/SP448.19

Keppie, J.D. and Keppie, D.F. 2014. Ediacaran-Middle Paleozoic oceanic voyage of Avalonia from Baltica via Gondwana to Laurentia: Paleomagnetic, faunal and geological constraints. *Geoscience Canada*, **41**, 5–18, https://doi.org/10.12789/geocanj.2014.41.039

King, A.F. 1988. *Geology of the Avalon Peninsula, Newfoundland (parts of 1K, 1L, 1M, 1N and 2C)*. Newfoundland Department of Mines and Energy Map **88-01**.

Knoll, A.H., Javaux, E.J., Hewitt, D. and Cohen, P. 2006. Eukaryotic organisms in Proterozoic oceans. *Philosophical Transactions of the Royal Society B*, **361**, 1023–1038, https://doi.org/10.1098/rstb.2006.1843

Laflamme, M. 2014. Modeling morphological diversity in the oldest large multicellular organisms. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 12962–12963, https://doi.org/10.1073/pnas.1412523111

Laflamme, M. and Narbonne, G.M. 2008a. Ediacaran fronds. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 162–179, https://doi.org/10.1016/j.palaeo.2007.05.020

Laflamme, M. and Narbonne, G.M. 2008b. Competition in a Precambrian world: Palaeoecology of Ediacaran fronds. *Geology Today*, **24**, 182–187, https://doi.org/10.1111/j.1365-2451.2008.00685.x

Laflamme, M., Narbonne, G.M. and Anderson, M.M. 2004. Morphometric analysis of the Ediacaran frond *Charniodiscus* from the Mistaken Point Formation, Newfoundland. *Journal of Paleontology*, **78**, 827–837, https://doi.org/10.1666/0022-3360(2004)078%3C0827:MAOTEF%3E2.0.CO;2

Laflamme, M., Narbonne, G.M., Greentree, C. and Anderson, M.M. 2007. Morphology and taphonomy of an Ediacaran frond: *Charnia* from the Avalon Peninsula of Newfoundland. *In*: Vickers-Rich, P. and Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, Special Publications, **286**, 237–257, https://doi.org/10.1144/SP286.17

Laflamme, M., Xiao, S. and Kowaleski, M. 2009. Osmotrophy in modular Ediacara organisms. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 14438–14443, https://doi.org/10.1073/pnas.0904836106

Laflamme, M., Schiffbauer, J.D. and Narbonne, G.M. 2011. Deep-water microbially induced sedimentary structures (MISS) in deep time: The Ediacaran fossil *Ivesheadia*. *In*: Noffke, N. and Chafetz, H. (eds) *Microbial Mats in Siliciclastic Depositional Systems Through Time*. SEPM Special Publications, **101**, 111–123, https://doi.org/10.2110/sepmsp.101.111

Laflamme, M., Flude, L.I. and Narbonne, G.M. 2012. Ecological tiering and the evolution of a stem: The oldest stemmed frond from the Ediacaran of Newfoundland, Canada. *Journal of Paleontology*, **86**, 193–200, https://doi.org/10.1666/11-044.1

Laflamme, M., Darroch, S.A.F., Tweedt, S.M., Peterson, K.J. and Erwin, D.H. 2013. The end of the Ediacara biota: Extinction, biotic replacement, or Cheshire Cat? *Gondwana Research*, **23**, 558–573, https://doi.org/10.1016/j.gr.2012.11.004

Laflamme, M., Gehling, J.G. and Droser, M.L. 2018. Deconstructing an Ediacaran frond: Three-dimensional preservation of *Arborea* from Ediacara, South Australia. *Journal of Paleontology*, **92**, 323–335, https://doi.org/10.1017/jpa.2017.128

Landing, E., Antcliffe, J.B., Geyer, G., Kouchinsky, A., Bowser, S.S. and Andreas, A. 2018. Early evolution of colonial animals (Ediacaran Evolutionary Radiation–Cambrian Evolutionary Radiation–Great Ordovician Biodiversification Interval). *Earth-Science Reviews*, **178**, 105–135, https://doi.org/10.1016/j.earscirev.2018.01.013

Leatherman, S.P., Zhang, K. and Douglas, B.C. 2000. Sea level rise shown to drive coastal erosion. *Eos, Transactions American Geophysical Union*, **81**, 55–57, https://doi.org/10.1029/00EO00034

Legwold, G. 1996. *The Last Word on Lutefisk: True Tales of Cod and Tradition*. Conrad Henry Press.

Liu, A.G. 2016. Framboidal pyrite shroud confirms the 'death mask' model for moldic preservation of Ediacaran soft-bodied organisms. *Palaios*, **31**, 259–274, https://doi.org/10.2110/palo.2015.095

Liu, A.G. and Conliffe, J. 2015. *2015 Fall Field Trip, The Ediacaran fossils of the Avalon Peninsula*. Geological Association of Canada, Newfoundland and Labrador Section.

Liu, A.G. and McIlroy, D. 2015. Horizontal surface traces from the Fermeuse Formation, Ferryland (Newfoundland, Canada), and their place within the late Ediacaran ichnological revolution. *In*: McIlroy, D. (ed.) *Ichnology: Publications arising from ICHNIA III*. Geological Association of Canada, Miscellaneous Publication, **9**, 141–156.

Liu, A.G., McIlroy, D. and Brasier, M.D. 2010. First evidence for locomotion in the Ediacara biota from the 565 Ma Mistaken Point Formation, Newfoundland. *Geology*, **38**, 123–126, https://doi.org/10.1130/G30368.1

Liu, A.G., McIlroy, D., Antcliffe, J.B. and Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630, https://doi.org/10.1111/j.1475-4983.2010.01024.x

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2012. A new assemblage of juvenile Ediacaran fronds from the Drook Formation, Newfoundland. *Journal of the Geological Society*, **169**, 395–403, https://doi.org/10.1144/0016-76492011-094

Liu, A.G., McIlroy, D., Matthews, J.J. and Brasier, M.D. 2013. Exploring an Ediacaran 'nursery': Growth, ecology and evolution in a rangeomorph palaeocommunity. *Geology Today*, **29**, 23–26, https://doi.org/10.1111/j.1365-2451.2013.00860.x

Liu, A.G., Matthews, J.J., Menon, L.R., McIlroy, D. and Brasier, M.D. 2014. *Haootia quadriformis* n. gen., n. sp., interpreted as a muscular cnidarian impression from the Late Ediacaran period (approx. 560 Ma). *Proceedings of the Royal Society B*, **281**, 20141202, https://doi.org/10.1098/rspb.2014.1202

Liu, A.G., Kenchington, C.G. and Mitchell, E.G. 2015. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380, https://doi.org/10.1016/j.gr.2014.11.002

Liu, A.G., Matthews, J.J. and McIlroy, D. 2016. The *Beothukis*/*Culmofrons* problem and its bearing on Ediacaran macrofossil taxonomy: Evidence from an exceptional new fossil locality. *Palaeontology*, **59**, 45–58, https://doi.org/10.1111/pala.12206

Liu, A.G., Matthews, J.J. and McIlroy, D. 2017. *Field Trip 3, Late Ediacaran Geology and Palaeobiology of the Bonavista Peninsula, Newfoundland*. International Symposium on the Ediacaran–Cambrian Transition 2017.

Liverman, D.G.E. 1994. Relative sea-level history and isostatic rebound in Newfoundland, Canada. *Boreas*, **23**, 217–230, https://doi.org/10.1111/j.1502-3885.1994.tb00944.x

MacDougall, M.D.J., Braun, A. and Fotopoulos, G. 2020. Implications of glacial isostatic adjustment on petroleum reservoirs in the Grand Banks of Newfoundland. *Journal of Geodynamics*, **140**, 101781, https://doi.org/10.1016/j.jog.2020.101781

Machado, S., Mergulhão, L., Pereira, B.C., Pereira, P., Carvalho, J., Anacleto, J.A., Neto de Carvalho, C., Belo, J., Paredes, R. and Baucon, A. 2021. Geoconservation in the Cabeço da Ladeira Paleontological Site (Serras de Aire e Candeeiros Nature Park, Portugal): Exquisite Preservation of Animals and Their Behavioral Activities in a Middle Jurassic Carbonate Tidal Flat. *Geosciences*, 11, 366, https://doi.org/10.3390/geosciences11090366

Magnus, O. 1555. *Historia de gentibus septentrionalibus (The history of the Nordic people)*. Rome.

Mason, S.J. and Narbonne, G.M. 2016. Two new Ediacaran small fronds from Mistaken Point, Newfoundland. *Journal of Paleontology*, **90**, 183–194, https://doi.org/10.1017/jpa.2016.14

Matsuoka, N. and Murton, J. 2008. Frost weathering: Recent advances and future directions. *Permafrost and Periglacial Processes*, **19**, 195–210, https://doi.org/10.1002/ppp.620

Matthews, J.J. and McIlroy, D. 2019. On the adhesion of sediment to footwear and the implications for geoconservation. *Geoheritage*, **11**, 1749–1756, https://doi.org/10.1007/s12371-019-00380-3

Matthews, J.J., Liu, A.G. and McIlroy, D. 2017. Post-fossilization processes and their implications for understanding Ediacaran macrofossil assemblages. *In*: Brasier, A.T., McIlroy, D. and McLoughlin, N. (eds) *Earth System Evolution and Early Life: A Celebration of the Work of Martin Brasier*. Geological Society, London, Special Publications, **448**, 251–269, https://doi.org/10.1144/SP448.20

Matthews, J.J., Liu, A.G., Yang, C., McIlroy, D., Levell, B. and Condon, D.J. 2020. A chronostratigraphic framework for the rise of the Ediacaran macrobiota: New constraints from Mistaken Point Ecological Reserve, Newfoundland. *GSA Bulletin*, **133**, 612–624, https://doi.org/10.1130/B35646.1

McArthur, R.H. and Wilson, E.O. 1967. *The Theory of Island Biogeography*. Princeton University Press.

McIlroy, D. and Horák, J.M. 2006. Neoproterozoic: The late Precambrian terranes that formed Eastern Avalonia. *In*: Brenchley, P.J. and Rawson, P.F. (eds) *The Geology of England and Wales*, *Second Edition*. Geological Society, London, 9–23, https://doi.org/10.1144/GOEWP

McIlroy, D. and Logan, G.A. 1999. The impact of bioturbation on infaunal ecology and evolution during the Proterozoic-Cambrian transition. *Palaios*, **14**, 58–72, https://doi.org/10.2307/3515361

McIlroy, D., Dufour, S.C., Taylor, R. and Nicholls, R. 2021. The role of symbiosis in the first colonization of the seafloor by macrobiota: Insights from the oldest Ediacaran biota (Newfoundland, Canada). *Biosystems*, **205**, 104413, https://doi.org/10.1016/j.biosystems.2021.104413

McIlroy, D., Pérez-Pinedo, D., Pasinetti, G., McKean, C., Taylor, R.S. and Hiscott, R.N. 2022a. Rheotropic epifaunal growth, not felling by density currents is responsible for many Ediacaran fossil orientations at Mistaken Point. *Frontiers in Earth Science*, **10**, 849194, https://doi.org/10.3389/feart.2022.849194

McIlroy, D., Hawco, J.B., McKean, C., Nicholls, R., Pasinetti, G. and Taylor, R.S. 2022b. Palaeobiology of the reclining rangeomorph *Beothukis* from the Ediacaran Mistaken Point Formation of southeastern Newfoundland. *Geological Magazine*, **159**, 1160–1174, https://doi.org/10.1017/S0016756820000941

McKean, C., Taylor, R.S. and McIlroy, D. 2023. New taphonomic and sedimentological insights into the preservation of high-relief Ediacaran fossils at Upper Island Cove, Newfoundland. *Lethaia*, **56**, 1–17, https://doi.org/10.18261/let.56.4.2

McKean, C., Matthews, J.J., Rideout, B.W.T., Taylor, R.S. and McIlroy, D. 2024. Protecting Newfoundland's palaeontological geoheritage: mitigating anthropic and environmental damage to the Ediacaran fossils of Upper Island Cove. *Geoheritage*, **16**, 1–19, http://doi.org/10.1007/s12371-024-00959-5

Menon, L.R., McIlroy, D. and Brasier, M.D. 2013. Evidence for Cnidaria-like behavior in ca. 560 Ma Ediacaran *Aspidella*. *Geology*, **41**, 895–898, https://doi.org/10.1130/G34424.1

Mir, B.H., Lone, M.A. and Bhat, J.A. 2019. Laboratory investigation for development of local scour depth model for varying shapes of obstruction. *International Journal of*

Hydrology Science and Technology, **9**, 303–312, https://doi.org/10.1504/IJHST.2019.102319

Mitchell, E.G. and Butterfield, N.J. 2018. Spatial analyses of Ediacaran communities at Mistaken Point. *Paleobiology*, **44**, 40–57, https://doi.org/10.1017/pab.2017.35

Mitchell, E.G. and Kenchington, C.G. 2018. The utility of height for the Ediacaran organisms of Mistaken Point. *Nature Ecology & Evolution*, **2**, 1218–1222, https://doi.org/10.1038/s41559-018-0591-6

Mitchell, E.G., Kenchington, C.G., Liu, A.G., Matthews, J.J. and Butterfield, N.J. 2015. Reconstructing the reproductive mode of an Ediacaran macro-organism. *Nature*, **524**, 343–346, https://doi.org/10.1038/nature14646

Mitchell, E.G., Harris, S., Kenchington, C.G., Vixseboxse, P., Roberts, L., Clark, C., Dennis, A., Liu, A.G. and Wilby, P.R. 2019. The importance of neutral over niche processes in structuring Ediacaran early animal communities. *Ecology Letters*, **22**, 2028–2038, https://doi.org/10.1111/ele.13383

Mitchell, E.G., Bobkov, N., Bykova, N., Dhungana, A., Kolesnikov, A.V., Hogarth, I.R.P., Liu, A.G., Mustill, T.M.R., Sozonov, N., Rogov, V.I., Xiao, S. and Grazhdankin, D.V. 2020. The influence of environmental setting on the community ecology of Ediacaran organisms. *Interface Focus*, **10**, 20190109, http://doi.org/10.1098/rsfs.2019.0109

Murphy, J.B. and Nance, R.D. 1989. Model for the evolution of the Avalonian-Cadomian belt. *Geology*, **17**, 735–738, https://doi.org/10.1130/0091-7613(1989)017%3C0735:MFTEOT%3E2.3.CO;2

Murphy, J.B. and Nance, R.D. 2002. Sm–Nd isotopic systematics as tectonic tracers: An example from West Avalonia in the Canadian Appalachians. *Earth-Science Reviews*, **59**, 77–100, https://doi.org/10.1016/S0012-8252(02)00070-3

Murphy, J.B., Pisarevsky, S.A., Nance, R.D. and Keppie, J.D. 2004. Neoproterozoic—Early Paleozoic evolution of peri-Gondwanan terranes: Implications for Laurentia-Gondwana connections. *International Journal of Earth Sciences*, **93**, 659–682, https://doi.org/10.1007/s00531-004-0412-9

Narbonne, G.M. 1998. The Ediacara biota: A terminal Neoproterozoic experiment in the evolution of life. *GSA Today*, **8**, 1–6.

Narbonne, G.M. 2004. Modular construction of early Ediacaran complex life forms. *Science*, **305**, 1141–1144, https://doi.org/10.1126/science.1099727

Narbonne, G.M. 2005. The Ediacara biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442, https://doi.org/10.1146/annurev.earth.33.092203.122519

Narbonne, G.M. and Gehling, J.G. 2003. Life after snowball: The oldest complex Ediacaran fossils. *Geobiology*, **31**, 27–30, https://doi.org/10.1130/0091-7613(2003)031%3C0027:LASTOC%3E2.0.CO;2

Narbonne, GM., Gehling, J.G. and Vickers-Rich, P. 2007. The Misty Coasts of Newfoundland. *In*: Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. Vickers-Rich, P. (eds) *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press, 49–68.

Narbonne, G.M., Laflamme, M., Greentree, C. and Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard's Bay, Newfoundland. *Journal of Paleontology*, **83**, 503–523, https://doi.org/10.1666/08-072R1.1

Nedin, C. and Jenkins, R.J.F. 1998. First occurrence of the Ediacaran fossil *Charnia* from the southern hemisphere. *Alcheringa: An Australasian Journal of Palaeontology*, **22**, 315–316, https://doi.org/10.1080/03115519808619329

Newsome, D. and Johnson, C.P. 2013. Potential geotourism and the prospect of raising awareness about geoheritage and the environment on Mauritius. *Geoheritage*, **5**, 1–9, https://doi.org/10.1007/s12371-012-0070-4

Nicholson, D.T. and Nicholson, F.H. 2000. Physical deterioration of sedimentary rocks subjected to experimental freeze-thaw weathering. *Earth Surface Processes and Landforms*, **25**, 1295–1307, https://doi.org/10.1002/1096-9837(200011)25:12%3C1295::AID-ESP138%3E3.0.CO;2-E

Noble, S.R., Condon, D.J., Carney., J.N., Wilby, P.R., Pharaoh, T.C. and Ford, T.D. 2015. U-Pb geochronology and global context of the Charnian Supergroup, UK: Constraints on the age of key Ediacaran fossil assemblages. *Geological Society of America Bulletin*, **127**, 250–265, https://doi.org/10.1130/B31013.1

Noffke, N., Gerdes, G., Klenke, T. and Krumbein, W.E. 1996. Microbially induced sedimentary structures—Examples from modern sediments of siliciclastic tidal flats. *Zentralblatt für Geologie und Paläontologie Teil I*, 307–316.

Noffke, N., Gerdes, G., Klenke, T. and Krumbein, W.E. 2001. Microbially induced sedimentary structures—A new category within the classification of primary sedimentary structures. *Journal of Sedimentary Research*, **71**, 649–656, https://doi.org/10.1306/2DC4095D-0E47-11D7-8643000102C1865D

Overeem, I., Anderson, R.S., Wobus, C.W., Clow, G.D., Urban, F.E. and Matell, N. 2011. Sea ice loss enhances wave action at the Arctic coast. *Geophysical Research Letters*, **38**, L17503, https://doi.org/10.1029/2011GL048681

O'Brien, C. 2020. Winter weather escalates across Canada as army sent to help Newfoundland, CTV News, https://www.ctvnews.ca/canada/winter-weather-escalates-across-canada-as-army-sent-to-help-newfoundland-1.4773937. Accessed 21 June 2023.

O'Brien, S.J. and King, A.F. 2004. Ediacaran fossils from the Bonavista Peninsula (Avalon Zone), Newfoundland: Preliminary descriptions and implications for regional correlation. *Newfoundland Department of Mines and Energy—Geological Survey,* **04-1**, 203–212.

Pasinetti, G. and McIlroy, D. 2023. Paleobiology and taphonomy of the rangeomorph *Culmofrons plumosa*. *Palaeontology*, **66**, e12671, https://doi.org/10.1111/pala.12671

Pérez-Pinedo, D., McKean, C., Taylor, R.S. and McIlroy, D. 2022. *Charniodiscus* and *Arborea* are separate genera within the Arboreomorpha: Using the holotype of *C. concentricus* to resolve a taxonomic tangle. *Frontiers in Earth Science*, **9**, 785929, https://doi.org/10.3389/feart.2021.785929

Pérez-Pinedo, D., Neville, J.M., Pasinetti, G., McKean, C., Taylor, R. and McIlroy, D. 2023. Frond orientations with independent current indicators demonstrate the reclining rheotropic mode of life of several Ediacaran rangeomorph taxa. *Paleobiology*, **49**, 471–492, https://doi.org/10.1017/pab.2023.2

Pérez-Pinedo, D., Nicholls, R., Neville, J. and McIlroy, D. 2024. Hydrodynamic insights into the palaeobiology of the Ediacaran rangeomorph *Fractofusus misrai*. *iScience*, **27**, 110107, https://doi.org/10.1016/j.isci.2024.110107

Peterson, K.J., Waggoner, B. and Hagadorn, J.W. 2003. A fungal analog for Newfoundland Ediacaran fossils? *Integrative and Comparative Biology*, **43**, 127–136, https://doi.org/10.1093/icb/43.1.127

Pflüg, H.D. 1972. Systematik der jung-präkambrischen Petalonamae. *Paläontologische Zeitschrift*, **46**, 56–67, https://doi.org/10.1007/BF02989552

Pisarevsky, S.A., Murphy, J.B., Cawood, P.A. and Collins, A.S. 2008. Late Neoproterozoic and Early Cambrian palaeogeography: Models and problems. *In*: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B. and Se Wit, M.J. (eds) *West Gondwana: Pre-Cenozoic correlations across the South Atlantic region*. Geological Society, London, Special Publications, **294**, 9–31, https://doi.org/10.1144/SP294.2

Pisarevsky, S.A., McCausland, P.J.A., Hodych, J.P., O'Brien, S.J., Tait, J.A. and Murphy, J.B. 2012. Paleomagnetic study of the late Neoproterozoic Bull Arm and Crown Hill formations (Musgravetown Group) of eastern Newfoundland: Implications for Avalonia and West Gondwana paleogeography. *Canadian Journal of Earth Sciences*, **49**, 308–327, https://doi.org/10.1139/e11-045

Pollock, J.C., Hibbard, J.P. and Sylvester, P.J. 2009. Early Ordovician rifting of Avalonia and birth of the Rheic Ocean: U–Pb detrital zircon constraints from Newfoundland. *Journal of the Geological Society*, **166**, 501–515, https://doi.org/10.1144/0016-76492008-088

Prave, A.R., Condon, D.J., Hoffmann, K.H., Tapster, S. and Fallick, A.E. 2016. Duration and nature of the end-Cryogenian (Marinoan) glaciation. *Geology*, **44**, 631–634, https://doi.org/10.1130/G38089.1

Province of Newfoundland and Labrador 1997. Fossil Ecological Reserve Regulations 63/97 under the Wilderness and Ecological Reserves Act 1990, https://faolex.fao.org/docs/pdf/nf53903.pdf. Accessed 18 July 2023.

Province of Newfoundland and Labrador 2009. Fossil Ecological Reserve Regulations 13/09 under the Wilderness and Ecological Reserves Act 1990, https://www.assembly.nl.ca/legislation/sr/regulations/rc090013.htm. Accessed 23 June 2023.

Province of Newfoundland and Labrador 2011. Palaeontological Resource Regulations 67/11 under the Historic Resources Act 1990, https://www.assembly.nl.ca/legislation/sr/regulations/rc110067.htm#5_. Accessed 23 June 2023.

Pu, J.P., Bowring, S.A., Ramezani, J., Myrow, P., Raub, T.D., Landing, E., Mills, A., Hodgin, E. and Macdonald, F.A. 2016. Dodging snowballs: Geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. *Geology*, **44**, 955–958, https://doi.org/10.1130/G38284.1

Raja, N.B., Dunne, E.M., Matiwane, A., Ming Khan, T., Nätscher, P.S., Ghilardi, A.M. and Chattopadhyay, D. 2022. Colonial history and global economics distort our understanding of deep-time biodiversity. *Nature Ecology & Evolution*, **6**, 145–154, https://doi.org/10.1038/s41559-021-01608-8

Ryland, J.S. 1977. Taxes and tropisms of bryozoans. *In*: Woollacott, R.M. and Zimmer, R.L. (eds) *Biology of Bryozoans*. Academic Press, 411–436, https://doi.org/10.1016/B978-0-12-763150-9.50018-0

Sahoo, S.K., Planavsky, N.J., Kendall, B., Wang, X., Shi, X., Scott, C., Anbar, A.D., Lyons, T.W. and Jiang, G. 2012. Ocean oxygenation in the wake of the Marinoan glaciation. *Nature*, **489**, 546–549, https://doi.org/10.1038/nature11445

Santos, V.F., Callapez, P.M. and Rodrigues, N.P.C. 2013. Dinosaur footprints from the Lower Cretaceous of the Algarve Basin (Portugal): New data on the ornithopod palaeoecology and palaeobiogeography of the Iberian Peninsula. *Cretaceous Research*, **40**, 158–169, https://doi.org/10.1016/j.cretres.2012.07.001

Seilacher, A. 1964. Biogenic sedimentary structures. *In*: Imbrie, J. and Newell, N. (eds) *Approaches to Paleoecology*. Wiley, 296–316.

Seilacher, A. 1989. Vendozoa: Organismic construction in the Proterozoic biosphere. *Lethaia*, **22**, 229–239, https://doi.org/10.1111/j.1502-3931.1989.tb01332.x

Seilacher, A. 1992. Vendobionta and Psammocorallia: Lost constructions of Precambrian evolution. *Journal of the Geological Society*, **149**, 607–613, https://doi.org/10.1144/gsjgs.149.4.0607

Shadrick, J.R., Rood, D.H., Hurst, M.D., Piggott, M.D., Hebditch, B.G., Seal, A.J. and Wilcken, K.M. 2022. Sea-level rise will likely accelerate rock coast cliff retreat rates. *Nature Communications*, **13**, 7005, https://doi.org/10.1038/s41467-022-34386-3

Sharp, A.C., Evans, A.R., Wilson, S.A. and Vickers-Rich, P. 2017. First non-destructive internal imaging of *Rangea*, an icon of complex Ediacaran life. *Precambrian Research*, **229**, 303–308, https://doi.org/10.1016/j.precamres.2017.07.023

Singer, A., Plotnick, R. and Laflamme, M. 2012. Experimental fluid mechanics of an Ediacaran frond. *Palaeontologia Electronica*, **15**, 19A, https://doi.org/10.26879/297

Sprigg, R.C. 1947. Early Cambrian (?) jellyfishes from the Flinders Ranges, South Australia. *Transactions of the Royal Society of South Australia*, **71**, 212–224.

Stephenson, W.J., Dickson, M.E. and Trenhaile, A.S. 2013. 10.11 Rock Coasts. *In*: Shroder, J.F. (ed) *Treatise on Geomorphology, Volume 10: Coastal Geomorphology*. Academic Press, 289–307.

Sunamura, T. 1976. Feedback relationship in wave erosion of laboratory rocky coast. *The Journal of Geology*, **84**, 427–437, https://doi.org/10.1086/628209

Tarhan, L.G., Hood, A.v.S., Droser, M.L., Gehling, J.G. and Briggs, D.E.G. 2016. Exceptional preservation of soft-bodied Ediacara Biota promoted by silica-rich oceans. *Geology*, **44**, 951–954, https://doi.org/10.1130/G38542.1

Taylor, R.S., Matthews, J.J., Nicholls, R. and McIlroy, D. 2021. A re-assessment of the taxonomy, palaeobiology and taphonomy of the rangeomorph organism *Hapsidophyllas flexibilis* from the Ediacaran of Newfoundland, Canada. *Paläontologische Zeitschrift*, **95**, 187–207, https://doi.org/10.1007/s12542-020-00537-4

Taylor, R.S., Nicholls, R., Neville, J.M. and McIlroy, D. 2023. Morphological variation in the rangeomorph organism *Fractofusus misrai* from the Ediacaran of Newfoundland, Canada. *Geological Magazine*, **160**, 146–166, https://doi.org/10.1017/S0016756822000723

Tohver, E., D'Agrella-Filho, M.S. and Trindade, R.I.F. 2006. Paleomagnetic record of Africa and South America for the 1200–500Ma interval, and evaluation of Rodinia and Gondwana assemblies. *Precambrian Research*, **147**, 193–222, https://doi.org/10.1016/j.precamres.2006.01.015

van Kranendonk, M.J., Gehling, J.G. and Shields, G.A. 2008. Precambrian. *In*: Ogg, J.G., Ogg, G. and Gradstein, F.M. (eds) *The Concise Geologic Time Scale*. Cambridge University Press, 23–36.

van Stall, C.R., Dewey, J.F., Niocaill, C.M. and McKerrow, W.S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *In*: Blundell, D.J. and Scott, A.C. (eds) *Lyell: The Past is the Key to the Present*. Geological Society, London, Special Publications, **143**, 197–242, https://doi.org/10.1144/GSL.SP.1998.143.01.17

Vickers-Rich, P., Ivantsov, A., Trusler, P.W., Narbonne, G.M., Hall, M., Wilson, S.A., Greentree, C., Fedonkin, M.A., Elliot, D.A., Hoffmann, K.H. and Schneider, G.I.C. 2013. Reconstructing *Rangea*: New discoveries from the Ediacaran of southern Namibia. *Journal of Paleontology*, **87**, 1–15, https://doi.org/10.1666/12-074R.1

Wade, M. 1968. Preservation of soft-bodied animals in Precambrian sandstones at Ediacara, South Australia. *Lethaia*, **1**, 238–267, https://doi.org/10.1111/j.1502-3931.1968.tb01740.x

Waggoner, B. 2003. The Ediacaran biotas in space and time. *Integrative and Comparative Biology*, **43**, 104–113, https://doi.org/10.1093/icb/43.1.104

Walker, J.D. and Geissman, J.W. (compilers). 2022. Geologic Time Scale v.6.0. *Geological Society of America*, https://doi.org/10.1130/2022.CTS006C

Walter, T.R., Harnett, C.E., Varley, N., Vargas Bracamontes, D., Salzer, J., Zorn, E.U., Bretón, M., Arámbula, R. and Thomas, M.E. 2019. Imaging the 2013 explosive crater excavation and new dome formation at Volcán de Colima with TerraSAR-X, time-lapse cameras and modelling. *Journal of Volcanology and Geothermal Research*, **369**, 224–237, https://doi.org/10.1016/j.jvolgeores.2018.11.016

Wang, X., Pang, K., Chen, Z., Wan, B., Xiao, S., Zhou, C. and Yuan, X. 2020. The Ediacaran frondose fossil *Arborea* from the Shibantan limestone of South China. *Journal of Paleontology*, **94**, 1034–1050, https://doi.org/10.1017/jpa.2020.43

Whipple, K.X., Hancock, G.S. and Anderson, R.S. 2000. River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. *GSA Bulletin*, **112**, 490–503, https://doi.org/10.1130/0016-7606(2000)112%3C490:RIIBMA%3E2.0.CO;2

Wilby, P.R., Carney, J.N. and Howe, M.P.A. 2011. A rich Ediacaran assemblage from eastern Avalonia: Evidence of early widespread diversity in the deep ocean. *Geology*, **39**, 655–658, https://doi.org/10.1130/G31890.1

Wilby, P.R., Kenchington, C.G. and Wilby, R.L. 2015. Role of low intensity environmental disturbance in structuring the earliest (Ediacaran) microbenthic tiered communities. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **434**, 14–27, https://doi.org/10.1016/j.palaeo.2015.03.033

Williams, G.C., Hoeksema, B.W. and van Ofwegen, L. 2012. A fifth morphological polyp in pennatulacean octocorals, with a review of polyp polymorphism in the genera *Pennatula* and *Pteroeides* (Anthozoa: Pennatulidae). *Zoological Studies*, **51**, 1006–1017.

Wimbledon, W.A. and Smith-Meyer, S. 2012. *Geoheritage in Europe and its conservation*. ProGEO.

Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, J.G. and Clapham, M.E. 2003. Paleoenvironmental analysis of the late Neoproterozoic Mistaken Point and Trepassey formations, southeastern Newfoundland. *Canadian Journal of Earth Sciences*, **40**, 1375–1391, https://doi.org/10.1139/e03-048

Wood, R., Bowyer, F.T., Alexander, R., Yilales, M., Uahengo, C.-I., Kaputuaza, K., Ndeunyema, J. and Curtis, A. 2023. New Ediacaran biota from the oldest Nama Group, Namibia (Tsaus Mountains), and re-definition of the Nama Assemblage. *Geological Magazine*, **160**, 1673–1686, https://doi.org/10.1017/S0016756823000638

Wu, C., Pang, K., Chen, Z., Wang, X., Zhou, C., Wan, B., Yuan, X. and Xiao, S. 2022. The rangeomorph fossil *Charnia* from the Ediacaran Shibantan biota in the Yangtze Gorges area, South China. *Journal of Paleontology*, 1–17, https://doi.org/10.1017/jpa.2022.97

Xiao, S. and Laflamme, M. 2009. On the eve of animal radiation: Phylogeny, ecology and evolution of the Ediacara biota. *Trends in Ecology & Evolution*, **24**, 31–40, https://doi.org/10.1016/j.tree.2008.07.015

Xiao, S., Narbonne, G.M., Zhou, C., Laflamme, M., Grazhdankin, D.V., Moczydlowska-Vidal, M. and Cui, H. 2016. Towards an Ediacaran time scale: Problems, protocols, and prospects. *Episodes*, **39**, 540–555, https://doi.org/10.18814/epiiugs/2016/v39i4/103886

Xiao, S., Chen, Z., Pang, K., Zhou, C. and Yuan, X. 2020. The Shibantan Lagerstätte: Insights into the Proterozoic-Phanerozoic transition. *Journal of the Geological Society*, **178**, jgs2020-135, https://doi.org/10.1144/jgs2020-135

Yang, C., Rooney, A.D., Condon D.J., Li, X., Grazhdankin, D.V., Bowyer, F.T., Hu, C., Macdonald, F.A. and Zhu, M. 2021. The tempo of Ediacaran evolution. *Science Advances*, **7**, eabi9643, http://doi.org/10.1126/sciadv.abi9643

Zhang, K., Douglas, B.C. and Leatherman, S.P. 2004. Global warming and coastal erosion. *Climatic Change*, **64**, 41–58, https://doi.org/10.1023/B:CLIM.0000024690.32682.48

APPENDIX A

Supplementary Material for Chapter 2

Table A.1 – Obstruction scour and frond orientations collected from the Allison Surface, Upper Island Cove.

Obstruction Scour #	Obstruction Scour Orientation (°)	Frond Orientation (°)
1	200	211
2	208	
3	204	
4	202	
5	195	209
6	202	
7	196	212
8	202	
9	203	211
10	208	
11	198	
12	202	
13	206	
14	202	
15	197	
16	198	
17	202	
18	200	
19	208	
20	196	
21	201	
22	201	
23	204	224

24	204	
25	210	
26	204	
27	206	
28	199	209
29	204	
30	201	
31	205	
32	205	
33	204	
34	200	211
35	214	
36	208	
37	208	
38	214	
39	205	
40	208	
41	198	
42	200	212
43	207	
44	210	
45	208	
46	209	
47	206	
48	198	
49	207	
50	205	
51	199	221
52	205	
53	200	
54	208	
55	204	

56	202	
57	207	230
58	198	
59	209	
60	200	
61	212	
62	208	
63	201	
64	203	
65	198	
66	208	
67	198	
68	211	
69	202	220
70	199	
71	202	209
72	205	
73	198	216
74	196	218
75	207	
76	210	
77	202	
78	199	212
79	202	212
80	200	
81	202	
82	201	
83	206	
84	202	
85	207	
86	207	216
87	208	194

88	204	
89	206	
90	211	
91	202	
92	205	
93	201	
94	205	209
95	203	220
96	204	
97	204	192
98	201	
99	204	
100	200	
101	206	
102	203	210
103	202	
104	209	
105	196	
106	204	
107	205	
108	202	
109	209	
110	200	
111	208	
112	208	
113	200	
114	199	
115	202	
116	204	
117	205	
118	206	
119	206	

120	210	219
121	196	
122	204	214
123	205	
124	209	
125	197	
126	202	
127	199	218
128	204	
129	202	
130	202	
131	201	
132	194	
133	208	
134	194	
135	207	
136	204	
137	204	210
138	204	207
139	204	
140	206	
141	200	
142	202	
143	204	
144	198	
145	201	209
146	198	212
147	200	
148	207	
149	198	
150	203	
151	196	

152	204	207
153	198	
154	198	210
155	200	
156	199	212
157	204	
158	196	
159	204	221
160	198	228
161	199	
162	202	209
163	214	
164	207	
165	202	196
166	202	209
167	204	
168	200	208
169	207	214
170	206	214
171	202	216
172	204	211
173	200	222
174	200	214
175	200	208
176	205	212
177	212	216
178	200	192
179	208	
180	196	
181	202	
182	200	
183	210	

184	198	222
185	206	
186	208	
187	206	
188	208	
189	204	
190	206	
191	202	
192	206	
193	205	
194	203	
195	200	
196	198	
197	205	
198	200	
199	209	
200	198	
201	206	
202	208	
203	206	223
204	202	195
205	208	
206	208	
207	204	
208	209	
209	202	
210	192	
211	201	
212	212	
213	212	
214	211	
215	213	

216	191	
217	198	
218	209	
219	199	
220	209	
221	198	210
222	196	
223	202	198
224	202	
225	198	
226	200	
227	203	
228	205	
229	196	
230	204	
231	180	
232	216	
233	204	
234	210	226
235	201	
236	196	
237	199	
238	196	208
239	204	218
240	198	210
241	201	212
242	202	
243	210	
244	205	
245	198	
246	197	
247	204	

248	208	
249	201	
250	206	
251	204	
252	198	
253	204	
254	194	
255	209	
256	201	
257	208	
258	204	
259	200	
260	203	
261	204	
262	205	
263	206	
264	206	
265	189	
266	210	
267	208	
268	198	221
269	196	
270	196	
271	199	
272	196	
273	206	
274	196	206
275	205	
276	207	221
277	218	
278	200	34
279	202	

280	197	
281	204	
282	205	
283	200	224
284	204	207
285	208	
286	202	
287	210	214
288	203	
289	200	
290	197	
291	196	
292	204	
293	193	
294	196	
295	196	
296	202	
297	209	
298	207	
299	207	
300	211	
301	204	
302	198	
303	198	
304	212	
305	192	
306	206	
307	197	
308	204	
309	203	
310	205	
311	194	

312	200	
313	206	
314	191	
315	198	
316	210	
317	199	
318	200	
319	202	
320	202	
321	205	
322	204	
323	202	
324	197	222
325	203	
326	188	
327	204	
328	198	
329	200	
330	197	
331	204	
332	206	
333	208	
334	207	
335	198	
336	202	
337	204	
338	200	
339	208	
340	201	
341	202	
342	206	
343	182	

344	192	199
345	214	
346	208	
347	190	
348	198	
349	210	
350	204	
351	208	
352	200	
353	207	
354	201	
355	196	220
356	201	
357	198	210
358	206	218
359	208	216
360	204	210
361	200	216
362	210	226
363	204	248
364	199	
365	202	
366	205	
367	202	
368	198	
369	205	
370	212	
371	208	
372	210	
373	211	
374	204	
375	200	

376	202	
377	196	
378	200	
379	210	
380	194	
381	196	
382	206	
383	194	
384	199	
385	212	
386	212	
387	206	
388	207	
389	200	
390	215	
391	206	
392	206	
393	204	221
394	203	
395	206	
396	200	
397	204	
398	210	
399	197	
400	204	
401	206	
402	216	
403	208	
404	209	
405	212	
406	208	
407	204	

408	203	
409	214	
410	204	
411	210	

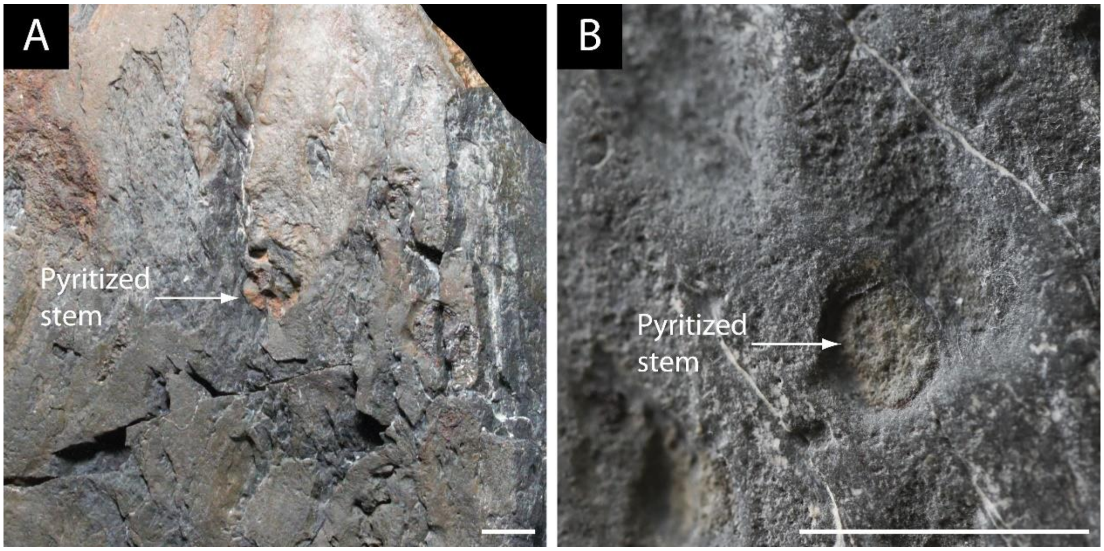


Fig. A.1 – Pyritic rims representing the pyritized stems of erect organisms crosscutting the fossiliferous surface. A, pyritized rim from the second community with an associated obstruction scour (NFM F-757). B, pyritized rim from the third community without an associated obstruction scour. (scale bars – 1 cm)

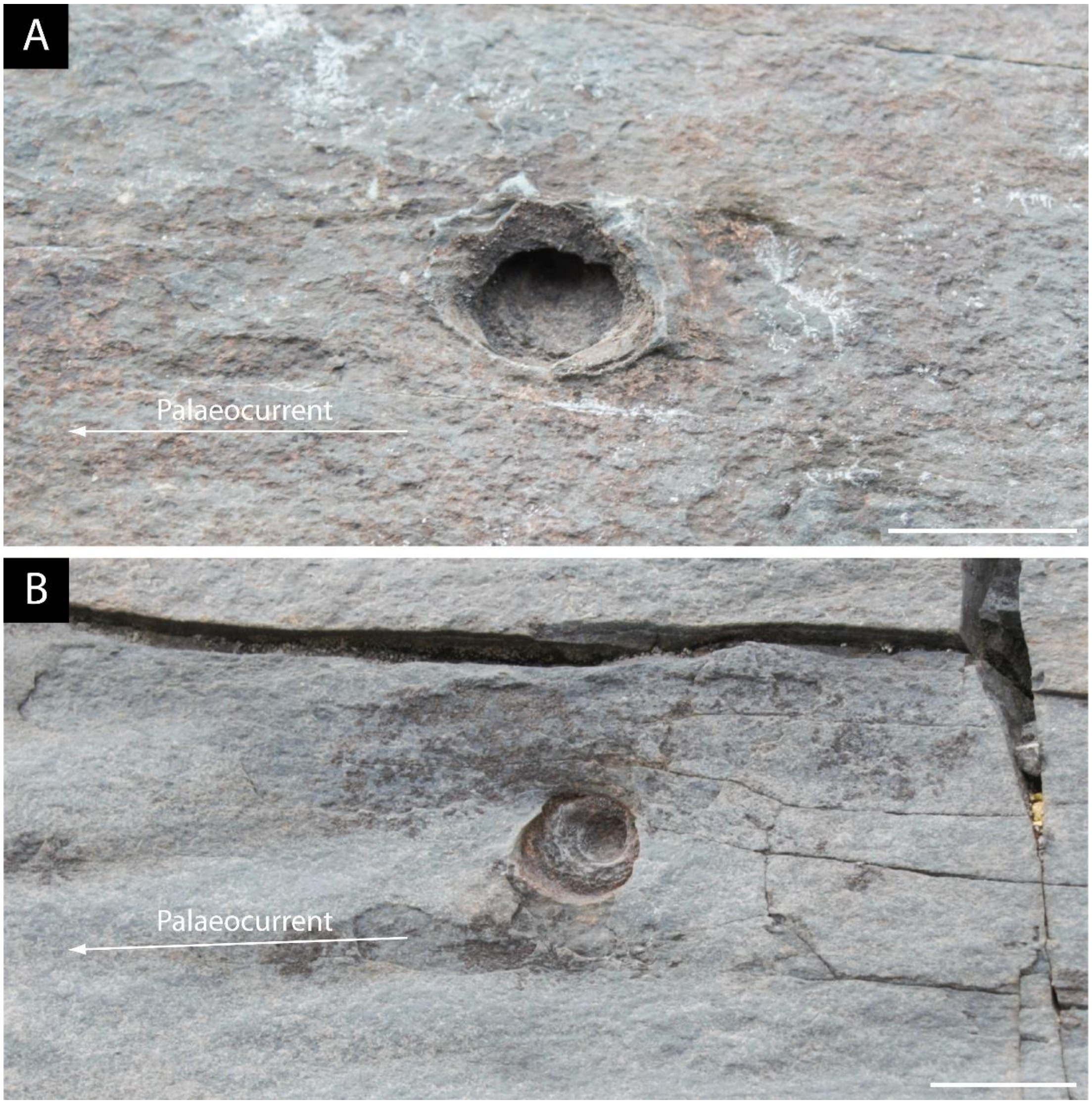


Fig. A.2 – Comparable holdfasts to the Upper Cove Specimens, found in Adams Cove. Note the depth of the bulbous holdfasts and signs of shallow scours beginning to form down-current. (scale bars – 1 cm)

APPENDIX B

Supplementary Material for Chapter 3

Table B.1 – Fossil identification of specimens from the Allison Surface, Upper Island Cove, used in this study.

Fossil ID	Silicone #	Jesmonite #	Identification	Notes	Relief	Duplicate?	Figured in thesis (Y/N)	Chapter(s)
SB-2019-001-a	SB-2019-001	N/A	Taphomorph	Poorly preserved, left-hand side of frond	Mixed	No	N	N/A
SB-2019-001-b	SB-2019-001	N/A	*Charnia masoni*	Well preserved right-hand side of frond	Positive	Original	N	N/A
SB-2019-001-c	SB-2019-001	N/A	*Charnia masoni*	Crosscut by holdfast	Positive	Original	N	N/A
SB-2019-001-d	SB-2019-001	N/A	Taphomorph (Avalofractus sp.?)	Highly decayed frond, positive relief is necrotic material	Positive	No	Y	3
SB-2019-001-e	SB-2019-001	N/A	*Avalofractus abaculus*	New paratype of *Avalofractus abaculus*	Positive	Original	N	N/A
SB-2019-001-f	SB-2019-001	N/A	Insufficiently exhumed frond (Avalofractus?)	Partially exposed specimen, largely obscured by sediment	Mixed	No	N	N/A
SB-2020-001a	SB-2020-001a	N/A	*Arborea*	Crosscut by holdfast	Positive	No	Y	2
SB-2020-001b	SB-2020-001b	N/A	Insufficiently exhumed frond	Partial preservation of frond, very little detail	Negative	No	Y	3
SB-2020-007	SB-2020-007	N/A	*Kannabuchia artkingii* (type b)	Crosscut frond with differing orientation, only partly exposed	Positive	No	Y	2
SB-2020-010ii	SB-2020-010	ii	Taphomorph	Exposed taphomorph within a narrow scour	Negative	No	Y	3
SB-2020-012i	SB-2020-012	i	*Kannabuchia artkingii* (type a)	Partial preservation of frond with clear branching detail found near top of scour	Mixed	No	N	N/A
SB-2020-012ii	SB-2020-012	ii	Taphomorph (Arboreomorph?)	Poorly preserved, likely necrotic frond exposed in scour	Mixed	No	N	N/A
SB-2020-012iii	SB-2020-012	iii	*Bradgatia* sp. A.	*Bradgatia*-style branching preserved deep in scour	Negative	No	N	N/A

SB-2020-012iv	SB-2020-012	iv	Insufficiently exhumed frond (Bradgatia?)	Partial frond which may have been part of a larger specimen, potential reversed branching	Negative	No	N	N/A
SB-2020-012v	SB-2020-012	v	*Bradgatia* sp. C.	Largely necrotic organic material, with some branching preserved	Negative	No	N	N/A
SB-2020-013i	SB-2020-013	i	Taphomorph	Largely decomposed taphomorph with some branching	Negative	No	N	N/A
SB-2020-013ii-a	SB-2020-013	ii	Insufficiently exhumed frond	Curved ridges with branching in between them	Negative	No	N	N/A
SB-2020-013ii-b	SB-2020-013	ii	Taphomorph (*Avalofractus sp.?*)	Poorly preserved Taphomorph, largely negative impressions of branches	Mixed	No	N	N/A
SB-2020-013iii	SB-2020-013	iii	Insufficiently exhumed frond	Partial branching found within scour - weathered	Negative	No	N	N/A
SB-2020-013iv	SB-2020-013	iv	Insufficiently exhumed frond	Faint branching in tip of the scour	Positive	No	Y	3
SB-2020-014ii	SB-2020-014	ii	Taphomorph	Frond in narrow scour	Negative	No	N	N/A
SB-2022-015i	SB-2022-015	i	Insufficiently exhumed frond	Minor preservation of frond within scour	Positive	No	N	N/A
SB-2022-015ii	SB-2022-015	ii	Taphomorph	Minor preservation of frond within scour	Positive	No	N	N/A
SB-2022-015iii	SB-2022-015	iii	*Kannabuchia artkingii* (type a)	Partial preservation of frond with visable midline and right-hand branches	Positive	No	N	N/A
SB-2022-015iv	SB-2022-015	iv	*Kannabuchia artkingii* (type b)	Partly exposed frond with left-hand side still largely buried	Mixed	No	N	N/A
SB-2022-015v	SB-2022-015	v	*Kannabuchia artkingii* (type a)	Partial preservation and exposure of frond	Mixed (weathered)	No	N	N/A
SB-2020-016i	SB-2020-016	i	Taphomorph	Partial remnant of a frond deep within the scour and cut by a fracture	Negative	No	N	N/A
SB-2020-016ii	SB-2020-016	ii	*Kannabuchia artkingii* (type ?)	Poorly preserved *Kannabuchia*	Mixed	No	N	N/A
SB-2020-018i	SB-2020-018	i	Insufficiently exhumed frond	Very partial branching, Aspidella at top appears to be covered by matground	Negative	No	Y	3
SB-2020-018ii	SB-2020-018	ii	Taphomorph	Partial specimen largely removed	Mixed	No	N	N/A
SB-2020-018iii	SB-2020-018	iii	Taphomorph (Avalofractus?)	Minor preservation of frond in scour	Mixed	No	N	N/A
SB-2020-018iv	SB-2020-018	iv	Taphomorph (Bradgatia?)	Branching on the right-hand side of a wide scour, appears tousled/reversed	Mixed	No	N	N/A
SB-2020-019(a)i	SB-2020-019(a)	i	Taphomorph	Remains of a frond at the top of small scour	Mixed	No	N	N/A
SB-2020-019(a)ii	SB-2020-019(a)	ii	Insufficiently exhumed frond (Arboreomorph?)	Partial branching preserved	Positive	No	N	N/A
SB-2020-019(b)i	SB-2020-019(b)	i	*Kannabuchia artkingii* (type a)	Partial preservation of large frond	Positive	No	Y	3

SB-2020-019(b)ii-a	SB-2020-019(b)	ii	*Kannabuchia artkingii* (type a)	Small exposure of frond with midline and branching on either side present	Positive	No	N	N/A
SB-2020-019(b)ii-b	SB-2020-019(b)	ii	*Kannabuchia artkingii* (type a)	Partial branching preserved in sections of scour	Positive (weathered)	No	N	N/A
SB-2020-019(b)iii-a	SB-2020-019(b)	iii	*Charnia* sp. b.	Rhombohedral *Charnia* specimen in high-relief	Negative	No	Y	1, 2, 3
SB-2020-019(b)iii-b	SB-2020-019(b)	iii	*Arborea*	Well preserved right-hand side of frond, can be seen to be go beneath the sediment	Positive	No	Y	2
SB-2020-019(b)iii-c	SB-2020-019(b)	iii	Insufficiently exhumed frond (Arboreomorph?)	Largely decayed frond with some branching present	Mixed	No	N	N/A
SB-2020-019(b)iii-d	SB-2020-019(b)	iii	Taphomorph (Avalofractus?)	Weathered branching preserved in negative epirelief	Negative	No	N	N/A
SB-2020-020(a)	SB-2020-020(a)	N/A	Taphomorph	Partial frond preservation beneath large scour	Mixed (predominantly negative)	No	N	N/A
SB-2020-020(b)i	SB-2020-020(b)	i	Pneu specimen	Pneu-specimen exposed within scour	Negative	Original	Y	3
SB-2020-020(b)ii	SB-2020-020(b)	ii	*Kannabuchia artkingii* (type b)	Partially preserved frond with branching appearing at different layers	Mixed	No	Y	2, 3
SB-2020-020(b)iii	SB-2020-020(b)	iii	Undetermined	"beothukid" with high variation in orientation when compared to scour	Positive	No	Y	2
SB-2020-020(b)iv	SB-2020-020(b)	iv	Taphomorph	Negative preservation of a partial frond	Negative	No	N	N/A
SB-2020-020(b)v	SB-2020-020(b)	v	*Arborea*	Mixed relief frond, with some necrotic material present	Mixed	No	Y	2, 3
SB-2020-021i	SB-2020-021	i	Insufficiently exhumed frond	Partially exhumed frond with some branching	Negative	No	Y	3
SB-2020-021ii	SB-2020-021	ii	Taphomorph	Necrotic material within scour, some branching visable	Negative	No	N	N/A
SB-2020-021iii	SB-2020-021	iii	*Bradgatia* sp. B.	Small exposure of I-shaped *Bradgatia*, branching in three(?) parallel rows	Negative	No	N	N/A
SB-2020-021iv	SB-2020-021	iv	*Arborea*	Left-hand side of an *Arborea* exposed within scour, remnants of central stalk present	Positive	No	N	N/A
SB-2020-021v	SB-2020-021	v	*Arborea*	Left-hand side of strange frond with high dissociation to orientation of scour	Positive	No	Y	3
SB-2020-022i-a	SB-2020-022	i	*Kannabuchia artkingii* (type b)	Possibly tousled frond	Positive	No	N	N/A
SB-2020-022i-b	SB-2020-022	i	*Avalofractus abaculus*	Some branching apparent on the edge of the scour	Mixed	No	N	N/A
SB-2020-022ii	SB-2020-022	ii	Insufficiently exhumed frond	Partial preservation of branching on the right edge of scour	Positive	No	Y	2
SB-2020-022iii	SB-2020-022	iii	*Kannabuchia artkingii* (type a)	Rare example of better preservation on left-hand side of frond	Mixed	No	N	N/A
SB-2020-022iv	SB-2020-022	iv	*Arborea*	Previously described as a beothukid, no rangeomorph branching and distinct peapod units	Positive (weathered)	No	N	N/A

SB-2020-022v	SB-2020-022	v	*Kannabuchia artkingii* (type ?)	Frond with clearly rotated branches	Mixed	No	N	N/A
SB-2020-024ii-a	SB-2020-024	ii	Undetermined	Four(?) primary order branches similar to *Fractofusus*, branching only visible under controlled light	Positive	No	Y	2
SB-2020-024ii-b	SB-2020-024	ii	Taphomorph	Poorly preserved specimen, only partial branching and potential midline visible	Negative	No	N	N/A
SB-2020-024iii	SB-2020-024	iii	Taphomorph	Poorly preserved specimen	Mixed	No	N	N/A
SB-2020-025i	SB-2020-025	i	Insufficiently exhumed frond	Some branching exposed beneath holdfast	Mixed	No	N	N/A
SB-2020-025ii	SB-2020-025	ii	Insufficiently exhumed frond (*Bradgatia?*)	Holdfast with a small exposure of branching above	Negative	No	N	N/A
SB-2020-025iii	SB-2020-025	iii	Arboreomorph	Partial exposure of arboreomorph branching	Negative	No	N	N/A
SB-2020-025iv	SB-2020-025	iv	*Bradgatia* sp. A.	Partial exposure of branches and midline	Mixed	No	N	N/A
SB-2020-026i	SB-2020-026	i	Insufficiently exhumed frond	Partial branching in scour	Negative	No	N	N/A
SB-2020-026ii	SB-2020-026	ii	Insufficiently exhumed frond	Small amount of branching in right-hand side of scour	Mixed	No	Y	2
SB-2020-027i-a	Sb-2020-027	i	Taphomorph	Very poorly preserved frond, only small remnants of branching	Negative	No	N	N/A
SB-2020-027i-b	Sb-2020-027	i	Taphomorph	Very poorly preserved frond, only small remnants of organic matter remain	Negative	No	N	N/A
SB-2020-027iii	SB-2020-027	iii	Taphomorph	Remnants of frond found in centre and top of scour, unidentifiable	Negative	No	N	N/A
SB-2020-027iv	SB-2020-027	iv	*Arborea*	Arboreomorph-type branching in central region of scour	Negative	No	Y	3
SB-2020-027v	SB-2020-027	v	Taphomorph	Partial preservation of a frond, with no discernable detail visible	Negative	No	N	N/A
SB-2020-028i	SB-2020-028	i	*Bradgatia* sp. A.	Arboriform *Bradgatia*, some primary branching preserved in exposure	Negative	No	N	N/A
SB-2020-028ii	SB-2020-028	ii	Taphomorph	Largely decayed specimen	Mixed	No	Y	3
SB-2020-028iii	SB-2020-028	iii	Taphomorph (Bradgatia?)	Large specimen in negative epirelief	Negative	No	N	N/A
SB-2020-028iv	SB-2020-028iv	iv	*Kannabuchia artkingii* (type b)	Frond shows change in orientation (kinked?) across its exposure within the scour	Positive	No	N	N/A
SB-2020-028v	SB-2020-028	v	Insufficiently exhumed frond	Branching visible either side of a very steep midline	Negative	No	Y	3
SB-2020-028vi	SB-2020-028	vi	Taphomorph	Partial remnants of a frond,	Negative	No	N	N/A
SB-2020-028vii-a	SB-2020-028	vii	*Kannabuchia artkingii* (type a?)	Poorly preserved (necrotic) *Kannabuchia*	Mixed	No	N	N/A

SB-2020-028vii-b	SB-2020-028	vii	*Avalofractus dosomitus*	Exposed in the same scour as SB-2020-028vii-a	Positive	No	Y	3
SB-2020-029i	SB-2020-029	i	*Corellia washageuis*	Paratype of *Corellia washageuis* showing the top surface of the taxon	Mixed	No	Y	3
SB-2020-029ii	SB-2020-029	ii	*Kannabuchia artkingii* (type a)	Poorly preserved frond, only partly exhumed	Mixed	No	N	N/A
SB-2020-029iii	SB-2020-029	iii	*Kannabuchia artkingii (type ?)*	Largely decayed specimen with at least one branch preserves good detail to the second-order	Mixed	No	N	N/A
SB-2020-029iv	SB-2020-029	iv	*Kannabuchia artkingii* (type b)	Mixed epirelief; predominantly negative, but positive in bottom right	Mixed	No	N	N/A
SB-2020-029v	SB-2020-029	v	Taphomorph	Partial preservation of frond with some perpendicular branching on the right-hand side of scour	Negative	No	N	N/A
SB-2020-030i	SB-2020-030	i	Pneu specimen	Exposed in scour and cross cutting bubble train	Negative	No	Y	3
SB-2020-030ii	SB-2020-030	ii	Insufficiently exhumed frond	Partial branching midway up a scour	Negative	No	N	N/A
SB-2020-030iii	SB-2020-030	iii	Insufficiently exhumed frond	Partial remains of a midline found at the end of a sedimentary ridge	Negative	No	N	N/A
SB-2021-034	SB-2021-034	N/A	*Kannabuchia artkingii* (type b)	Well preserved frond with clear branch details present	Positive	No	Y	4
SB-2021-035i-a	SB-2021-035	i	*Kannabuchia artkingii* (type b)	Two fronds in same scour - positive specimen	Positive	No	N	N/A
SB-2021-035i-b	SB-2021-035	i	Taphomorph	Two fronds in same scour - negative specimen	Negative	No	N	N/A
SB-2021-035ii	SB-2021-035	ii	Taphomorph	Poorly preserved frond with some second-order (charnid?) branching	Mixed	No	Y	3
SB-2021-035iii	SB-2021-035	iii	Undetermined	"beothukid" with differing branching on either side of the midline	Positive	No	N	N/A
SB-2021-035iv	SB-2021-035	iv	*Kannabuchia artkingii* (type b)	Partial preservation of a frond, right-hand side is better preserved than the left	Mixed (weathered)	No	N	N/A
SB-2021-036ii	SB-2021-036	ii	*Bradgatia* sp. A.	Arboriform *Bradgatia* with possible evidence for a midline (likely taphonomic)	Negative	No	N	N/A
SB-2021-037	SB-2021-037	N/A	*Arborea*	Secondary branch detail is only visible at the tip, with potential tertiary branches (?)	Positive	No	N	N/A
SB-2021-038i	SB-2021-038	i	*Bradgatia* sp. A.	Poorly preserved frond with central region preserving some branching	Negative	No	N	N/A
SB-2021-038ii	SB-2021-038	ii	Pneu specimen	Pneu specimen preserving three+ rows	Negative	No	Y	3
SB-2021-038iii	SB-2021-038	iii	*Kannabuchia artkingii* (type a)	Well preserved frond with clear branch details present	Positive	No	N	N/A
SB-2021-038iv	SB-2021-038	iv	*Charnia gracilis*	Partially exposed frond within a scour, shows clear charnid branching	Mixed	No	Y	3
SB-2021-039i	SB-2021-039	i	*Arborea*	S-shaped frond with clear arboreomorph branching	Mixed	No	Y	2

SB-2021-039ii	SB-2021-039	ii	*Bradgatia* sp. B.	Frond showing the same branching as the "I-shaped" Bradgatia at The Rooms	Negative	No	N	N/A
SB-2021-039iii	SB-2021-039	iii	Taphomorph	Small frond with partial branching preserved deep in scour	Positive	No	N	N/A
SB-2021-040i	SB-2021-040	i	Taphomorph (Avalofractus?)	Frond has been largely eroded away but general body plan can be made	Mixed (weathered)	No	N	N/A
SB-2021-040ii-a	SB-2021-040	ii	*Arborea*	Negative relief Arboreomorph showing clearly separation of units, possible backing sheet preserved	Negative	No	Y	2, 3
SB-2021-040ii-b	SB-2021-040	ii	*Arborea*	Positive relief *Arborea* showing right-hand branching	Positive	No	Y	3
SB-2021-040iii	SB-2021-040	iii	Arboreomorph	Left-hand side of frond preserved in narrow scour	Negative	No	N	N/A
SB-2021-040iv	SB-2021-040	iv	*Charnia gracilis*	Partial preservation of frond with clear charnid branching down to third order	Positive	No	Y	3
SB-2021-040v	SB-2021-040	v	*Kannabuchia artkingii* (type ?)	Partial specimen found at the tip of frond, some variation in second-order branching	Positive	No	N	N/A
SB-2021-040vi-a	SB-2021-040	vi	*Kannabuchia artkingii* (type b)	Well preserved *frond* in scour	Positive	No	N	N/A
SB-2021-040vi-b	SB-2021-040	vi	Taphomorph	Partially preserved taphomorph, midline and primary branches partially preserved	Negative	No	N	N/A
SB-2021-040vii	SB-2021-040	vii	*Kannabuchia artkingii* (type a)	Well preserved central region of frond within scour, midline and branching on either side clearly visible	Positive	No	N	N/A
SB-2021-041i	SB-2021-041	i	*Bradgatia* sp. A.	Frond with complex branching preserved	Negative	No	Y	3
SB-2021-041ii-a	SB-2021-041	ii	*Arborea*	Highly differing orientation, scour to left shows the paleocurrent	Positive	No	Y	2, 3
SB-2021-041ii-b	SB-2021-041	ii	Insufficiently exhumed frond	Small frond above *Arbore* - orientation is different to both *Arborea* and scour	Mixed	No	Y	2
SB-2021-041iii	SB-2021-041	iii	Taphomorph	Poorly preserved specimen with midline and minor first-order branching	Mixed	No	N	N/A
SB-2021-042i	SB-2021-042	i	*Kannabuchia artkingii* (type b)	Preservation is poor however shows enough detail to be placed into *Kannabuchia* (type b)	Positive (weathered)	No	Y	3
SB-2021-042ii	SB-2021-042	ii	Taphomorph	Faint impression of a frond with only minor evidence for preserved branching detail	Negative	No	N	N/A
SB-2021-042iii	SB-2021-042	iii	Insufficiently exhumed frond	Stem of a frond with some branching detail on the right, appears rangeomorph (charnid?)	Mixed	No	N	N/A
SB-2021-042iv	SB-2021-042	iv	Taphomorph	Shallow/weathered frond only partly preserved, branch detail not visible	Negative	No	N	N/A
SB-2021-042v	SB-2021-042	v	Insufficiently exhumed frond (Avalofractus?)	Partial preservation of branching going deep into scour	Positive	No	N	N/A
SB-2021-042vi	SB-2021-042	vi	Taphomorph	Poorly preserved frond, large amount of decay in lower section	Mixed	No	Y	3
SB-2021-042vii-a	SB-2021-042	vii	Insufficiently exhumed frond	Partial branching across scour, highly weathered with no visible higher order branching	Negative	No	N	N/A

SB-2021-042vii-b	SB-2021-042	vii	*Avalofractus abaculus*	Weathered specimen which shows positive preservation in the lowest regions of the scour	Mixed	No	Y	3
SB-2021-042vii-c	SB-2021-042	vii	Insufficiently exhumed frond	Partial branching in two areas of the scour, higher-order branching visible	Negative	No	N	N/A
SB-2021-043i	SB-2021-043	i	*Bradgatia* sp. A.	Bradgatia with arboriform appearance, specimen lacks further detail	Negative	No	N	N/A
SB-2021-043ii	SB-2021-043	ii	Taphomorph	Negative impression of some branching can be seen	Negative	No	N	N/A
SB-2021-043iii	SB-2021-043	iii	*Avalofractus abaculus*	Faint impression of branches preserved near to the top of a long scour	Mixed	No	Y	3
SB-2021-043iv	SB-2021-043	iv	Taphomorph	Poorly preserved specimen, with midline and some branching present	Mixed	No	N	N/A
SB-2021-043v	SB-2021-043	v	Undetermined	Small amount of branching (well preserved) in scour, similar to fronds seen in DUGG	Negative	No	N	N/A
SB-2021-043vi	SB-2021-043	vi	*Kannabuchia artkingii* (type b)	Some displayed style branches appear preserved near to the tip	Positive	No	N	N/A
SB-2021-043vii	SB-2021-043	vii	*Kannabuchia artkingii* (type b)	Outline of tip of specimen is clearly visible and corresponds well with other type b specimens	Positive (weathered)	No	N	N/A
SB-2021-043viii	SB-2021-043	viii	Insufficiently exhumed frond	Small frond with radiating branching seen at the tip of a scour	Mixed	No	N	N/A
SB-2021-043ix	SB-2021-043	ix	*Kannabuchia artkingii* (type b)	Any branching higher than first-order has been weathered away	Positive (weathered)	No	N	N/A
SB-2021-043x	SB-2021-043	x	*Avalofractus abaculus*	Collapsed specimen, partial preservation with some minor branching detail	Positive (weathered)	No	Y	3
SB-2021-043xi	SB-2021-043	xi	*Avalofractus abaculus*	Largely weathered specimen	Positive (weathered)	No	N	N/A
SB-2021-044	SB-2021-044	N/A	Taphomorph	Poorly preserved specimen with very fine branching detail in the top right of scour	Negative	No	N	N/A
SB-2021-045i	SB-2021-045	i	*Avalofractus abaculus*	Tip of unfurled primary branch preserved; rest of specimen heavily eroded	Positive	No	Y	3
SB-2021-045ii	SB-2021-045	ii	Insufficiently exhumed frond	Specimen only preserves first order branches and is covered by black lichen (unable to remove)	Positive	No	N	N/A
SB-2021-045iii	SB-2021-045	iii	Insufficiently exhumed frond	Specimen only preserves first order branches and is covered by black lichen (unable to remove)	Positive	No	N	N/A
SB-2021-045iv	SB-2021-045	iv	*Arborea*	Partly preserved frond with midline and elements of primary branches visible	Negative	No	Y	3
SB-2021-045v	SB-2021-045	v	Taphomorph	Minor preservation of a frond within a shallow scour	Mixed	No	N	N/A
SB-2021-045vi	SB-2021-045	vi	Taphomorph (Avalofractus?)	Branches exposed in narrow scour; most detail appears to have been weathered away	Negative	No	N	N/A
SB-2021-046i	SB-2021-046	i	Taphomorph	Poorly preserved frond, beyond general shape nothing else has been preserved	Negative	No	N	N/A
SB-2021-046ii	SB-2021-046	ii	*Corellia washageuis*	Copy of SBAS-CM-20-01(b)	Mixed	Yes (SBAS-01b)	Y	3

SB-2021-046iii	SB-2021-046	iii	Taphomorph	Poorly preserved frond, some minor branching visible	Negative	No	N	N/A
SB-2021-046iv	SB-2021-046	iv	*Bradgatia* sp. B.	A few branches preserved deep in scour	Negative	No	N	N/A
SB-2021-047i	SB-2021-047	i	Taphomorph (Bradgatia?)	Either a large exposure of microbial mat or a highly decayed example of *Bradgatia*	Negative	No	N	N/A
SB-2021-047ii	SB-2021-047	ii	Taphomorph	Minor branching close to the edge of a scour, potential arboreomorph	Mixed	No	N	N/A
SB-2021-050i-a	SB-2021-050	i	Taphomorph	Thick branching in edge of scour, lack of detail suggest it has gone under a high level of decay	Negative	Original	N	N/A
SB-2021-050i-b	SB-2021-050	i	Insufficiently exhumed frond	Small patch of partial branching to the right of the large specimen (050i-a)	Negative	No	N	N/A
SB-2021-050ii	SB-2021-050	ii	Taphomorph	Minor first order branching preserved which is crosscut by a holdfast	Negative	No	N	N/A
SB-2021-050iii	SB-2021-050	iii	Taphomorph	Poorly preserved branching only visible to first-order	Negative	No	N	N/A
SB-2021-050iv	SB-2021-050	iv	*Arborea*	Right-hand side of frond preserved, largely eroded with only primary branches visible	Positive (weathered)	No	N	N/A
SB-2021-050v	SB-2021-050	v	*Bradgatia* sp. C.	Circular 'O-shaped' *Bradgatia*	Negative	Original	Y	3
SB-2021-050vi	SB-2021-050	vi	*Charnia gracilis*	Remnants of frond found deep within scour, branching partial but well preserved	Positive	No	Y	2, 3
SB-2021-050vii	SB-2021-050	vii	Taphomorph	Partial branching preserved in base of scour, rest of scour shows no evidence of frond	Negative	No	N	N/A
SB-2021-050viii	SB-2021-050	viii	*Bradgatia* sp. A.	Arboriform *Bradgatia*, largely preserved in high detailed negative relief with some positive necromass	Mixed	No	Y	3
SB-2021-050ix	SB-2021-050	ix	Insufficiently exhumed frond (Arboreomorph?)	Frond shows three clear primary(?) branches (highly weathered)	Positive (weathered)	No	N	N/A
SB-2021-051i	SB-2021-051	i	Taphomorph (Avalofractus?)	Specimen that has gone under large amounts of decay, only the tips of the branches are preserved	Mixed	Original	N	N/A
SB-2021-051ii	SB-2021-051	ii	*Kannabuchia artkingii* (type b)	Partial preservation of a few sigmoidal branches	Positive	No	Y	2
SB-2021-051iii	SB-2021-051	iii	Taphomorph (Bradgatia?)	Largely decayed specimen around what appears to be a large holdfast	Negative	No	N	N/A
SB-2021-051iv	SB-2021-051	iv	*Kannabuchia artkingii* (type b?)	Well preserved right-hand side of frond, clearly offset from centre of scour	Mixed	No	Y	3
SB-2021-051v	SB-2021-051	v	*Kannabuchia artkingii* (type b)	Well preserved branches in a partial specimen	Positive	No	Y	3
SB-2021-051vi	SB-2021-051	vi	Taphomorph	Poorly preserved taphomorph	Negative	No	N	N/A
SB-2021-051vii	SB-2021-051	vii	*Avalofractus abaculus*	Poorly preserved specimen with tousled branching, high degree of damage/decay prior to preservation	Mixed	No	Y	3
SB-2021-051viii	SB-2021-051	viii	Taphomorph	Poor preservation of partial frond, decayed beyond recognition	Negative	No	N	N/A

SB-2021-051ix	SB-2021-051	ix	*Kannabuchia artkingii* (type a)	Small frond found deep withing scour, branching detail is incredibly fine	Positive	No	N	N/A
SB-2021-051x	SB-2021-051	x	Taphomorph	Poor preservation of left-hand side of frond, too small to determine any detail	Positive	No	N	N/A
SB-2021-052i	SB-2021-052	i	*Bradgatia* sp. A.	Large specimen with deep branches which may have been positioned into the sediment	Mixed (predominantly negative)	No	Y	3, 4
SB-2021-052ii	SB-2021-052	ii	*Arborea*	Poorly preserved frond, but enough branching detail preserved to assign to *Arborea*	Mixed	No	N	N/A
SB-2021-052iii	SB-2021-052	iii	Taphomorph	Partial branching seen in narrow scour, appears to bifurcate at the tip to the left	Negative	No	N	N/A
SB-2021-052iv	SB-2021-052	iv	Taphomorph (Avalofractus?)	Partial preservation of midline and branching deep within scour (changing topography)	Mixed	No	N	N/A
SB-2021-052v	SB-2021-052	v	*Kannabuchia artkingii* (type b)	Partial frond near the base of scour	Positive	No	N	N/A
SB-2021-052vi	SB-2021-052	vi	*Kannabuchia artkingii* (type b?)	Oddly, left-hand branching is better than the right	Positive	No	N	N/A
SB-2021-052vii	SB-2021-052	vii	*Kannabuchia artkingii* (type ?)	Detail largely weathered away, but shows clear sigmoidal branching	Positive (weathered)	No	N	N/A
SB-2021-052viii	SB-2021-052	viii	Arboreomorph	Midline and right-hand branches are preserved, branches clearly pointing reversed to palaeocurrent	Positive	No	Y	2
SB-2021-052ix	SB-2021-052	ix	Taphomorph	Poorly preserved specimen	Mixed	No	N	N/A
SB-2021-052x	SB-2021-052	x	Insufficiently exhumed frond	Tiny specimen showing part of a frond, high-relief detail preserved	Negative	No	N	N/A
SB-2021-053i	SB-2021-053	i	*Bradgatia* sp. B.	Partial specimen that shows one 'row' of branches	Negative	No	N	N/A
SB-2021-053iii	SB-2021-053	iii	*Bradgatia* sp. A.	Partially preserved frond previously thought to be a 'beothukid'	Negative	No	N	N/A
SB-2021-053iv	SB-2021-053	iv	*Bradgatia* sp. B.	Good example of an 'I-shaped' *Bradgatia* with several exposed branches	Negative	No	Y	3
SB-2021-053v	SB-2021-053	v	Insufficiently exhumed frond	Partial branching on the right of scour	Negative	No	Y	3
SB-2021-053vi	SB-2021-053	vi	*Bradgatia* sp. B.	Partial branching preserved is largely featureless	Negative	No	N	N/A
SB-2021-053vii	SB-2021-053	vii	Insufficiently exhumed frond	Scour which shows the remnants of a deeply buried frond	Negative	No	N	N/A
SB-2021-053viii-a	SB-2021-053	viii	Insufficiently exhumed frond (Arboreomorph?)	Partial exposure of left-hand branching in narrow scour	Mixed	No	N	N/A
SB-2021-053viii-b	SB-2021-053	viii	Insufficiently exhumed frond	Branching partially preserved close to holdfast	Negative	No	Y	3
SB-2021-053ix	SB-2021-053	ix	*Avalofractus dosomitus*	Partial preservation of midline and right-hand side branches within a scour	Positive	No	Y	2, 3
SB-2021-054ii	SB-2021-054	ii	Insufficiently exhumed frond	Very small amount of branching near to the top of the scour	Negative	No	N	N/A

SB-2021-054iii	SB-2021-054	iii	*Arborea*	Well preserved *Arborea* in positive epirelief	Positive	No	Y	2
SB-2021-054iv	SB-2021-054	iv	*Kannabuchia artkingii* (type a)	Partial preservation of frond with branching seen on two separate levels	Positive	No	Y	2
SB-2021-055i	SB-2021-055	i	*Kannabuchia artkingii* (type a)	Good *Kannabuchia* specimen, showing detailed branching on either side of midline	Positive	Original	Y	3
SB-2021-055ii	SB-2021-055	ii	*Kannabuchia artkingii* (type a)	Small *Kannabuchia* specimen showing branching continuing beneath the sediment	Mixed	Original	N	N/A
SB-2021-055iii	SB-2021-055	iii	Insufficiently exhumed frond	Minor amount of branching in the tip of scour, may have some swing marks lower in the scour	Negative	No	N	N/A
SB-2021-055iv	SB-2021-055	iv	*Kannabuchia artkingii* (type a)	Best preserved specimen of *Kannabuchia*, assigned as the holotype	Mixed (predominantly positive)	No	Y	1, 2, 3
SB-2021-055v	SB-2021-055	v	Taphomorph	Necrotic specimen with some visible second-order branching	Mixed	No	N	N/A
SB-2021-055vi	SB-2021-055	vi	*Kannabuchia artkingii* (type b?)	Specimen with two rows of branching orientated in same direction, but on slightly different planes	Positive	No	N	N/A
SB-2021-055vii	SB-2021-055	vii	Insufficiently exhumed frond	Small amount of branching found within scour, might be surrounding by necrotic material	Negative	No	N	N/A
SB-2021-055viii	SB-2021-055	viii	Taphomorph	Taphomorph preserved deeply within scour	Negative	No	N	N/A
SB-2021-055ix	SB-2021-055	ix	*Avalofractus sp.*	Small amount of branching right at the tip of the scour	Mixed	No	Y	2
SB-2021-055x	SB-2021-055	x	*Avalofractus abaculus*	Copy of 2019-001-e; paratype of A. *abaculus*	Positive	Yes (2019-001-e)	N	N/A
SB-2021-055xi	SB-2021-055	xi	*Charnia masoni*	Fantastic branching detail in right-hand side of frond in positive relief	Positive	Yes (2019-001-b)	Y	3
SB-2021-055xii	SB-2021-055	xii	*Charnia masoni*	Cross-cut *Charnia; copy of* SB-2019-001 and SB-2022-059ii	Positive	Yes (2019-001-c)	Y	2
SB-2022-056i-a	SB-2022-056	i	Taphomorph (*Kannabuchia/Bradgatia ?*)	Partially preserved frond showing negative relief preservation across scour	Negative	No	Y	3
SB-2022-056i-b	SB-2022-056	i	*Kannabuchia artkingii* (type a)	Clear dorsal section of frond found in the top of scour; detail preserved on either side of the midline	Negative	No	Y	3
SB-2022-056ii	SB-2022-056	ii	*Kannabuchia artkingii* (type a)	Frond and scour go deeper up-current as opposed to shallowing like most other scours	Mixed	No	Y	3
SB-2022-056iii	SB-2022-056	iii	Taphomorph	Poorly preserved frond, not much detail preserved	Negative	No	N	N/A
SB-2022-058i	SB-2022-058	i	*Bradgatia* sp. B.	I-shaped' *Bradgatia*	Negative	No	Y	3
SB-2022-058ii	SB-2022-058	ii	Undetermined	Good preservation of individual second-order branches, orientation of frond varies from scour	Positive	No	N	N/A

SB-2022-058iii	SB-2022-058	iii	*Bradgatia* sp. B.	I-shaped *Bradgatia*, negative epirelief with some potential positive(?)	Negative	No	Y	3
SB-2022-058iv-a	SB-2022-058	iv	*Avalofractus abaculus*	Poorly preserved *Avalofractus*, only lower section preserved	Positive	No	N	N/A
SB-2022-058iv-b	SB-2022-058	iv	*Bradgatia* sp. A.	Partial *Bradgatia* (arboriform) with only some minor branching within the exposed area	Negative	No	N	N/A
SB-2022-058iv-c	SB-2022-058	iv	*Avalofractus abaculus*	Handful of branches preserved within the scour	Positive	No	N	N/A
SB-2022-058v-a	SB-2022-058	v	*Bradgatia* sp. A.	Frond exposed in narrow scour; first-order branching is visible	Negative	No	N	N/A
SB-2022-058v-b	SB-2022-058	v	*Bradgatia* sp. A.	Deep branching similar to Bradgatia sp. A.	Negative	No	N	N/A
SB-2022-059i	SB-2022-059	i	*Avalofractus abaculus*	Copy of 2019-001-e; paratype of *A. abaculus*	Positive	Yes (2019-001-e)	Y	3
SB-2022-059ii	SB-2022-59	ii	*Charnia masoni*	*Charnia* crosscut by a holdfast; copy of SB-2019-001	Positive	Yes (2019-001-c)	N	N/A
SB-2022-059iii	SB-2022-059	iii	*Charnia masoni*	Clear preservation of right-hand side of frond, with clear second order branching	Positive	Yes (2019-001-b)	N	N/A
SB-2022-059iv-a	SB-2022-059	iv	*Kannabuchia artkingii* (type a)	Frond preserved with midline, as well as branching on both sides	Positive	Yes (055i)	N	N/A
SB-2022-059iv-b	SB-2022-059	iv	*Kannabuchia artkingii* (type ?)	Partial frond with sigmoidal branching	Positive	No	N	N/A
SB-2022-059v	SB-2022-059	v	*Kannabuchia artkingii* (type a)	Frond with varying orientation to scour	Mixed	Yes (055ii)	N	N/A
SB-2022-059vii-a	SB-2022-059	vii	*Kannabuchia artkingii* (type a)	Partial preservation of frond, which is tilted within scour, right better preserved than left	Positive	No	N	N/A
SB-2022-059vii-b	SB-2022-059	vii	*Arborea*	Small *Arborea* (evidence for backing sheet) preserved in upper scour	Negative	No	N	N/A
SB-2022-059viii	SB-2022-059	viii	Insufficiently exhumed frond	Partial branching preserved above obstruction scour	Negative	No	Y	3
SB-2022-060i	SB-2022-060	i	Taphomorph	Copy of SB-2021-050i-a	Negative	Yes (050i-a)	N	N/A
SB-2022-060ii	SB-2022-060	ii	Taphomorph	Poorly preserved remnant of a frond in lower scour	Negative	No	N	N/A
SB-2022-061i-a	SB-2022-061	i	Insufficiently exhumed frond	Recast of SBAS-CM-20-04 after pressure wash, much clearer branching seen but still not identifiable	Mixed	Yes (SBAS-04)	N	N/A
SB-2022-061i-b	SB-2022-061	i	Taphomorph	Top of small taphomorph, lower part of organism and scour removed by fracture	Negative	No	N	N/A
SB-2022-061ii	SB-2022-061	ii	Insufficiently exhumed frond	Small amount of first-order branches preserved within scour (top = negative, bottom = positive)	Mixed	No	N	N/A

SB-2022-061iii	SB-2022-061	iii	Insufficiently exhumed frond	Minor preservation of frond within scour, not enough to be identifiable	Undetermined	No	N	N/A
SB-2022-061iv	SB-2022-061	iv	Taphomorph	Highly decayed frond, some first- and second-order branching might be preserved	Mixed	No	N	N/A
SB-2022-061v	SB-2022-061	v	Taphomorph (Avalofractus?)	Poorly preserved frond with partial branching	Mixed	No	N	N/A
SB-2022-061vi	SB-2022-061	vi	*Avalofractus dosomitus*	Large Avalofractus specimen, similar to holotype but with better preservation	Positive	No	Y	3
SB-2022-061vii-a	SB-2022-061	vii	Taphomorph	Highly decayed frond within obstrution scour	Negative	No	N	N/A
SB-2022-061vii-b	SB-2022-061	vii	Taphomorph	Minor partial branching of a taphomorph to the right of sedimentary ridge	Mixed	No	N	N/A
SB-2022-062i	SB-2022-062	i	Taphomorph	Highly weathered specimen, some branching is still visible	Positive (weathered)	No	N	N/A
SB-2022-062ii	SB-2022-062	ii	Taphomorph (Avalofractus?)	Largely decayed specimen, but some positive relief branching in the lower right	Negative	No	N	N/A
SB-2022-062iii	SB-2022-062	iii	Insufficiently exhumed frond	Poorly preserved branching on the right-hand side of the scour	Negative	No	N	N/A
SB-2022-062iv	SB-2022-062	iv	Arboreomorph	Sideways(?) specimen	Negative	No	N	N/A
SB-2022-062v	SB-2022-062	v	*Avalofractus dosomitus*	Interesting frond preserving the left-hand side deep within scour	Positive	No	Y	3, 4
SB-2022-062vi	SB-2022-062	vi	*Bradgatia* sp. C.	O-shaped' *Bradgatia* in negative epirelief	Negative	No	Y	3
SB-2022-063i	SB-2022-063	i	Insufficiently exhumed frond	Very partial branching preserved within shallow scour	Negative	No	N	N/A
SB-2022-063ii	SB-2022-063	ii	Insufficiently exhumed frond	Small amount of branching on right-hand side above holdfast, very poor preservation	Undetermined	No	N	N/A
SB-2022-063iii	SB-2022-063	iii	*Avalofractus dosomitus*	Partial preservation of frond with visible tip and right-hand branches	Positive (weathered)	No	N	N/A
SB-2022-063iv	SB-2022-063	iv	Taphomorph (charnid?)	Partial preservation of frond near top of scour, poorly preserved second-order branching	Positive	No	N	N/A
SB-2022-063v	SB-2022-063	v	*Kannabuchia artkingii* (type b)	Partly exposed frond, left-hand side better preserved than right	Positive	No	N	N/A
SB-2022-063vi	SB-2022-063	vi	*Avalofractus* sp.	Highly decayed frond, *Avalofractus* branching is visible within the top of the scour	Mixed (predominantly positive)	No	N	N/A
SB-2022-063vii-a	SB-2022-063	vii	*Avalofractus dosomitus*	Highly decayed frond, *A. dosomitus* branching is visible within the top of the scour	Mixed	No	N	N/A
SB-2022-063vii-b	SB-2022-063	vii	Insufficiently exhumed frond	Small branch preservation found in left scour	Mixed	No	N	N/A
SB-2022-063viii-a	SB-2022-063	viii	Insufficiently exhumed frond (Kannabuchia?)	Silicone damaged by water flow, partly preserved branching suggest *Kannabuchia* affinity	Mixed	No	N	N/A
SB-2022-063viii-b	SB-2022-063	viii	Kannabuchia artkingii (type b)	Silicone damaged by water flow, deflated but positive branching in top of scour	Positive (deflated?)	No	N	N/A

SB-2022-063viii-c	SB-2022-063	viii	*Kannabuchia artkingii* (type a)	Partial preservation of a weathered specimen, branching clearer on left-hand side than right-hand side	Mixed	No	N	N/A
SB-2022-064i	SB-2022-064	i	Insufficiently exhumed frond (Bradgatia?)	Minor preservation of frond within scour, positive epirelief on left, negative epirelief on right	Mixed	No	N	N/A
SB-2022-064ii	SB-2022-064	ii	*Avalofractus dosomitus*	Top side of *Avalofractus*, similar to that of *A. dosomitus* holotype but not as well preserved	Positive	No	Y	3
SB-2022-065i	SB-2022-065	i	*Charnia masoni*	Partial preservation of a charnid, downward branching as noted in Narbonne (2004)	Positive	No	N	N/A
SB-2022-065ii	SB-2022-065	ii	Taphomorph	Decayed frond with some branching, mixed epirelief in patches (left = positive, right = negative)	Mixed	No	Y	3
SB-2022-067	SB-2022-067	N/A	Taphomorph (*Arborea?*)	Decayed frond with partial features preserved on right-hand side	Mixed	No	Y	3
SBAS-CM-20-01b	SBAS-CM-20-01b	N/A	*Corellia washageuis*	Holotype (original recast) of *Corellia washageuis*, detail better in later duplicates	Mixed	Original	N	N/A
SBAS-CM-20-02	SBAS-CM-20-02	N/A	*Charnia* sp. a.	Reversed *Charnia*	Positive	No	Y	2, 3
SBAS-CM-20-04	SBAS-CM-20-04	N/A	Insufficiently exhumed frond	Weird partial branching specimen prior to pressure washer cleaning	Mixed	Original	N	N/A
SBAS-CM-22-05-a	SBAS-CM-22-05	N/A	Taphomorph (*Avalofractus*?)	Partially preserved taphomorph, some second-order branching preserved	Mixed	Yes (051i)	N	N/A
SBAS-CM-22-05-b	SBAS-CM-22-05	N/A	*Bradgatia* sp. c.	Circular 'O-shaped' *Bradgatia*; copy of SB-2021-050v	Negative	Yes (050v)	N	N/A
SBAS-CM-20-06	SBAS-CM-20-06	N/A	Pneu specimen	Pneu-structure organism within scour	Negative	Yes (020(b)i)	N	N/A
SBNO-CM-20-01	SBNO-CM-20-01	N/A	*Charniodiscus*	Full relief *Charniodiscus*; *field photo figured in thesis	Positive/full	No	Y*	2, 3
SBNO-CM-20-02b	SBNO-CM-20-02b	N/A	Pneu specimen	Original pneu specimen	Negative	No	Y	3
SBNO-CM-20-04	SBNO-CM-20-04	N/A	*Charnia gracilis*	Partially preserved large specimen, positive relief with angled branching	Positive	No	Y	2, 3
NFM F-754	N/A	N/A	*Avalofractus dosomitus*	Holotype of *Avalofractus dosomitus*	Positive	No	Y	1, 3, 4
NFM F-755	N/A	N/A	*Bradgatia* sp. B.	Original 'I-shaped' *Bradgatia* from Flude and Narbonne (2008)	Negative	No	Y	1, 2, 3
NFM F-756	N/A	N/A	*Avalofractus abaculus*	*Avalofractus abaculus* holotype	Positive	No	Y	2, 3, 4

NFM F-757	N/A	N/A	*Bradgatia* sp. A.	Arboriform specimen with clear *Bradgatia* branching	Negative	No	Y	2, 3
NFM F-758	N/A	N/A	*Kannabuchia artkingii* (type b)	Previously described as *Beothukis* (Narbonne *et al*. 2009)	Positive	No	Y	1, 2, 3
Field specimen	N/A	N/A	*Charniodiscus*	Field specimen on new outcrop, has not been cast	Negative	No	Y	2, 3

Table B.2 – Characteristic dataset for unipolar rangeomorphs.

Fossil ID	1st order – displayed *or* rotated	1st order – furled *or* unfurled	2nd order – displayed *or* rotated	2nd order – furled *or* unfurled	3rd order – present *or* not present	Axis – concealed *or* unconcealed	Stem – yes *or* no
SB-2019-001-b	Rotated	Furled	Rotated	Furled	Present		No
SB-2019-001-c	Rotated	Furled	Rotated	Furled	Not present		No
SB-2019-001-e	Displayed	Unfurled	Displayed	Unfurled	Present	N/A	Yes
SB-2020-007	Rotated	Furled	Rotated	Unfurled	Present		No
SB-2020-012i	Rotated		Rotated	Unfurled	Present	Unconcealed	No
SB-2022-015iii	Rotated	Furled	Rotated	Unfurled	Not present	Unconcealed	No
SB-2022-015iv	Both	Furled	Rotated	Unfurled	Not present		No
SB-2022-015v	Rotated	Furled	Rotated		Not present		No
SB-2020-016ii	Rotated	Furled	Rotated		Not present	Unconcealed	No
SB-2020-019(b)i	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2020-019(b)ii-a	Rotated		Rotated	Unfurled	Not present		No
SB-2020-019(b)ii-b	Rotated	Furled	Rotated	Unfurled	Present		No
SB-2020-019(b)iii-a	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
SB-2020-020(b)ii	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2020-022i-a	Rotated	Furled			Present		No
SB-2020-022i-b	Displayed	Unfurled			Not present		
SB-2020-022iii	Rotated		Rotated	Unfurled	Present	Unconcealed	No
SB-2020-022v	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2020-028iv	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No

SB-2020-028vii-a	Rotated		Rotated	Unfurled	Not present		No
SB-2020-028vii-b	Displayed		Displayed	Unfurled	Not present		
SB-2020-029ii	Rotated	Furled	Rotated	Unfurled	Not present		No
SB-2020-029iii	Rotated	Unfurled	Rotated	Furled	Not present		
SB-2020-029iv	Rotated	Furled	Rotated	Unfurled	Not present	Unconcealed	No
SB-2021-034	Rotated	Furled	Rotated	Unfurled	Present	Concealed	No
SB-2021-035i-a	Rotated	Furled	Rotated	Unfurled	Not present		No
SB-2021-035iv	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-038iii	Rotated	Furled	Rotated	Unfurled	Not present	Unconcealed	No
SB-2021-038iv	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
SB-2021-040iv	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
SB-2021-040v	Rotated	Furled	Rotated		Not present		No
SB-2021-040vi-a	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-040vii	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
SB-2020-042i	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	
SB-2021-042vii-b	Rotated		Rotated	Unfurled	Not present		
SB-2021-043iii					Not present		Yes
SB-2021-043vi	Rotated	Furled	Rotated	Unfurled	Not present	Unconcealed	No
SB-2021-043vii	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-043ix	Rotated		Rotated	Unfurled	Not present	Unconcealed	No
SB-2021-043x	Displayed	Unfurled			Not present		Yes
SB-2021-043xi	Displayed	Unfurled	Both	Unfurled	Not present		

SB-2021-045i	Displayed	Unfurled			Not present		
SB-2021-050vi	Rotated	Furled	Rotated	Furled	Not present		No
SB-2021-051ii	Both	Unfurled	Rotated	Unfurled	Present		
SB-2021-051iv	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-051v	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-051vii					Not present		
SB-2021-051ix	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-052v					Not present	Unconcealed	
SB-2021-052vi	Rotated	Furled	Rotated	Unfurled	Present		No
SB-2021-052vii	Rotated	Furled			Not present		No
SB-2021-053ix	Displayed	Unfurled	Rotated	Unfurled	Not present	N/A	Yes
SB-2021-054iv	Rotated	Furled	Rotated	Unfurled	Not present		No
SB-2021-055i	Rotated	Furled	Both	Unfurled	Present	Unconcealed	No
SB-2021-055ii	Rotated		Rotated	Unfurled	Present		No
SB-2021-055iv	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-055vi	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2021-055ix	Displayed				Not present		
SB-2022-056i-b	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2022-056ii	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2022-058iv-a			Rotated	Unfurled	Present		
SB-2022-058iv-c	Displayed	Unfurled	Both	Unfurled	Present		
SB-2022-059iv-b	Rotated	Furled	Rotated	Unfurled	Not present		

SB-2022-059vii-a	Rotated	Furled	Rotated	Unfurled	Present		
SB-2022-061vi	Displayed	Unfurled	Rotated	Unfurled	Not present		
SB-2022-062v	Displayed	Unfurled	Rotated	Unfurled	Present		
SB-2022-063iii		Unfurled	Rotated		Not present		
SB-2022-063v	Rotated	Furled	Rotated	Unfurled	Present	Unconcealed	No
SB-2022-063vi		Unfurled	Rotated	Unfurled	Present		
SB-2022-063vii-a	Rotated		Rotated		Not present		
SB-2022-063viii-b	Rotated	Furled	Rotated	Unfurled	Not present	Unconcealed	No
SB-2022-063viii-c	Rotated		Rotated	Unfurled	Not present	Unconcealed	No
SB-2022-064ii	Displayed	Unfurled	Rotated	Unfurled	Not present	N/A	Yes
SB-2022-065i	Rotated	Furled	Rotated		Not present		No
SBAS-CM-20-02	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
SBNO-CM-20-04	Rotated	Furled	Rotated	Furled	Not present	Concealed	No
NFM F-754	Displayed	Unfurled	Rotated	Unfurled	Not present	N/A	Yes
NFM F-756	Displayed	Unfurled	Both	Unfurled	Present	N/A	Yes
NFM F-758	Rotated	UF	Rotated	Unfurled	Present	Unconcealed	No

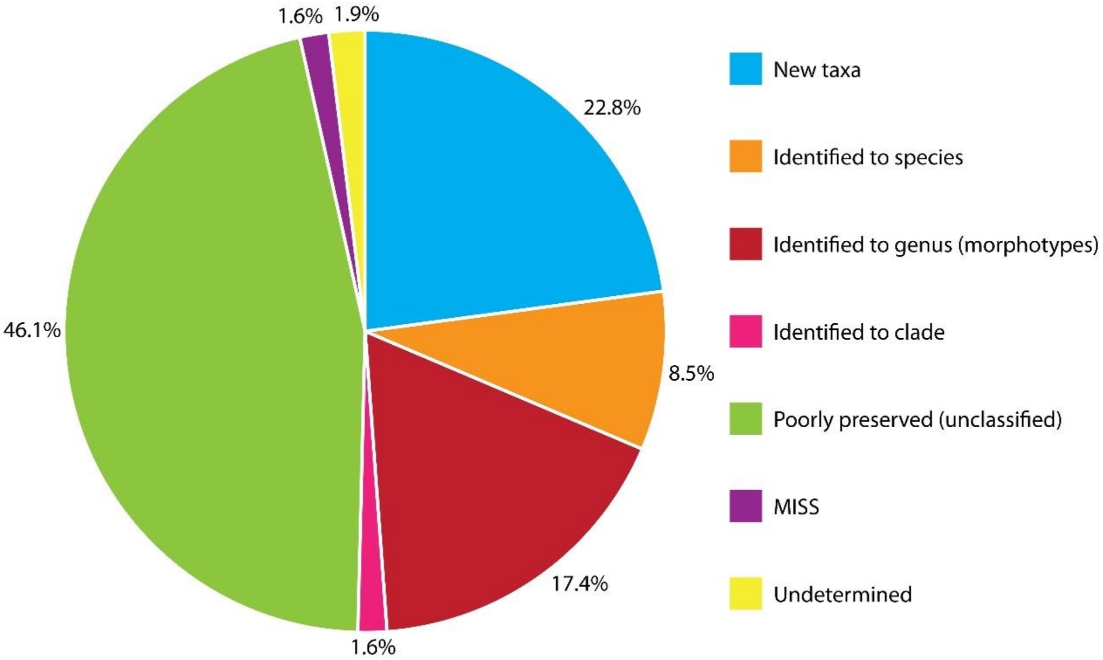


Fig. B.1 – Pie chart showing the assignment of the 258 specimens from the Upper Island Cove assemblage into broad categories.

APPENDIX C

Supplementary Material for Chapter 4

Table C.1 – Raw camera data collected from the Allison Surface, Upper Island Cove, over the study period; the 1st November 2021 to the 31st October 2022.

Date	Day	No. of videos	Cameras	Camera duration	Primary camera	Secondary camera(s)	Weather conditions	Visitation (people)	Visitation (duration)	Additional notes
01/11/2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast	0	00hr 00min	N/A
02/11/2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Overcast, clear	5	00hr 11min	N/A
03/11/2021	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	N/A	Clear	1	00hr 01min	N/A
04/11/2021	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Cloud	0	00hr 00min	N/A
05/11/2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Cloud	0	00hr 00min	N/A
06/11/2021	Saturday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Cloud, clear, cloud, waves	0	00hr 00min	Waves covering weathered surface in AM
07/11/2021	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Cloud, clear, cloud, waves	15	00hr 29min	Waves covering weathered surface in AM
08/11/2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, clear, cloud, waves	0	00hr 00min	Waves covering weathered surface in AM
09/11/2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, clear, waves	1	00hr 01min	Waves in AM

10/11/2021	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, cloud, waves	2	00hr 01min	Few large waves in AM covering lower half of fossiliferous surface
11/11/2021	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, raining, waves	2	00hr 04min	Waves cover surface in late AM/early PM
12/11/2021	Friday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Cloud, clear, rain, waves	3	00hr 05min	Large wave covering surface at 15:00 (more occur in PM)
13/11/2021	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, waves	2	00hr 03min	Waves on lower portion of fossiliferous surface in PM
14/11/2021	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Raining	0	00hr 00min	N/A
15/11/2021	Monday	3	Cliff, cement, graffiti	07:00/18:59	Cement	Graffiti	Clear, overcast	2	00hr 01min	N/A
16/11/2021	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Graffiti	N/A	Clear, overcast, showers	0	00hr 00min	Periodic showers during the day
17/11/2021	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, overcast	0	00hr 00min	N/A
18/11/2021	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, cloud	2	00hr 02min	Waves on lowest section in AM
19/11/2021	Friday	3	Cliff, cement, graffiti	07:00/18:59	Graffiti	N/A	Overcast, showers	0	00hr 00min	N/A
20/11/2021	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Graffiti	N/A	Raining, clear	5	00hr 26min	N/A
21/11/2021	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear	1	00hr 03min	N/A
22/11/2021	Monday	3	Cliff, cement, graffiti	07:00/18:59	Graffiti	N/A	Clear	0	00hr 00min	N/A
23/11/2021	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast	0	00hr 00min	N/A
24/11/2021	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast	0	00hr 00min	N/A

25/11/2021	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Raining, waves	0	00hr 00min	Waves covering weathered surface in AM
26/11/2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, clear, waves	0	00hr 00min	Waves covering weathered surface throughout the day
27/11/2021	Saturday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	N/A	Overcast, cloud and raining	3	00hr 14min	N/A
28/11/2021	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear	4	00hr 46min	All people activity between 16:00 and 17:00. One person wearing high heels on surface
29/11/2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear and cloud	0	00hr 00min	N/A
30/11/2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Raining	0	00hr 00min	N/A
01/12/2021	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	N/A	Clear and cloud	0	00hr 00min	N/A
02/12/2021	Thursday	6	Cliff, cement, graffiti	07:00/ 18:59 (overlap)	Graffiti	Cement	Clear and cloud	2	00hr 41min	Battery/Memory card day, change from daylight saving time
03/12/2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	Cement	Raining and windy	0	00hr 00min	Plank of wood from house hits upper surface at approx. 12:45
04/12/2021	Saturday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear, snow flurry, cloud, clear, waves	1	00hr 04min	Sea/waves covering weathered portion in AM
05/12/2021	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, pos. ice on surface	4	00hr 11min	Ice occurs for a maximum of two hours, listed as moderate as extent was not obvious
06/12/2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear , cloud, snowed over night, ice formation	0	00hr 00min	Ice formation over the course of the day, extends over normal wet patch
07/12/2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Raining	0	00hr 00min	Ice gone
08/12/2021	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, overcast, waves	0	00hr 00min	Sea/waves covering weathered portion in AM
09/12/2021	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Snow, rain, waves	0	00hr 00min	High waves throughout the day

10/12/ 2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, ice formation, waves	0	00hr 00min	Waves across lower part of fossiliferous surface until early PM, ice forming across surface, graffiti frozen
11/12/ 2021	Saturday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, snowing, ice persists growth	0	00hr 00min	Snow and ice covers the entire surface, ice persists from previous day but increases in size
12/12/ 2021	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, raining, ice	0	00hr 00min	Remaining ice melts in the PM
13/12/ 2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear, overcast	7	00hr 28min	Planks of wood dragged across surface, then finally removed in PM at approx. 16:40
14/12/ 2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Cloud, overcast, snowing	0	00hr 00min	N/A
15/12/ 2021	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, cloud, ice formation, snow	0	00hr 00min	Ice forming across surface
16/12/ 2021	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Cloud, clear	0	00hr 00min	Ice remains on the surface
17/12/ 2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	N/A	Cloud, snowing	0	00hr 00min	Ice remains on the surface, heavy snowfall in PM
18/12/ 2021	Saturday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Raining, snowing	0	00hr 00min	Ice remains on the surface
19/12/ 2021	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Graffiti	N/A	Clear	0	00hr 00min	Ice remains on the surface, lowest surface covered in water in AM
20/12/ 2021	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast	0	00hr 00min	Ice remains on the surface
21/12/ 2021	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, snowing, clear	0	00hr 00min	Ice remains on the surface
22/12/ 2021	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear	0	00hr 00min	Ice remains on the surface, snow also covers surface
23/12/ 2021	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, waves	0	00hr 00min	High waves covering lower portion of fossiliferous surface in the AM, ice remains on surface but removed from lower portion by waves
24/12/ 2021	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, cloud, snow	0	00hr 00min	Ice remains on the surface, and partially reforms in area removed, small snow fall

25/12/2021	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Snow, waves	0	00hr 00min	Heavy snowfall overnight, ice receding due to wave action - waves reach lower portion of fossiliferous surface
26/12/2021	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cliff	Cement	Clear, cloud, waves	0	00hr 00min	Waves cover lowest portion of fossiliferous surface, ice recedes even further
27/12/2021	Monday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Cloud, light rain, waves	0	00hr 00min	Waves cover large portions of the fossiliferous surface across the entire day (from 10:30am to nightfall), ice continues to recede
28/12/2021	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, clear, waves	0	00hr 00min	Snow and ice completely removed from surface overnight prior to recording, high waves cover surface over course of the day (9am to nightfall)
29/12/2021	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, clear, cloud, rain, waves	0	00hr 00min	High waves across the entire surface from 11am to nightfall
30/12/2021	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, clear, rain and snow showers, waves	0	00hr 00min	High waves across the entire surface from 7 am to nightfall
31/12/2021	Friday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, waves	0	00hr 00min	Largely uneventful day, surface begins to dry out, waves on weathered surface
01/01/2022	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cement	Graffiti	Clear, overcast	4	00hr 10min	This time of year most people are staying on lowest most part of the surface where fossils are no longer preserved
02/01/2022	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, rain showers	0	00hr 00min	N/A
03/01/2022	Monday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, waves	0	00hr 00min	Waves covering entire surface in the morning, waves covering lower portion of surface in the evening
04/01/2022	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Waves, snow, ice formation	0	00hr 00min	High waves on the lower portion of the fossiliferous surface in the am, snow and ice formation from approx. 10am
05/01/2022	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, cloud, clear	2	00hr 02min	Ice persists on surface
06/01/2022	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, rain	0	00hr 00min	Snow completely gone by start of recording, ice sheet melts over course of the day
07/01/2022	Friday	3	Cliff, cement, graffiti	07:00/18:59	Cement	Graffiti	Clear, small ice sheet formation	0	00hr 00min	Small ice sheet forms and melts on the surface in the usual location across the duration of the day

08/01/2022	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cliff	N/A	Rain, snow	0	00hr 00min	N/A
09/01/2022	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cement	Graffiti	Clear, ice formation	0	00hr 00min	Ice forms across entire surface
10/01/2022	Monday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Rain	0	00hr 00min	Ice sheet recedes
11/01/2022	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, cloud, ice formation	0	00hr 00min	Ice sheet covers surface again, and then begins to recede in the afternoon
12/01/2022	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, ice	1	00hr 02min	Ice sheet persists, slight melt then growth
13/01/2022	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Overcast, rain, ice	1	00hr 01min	Ice sheet persists, slight melt then growth
14/01/2022	Friday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Raining, overcast	3	00hr 04min	Ice sheet recedes a small amount
15/01/2022	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Rain	0	00hr 00min	Ice sheet gone by end of day
16/01/2022	Sunday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Snow, overcast, clear, ice formation	0	00hr 00min	Ice sheet formed overnight
17/01/2022	Monday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear	0	00hr 00min	Ice sheet persists
18/01/2022	Tuesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Rain, ice	0	00hr 00min	Ice sheet growth on higher part of surface
19/01/2022	Wednesday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, overcast	1	00hr 01min	Ice sheet recedes
20/01/2022	Thursday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Snow, rain	0	00hr 00min	Ice sheet persists
21/01/2022	Friday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Rain, snow, overcast	0	00hr 00min	Ice sheet persists
22/01/2022	Saturday	3	Cliff, cement, graffiti	07:00/18:59	Cement	N/A	Clear, ice growth	3	00hr 07min	Ice sheet grows to cover large portion of surface again, people only walk on lower most eroded part of surface

23/01/2022	Sunday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Snow, overcast	0	00hr 00min	Snow covering entire surface, ice sheet persists
24/01/2022	Monday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Overcast, snow, rain	0	00hr 00min	Ice sheet persists
25/01/2022	Tuesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, snow, overcast	0	00hr 00min	Ice sheet persists
26/01/2022	Wednesday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Rain, overcast	0	00hr 00min	Ice sheet persists
27/01/2022	Thursday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, overcast, snow	0	00hr 00min	Ice sheet persists
28/01/2022	Friday	3	Cliff, cement, graffiti	07:00/ 18:59	Cement	N/A	Clear, overcast	0	00hr 00min	Ice sheet persists
29/01/2022	Saturday	2	Cement, graffiti	07:00/ 18:59	Cement	Graffiti	Cloud, clear, overcast	0	00hr 00min	Ice sheet persists
30/01/2022	Sunday	2	Cement, graffiti	07:00/ 18:59	Cement	Graffiti	Rain	0	00hr 00min	Ice sheet gone by end of day
31/01/2022	Monday	2	Cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear, overcast	0	00hr 00min	N/A
01/02/2022	Tuesday	2	Cement, graffiti	07:00/ 18:59	Cement	Graffiti	Clear, ice formation	0	00hr 00min	Ice formation over the course of the day, extends over normal wet patch
02/02/2022	Wednesday	2	Cement, graffiti	07:00/ 18:59	Cement	Graffiti	Cloud, clear, ice formation	2	00hr 02min	Ice formation over the rest of the surface
03/02/2022	Thursday	5	Cliff, cement, graffiti	07:00/ 18:59 (overlap)	Cliff	Graffiti	Cloud, ice growth	2	00hr 35min	Battery/Memory card day, ice sheet recedes on lower surface, grows on upper part of surface
04/02/2022	Friday	3	Cliff, cement, graffiti	06:00/ 18:59	Graffiti	Cliff	Rain, snow	0	00hr 00min	Ice sheet recedes
05/02/2022	Saturday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	N/A	Rain	0	00hr 00min	Ice sheet recedes, cement and graffiti water logged
06/02/2022	Sunday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Clear, cloud, clear, ice formation	0	00hr 00min	Snowed overnight, ice sheet regrows to cover most of surface
07/02/2022	Monday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Clear	0	00hr 00min	Ice sheet persists

08/02/ 2022	Tuesday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Graffiti	Cloud, overcast	0	00hr 00min	Ice sheet persists
09/02/ 2022	Wednesday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Graffiti	Rain	0	00hr 00min	Ice sheet recedes on upper surface
10/02/ 2022	Thursday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Clear	5	00hr 26min	Ice sheet recedes
11/02/ 2022	Friday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Overcast, clear, overcast	8	00hr 08min	Ice sheet recedes (small amount)
12/02/ 2022	Saturday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Clear, cloud, rain showers	3	00hr 01min	Ice sheet recedes
13/02/ 2022	Sunday	3	Cliff, cement, graffiti	06:00/ 18:59	Graffiti	N/A	Overcast, cloud, clear	3	00hr 43min	Ice sheet gone by start of recording, footfall time largely from sitting on lower section of surface
14/02/ 2022	Monday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Cement	Snow, ice formation	0	00hr 00min	Snowed overnight and throughout the day, ice sheet regrows to cover most of surface
15/02/ 2022	Tuesday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	N/A	Clear, snow, clear	0	00hr 00min	Ice sheet persists
16/02/ 2022	Wednesday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Graffiti	Clear, cloud, clear	0	00hr 00min	Ice sheet persists
17/02/ 2022	Thursday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Cement	Overcast, rain	0	00hr 00min	Ice sheet recedes
18/02/ 2022	Friday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	N/A	Rain	0	00hr 00min	Ice sheet gone by the start of recording
19/02/ 2022	Saturday	3	Cliff, cement, graffiti	06:00/ 18:59	Graffiti	Cliff	Cloud, clear	2	00hr 49min	Footfall time largely from sitting on lower section of surface
20/02/ 2022	Sunday	3	Cliff, cement, graffiti	06:00/ 18:59	Cliff	Graffiti	Overcast, snow shower, clear, ice formation	1	00hr 03min	Ice forms at start of day and is gone by the end
21/02/ 2022	Monday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	Graffiti	Overcast, rain, ice formation	0	00hr 00min	Ice forms during the course of the day
22/02/ 2022	Tuesday	3	Cliff, cement, graffiti	06:00/ 18:59	Cement	N/A	Clear	0	00hr 00min	Ice sheet recedes

23/02/2022	Wednesday	3	Cliff, cement, graffiti	06:00/18:59	Cement	Cliff	Rain, ice	0	00hr 00min	Ice sheet grows slightly before receding, net loss of ice
24/02/2022	Thursday	3	Cliff, cement, graffiti	06:00/18:59	Graffiti	Cement	Rain, overcast, clear	4	00hr 29min	Ice sheet gone, graffiti inspected by group of people
25/02/2022	Friday	3	Cliff, cement, graffiti	06:00/18:59	Graffiti	Cement	Clear, ice formation	5	00hr 23min	Ice sheet develops over the course of the day, a1 16:58 group of 5 people smash ice across surface
26/02/2022	Saturday	3	Cliff, cement, graffiti	06:00/18:59	Cement	N/A	Snow, overcast, clear, ice formation	0	00hr 00min	Snowed over night, with ice sheet developing then - slight regression over the course of the day, by end of day ice was found over 'wet' area
27/02/2022	Sunday	3	Cliff, cement, graffiti	06:00/18:59	Cement	Graffiti	Overcast, cloud, snow, ice growth	1	00hr 04min	Ice sheet continues to grow over main fossiliferous area, mild ice growth
28/02/2022	Monday	3	Cliff, cement, graffiti	06:00/18:59	Graffiti	Cement	Snow, overcast, clear, ice growth	8	00hr 58min	Snowed overnight, ice sheet regrows to cover most of surface. Despite prolonged footfall, most occurred on lower surface or on ice
01/03/2022	Tuesday	3	Cliff, cement, graffiti	06:00/18:59	Cement	N/A	Clear	0	00hr 00min	Ice sheet persists
02/03/2022	Wednesday	3	Cliff, cement, graffiti	06:00/18:59	Cement	N/A	Cloud, overcast	0	00hr 00min	Ice sheet persists
03/03/2022	Thursday	3	Cliff, cement, graffiti	06:00/18:59	Cement	Graffiti	Clear, cloud, overcast	0	00hr 00min	Ice sheet recedes
04/03/2022	Friday	3	Cliff, cement, graffiti	06:00/18:59	Cement	Cliff	Clear, snow, overcast, clear, ice growth	0	00hr 00min	Ice sheet grows back to maximum extent
05/03/2022	Saturday	3	Cliff, cement, graffiti	06:00/18:59	Cement	N/A	Clear, overcast, snow showers	2	00hr 02min	Ice sheet persists
06/03/2022	Sunday	3	Cliff, cement, graffiti	06:00/18:59	Cement	N/A	Cloud, clear	0	00hr 00min	Ice sheet recedes a small amount
07/03/2022	Monday	3	Cliff, cement, graffiti	06:00/18:59	Cliff	N/A	Snow, overcast, ice growth	2	00hr 14min	Ice sheet grows back to maximum extent (mild ice growth), people stay on lowermost section of the surface
08/03/2022	Tuesday	3	Cliff, cement, graffiti	06:00/18:59	Cliff	Graffiti	Snow, rain	0	00hr 00min	Ice sheet recedes

09/03/2022	Wednesday	3	Cliff, cement, graffiti	06:00/18:59	Cliff	Cement	Clear	0	00hr 00min	Ice sheet recedes
10/03/2022	Thursday	6	Cliff, cement, graffiti	06:00/19:59 (overlap)	Cliff	Graffiti	Overcast, cloud, clear	4	00hr 08min	Ice sheet persists, battery/memory card day
11/03/2022	Friday	3	Cliff, cement, graffiti	04:30/19:59	Cement	Graffiti	Clear, cloud, clear	2	00hr 19min	Ice sheet recedes
12/03/2022	Saturday	3	Cliff, cement, graffiti	04:30/19:59	Graffiti	N/A	Clear, overcast, rain	5	00hr 15min	Ice sheet recedes
13/03/2022	Sunday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	Cliff	Rain, snow, overcast	0	00hr 00min	Change to daylight savings time, ice sheer disappears over course of the day
14/03/2022	Monday	3	Cliff, cement, graffiti	05:30/20:59	Cliff	Graffiti	Overcast, snow showers, ice formation	3	00hr 02min	Ice forms overnight and over the course of the day
15/03/2022	Tuesday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	N/A	Clear, overcast, clear, ice growth	0	00hr 00min	Ice grows over main fossiliferous area
16/03/2022	Wednesday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	N/A	Clear, overcast, ice growth	12	00hr 25min	Ice growth and recession, net loss in ice
17/03/2022	Thursday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	Cliff	Overcast, snow, cloud, ice growth	5	00hr 26min	Ice growth and recession, net gain in ice
18/03/2022	Friday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	Cliff	Rain	0	00hr 00min	Ice sheet persists
19/03/2022	Saturday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	Cement	Overcast, clear	4	00hr 08min	Ice sheet melts completely in early afternoon
20/03/2022	Sunday	3	Cliff, cement, graffiti	05:30/20:59	Graffiti	N/A	Overcast, snow, ice formation	3	00hr 03min	Initial ice formation occurs earlier in the day prior to snow in the afternoon
21/03/2022	Monday	3	Cliff, cement, graffiti	05:30/20:59	Cliff	Cement	Overcast, rain	0	00hr 00min	Ice sheet recedes
22/03/2022	Tuesday	3	Cliff, cement, graffiti	05:30/20:59	Cliff	Graffiti	Rain and snow showers, overcast	0	00hr 00min	Ice sheet gone by evening

23/03/ 2022	Wednesday	3	Cliff, cement, graffiti	05:30/ 20:59	Cement	Cliff	Rain, overcast, clear, ice formation, waves	2	00hr 01min	Small amount of ice formation on 'wet' part of surface, gone by the end of the day. Few waves on lowest (weathered) part of surface
24/03/ 2022	Thursday	3	Cliff, cement, graffiti	05:30/ 20:59	Cement	Cliff	Overcast, ice formation, waves	0	00hr 00min	Small amount of ice formation on 'wet' part of surface, gone by the end of the day. Few waves on lowest (weathered) part of surface
25/03/ 2022	Friday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cliff	Clear, overcast, waves	0	00hr 00min	Waves only on already weathered part of surface
26/03/ 2022	Saturday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cliff	Snow, overcast, waves	1	00hr 03min	Light snow, interesting to note there is no ice formation during this time. Few waves on already weathered part of surface
27/03/ 2022	Sunday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	N/A	Clear, overcast, rain	3	00hr 02min	N/A
28/03/ 2022	Monday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cement	Clear, cloud, clear, overcast	12	00hr 30min	N/A
29/03/ 2022	Tuesday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cliff	Overcast, clear, overcast, rain, snow	3	00hr 09min	Snow begins early evening, no ice formation during this time
30/03/ 2022	Wednesday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cement	Cloud, overcast	6	00hr 20min	Most activity occurs on lowest part (weathered) of surface
31/03/ 2022	Thursday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cement	Clear, cloud	13	01hr 15min	Most activity occurs on lowest part (weathered) of surface
01/04/ 2022	Friday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	N/A	Overcast, clear, overcast, rain	3	00hr 04min	N/A
02/04/ 2022	Saturday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	Cliff	Rain, waves	0	00hr 00min	Waves only on already weathered part of surface
03/04/ 2022	Sunday	3	Cliff, cement, graffiti	05:30/ 20:59	Graffiti	N/A	Rain, overcast, rain, clear, rain, clear	3	00hr 08min	N/A
04/04/ 2022	Monday	3	Cliff, cement, graffiti	05:30/ 20:59	Cement	Graffiti	Clear, cloud, overcast	15	00hr 40min	N/A
05/04/ 2022	Tuesday	6	Cliff, cement, graffiti	05:30/ 21:59 (overlap)	Graffiti	N/A	Overcast, rain, clear, overcast	4	00hr 08min	Battery/memory card day

06/04/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Snow, overcast, rain, waves	0	00hr 00min	Waves only on already weathered part of surface
07/04/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Overcast	0	00hr 00min	N/A
08/04/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Overcast, snow showers, clear	2	00hr 06min	N/A
09/04/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain	2	00hr 03min	N/A
10/04/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain, overcast, rain	4	00hr 04min	N/A
11/04/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain, overcast, rain and snow showers	3	00hr 03min	N/A
12/04/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud, waves	0	00hr 00min	Waves mostly on weathered part of surface, few larger waves in morning and evening but none that reach the fossils
13/04/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain showers, waves	2	00hr 02min	Lower half of fossiliferous surface covered in waves in early AM and late PM
14/04/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud, clear, waves	2	00hr 07min	Lower half of fossiliferous surface covered in early AM, whole surface in late PM
15/04/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Clear, cloud, clear, waves	24	00hr 53min	Good Friday, Waves only on already weathered part of surface (lowest part), footfall across entire surface
16/04/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Rain, cloud, clear	13	00hr 52min	Easter Saturday, all footfall occurs once clear, footfall across entire surface
17/04/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Overcast	14	01hr 15min	Easter Sunday, 'photoshoot' occurs at around 3pm
18/04/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Rain, clear, overcast, clear	8	00hr 10min	Easter Monday 'Graffiti' obscured at 19:31, 'Cement' interfered with at 19:36 by same group
19/04/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Clear	6	00hr 04min	N/A
20/04/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain	0	00hr 00min	N/A

21/04/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, clear, overcast, clear	3	00hr 20min	N/A
22/04/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Clear, cloud, overcast	11	00hr 55min	Most activity occurs on lowest part (weathered) of surface
23/04/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain showers	2	00hr 01min	N/A
24/04/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain, overcast	0	00hr 00min	N/A
25/04/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cliff	Cement	Rain, overcast	0	00hr 00min	N/A
26/04/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain, overcast	0	00hr 00min	N/A
27/04/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cliff	N/A	Rain, overcast, cloud, clear	1	00hr 01min	N/A
28/04/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Overcast, cloud, rain	4	00hr 57min	Picnic on rocks in PM
29/04/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain, overcast, rain	4	00hr 05min	N/A
30/04/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cliff	Cement	Rain, overcast, rain	0	00hr 00min	N/A
01/05/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Rain, overcast, cloud, rain, cloud	3	00hr 24min	N/A
02/05/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain showers	2	00hr 07min	N/A
03/05/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain showers, cloud, clear, overcast	4	00hr 05min	N/A
04/05/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud	0	00hr 00min	N/A

05/05/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, rain	2	00hr 02min	N/A
06/05/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Rain showers, overcast	3	00hr 06min	N/A
07/05/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud, overcast, cloud, overcast	6	00hr 31min	Most activity occurs on lowest part (weathered) of surface
08/05/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Clear	11	00hr 20min	N/A
09/05/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Clear	5	00hr 12min	N/A
10/05/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Clear, cloud, clear	11	00hr 44min	At ~16:30 group performing scooter tricks on the surface
11/05/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Clear, cloud	5	00hr 10min	Most activity occurs on lowest part (weathered) of surface
12/05/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Rain, overcast, clear	10	01hr 04min	Most time on the surface was spent sitting on the edges
13/05/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Clear, cloud	1	00hr 02min	N/A
14/05/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Graffiti	Rain, overcast, cloud, clear, waves	2	00hr 03min	Waves only on already weathered part of surface
15/05/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:59	Cement	Cliff	Cloud, overcast, rain showers, clear, waves	0	00hr 00min	Waves only on already weathered part of surface
16/05/2022	Monday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud, waves	9	00hr 21min	Waves only on already weathered part of surface
17/05/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:59	Cement	N/A	Overcast, cloud, waves	4	00hr 06min	Waves only on already weathered part of surface
18/05/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	Cliff	Overcast, rain, clear, waves	0	00hr 00min	Waves only on already weathered part of surface

19/05/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:59	Graffiti	N/A	Overcast, cloud, clear, waves	4	00hr 05min	Waves only on already weathered part of surface
20/05/2022	Friday	3	Cliff, cement, graffiti	04:30/21:59 (overlap)	Cement	Graffiti	Clear, cloud	7	00hr 27min	Battery/memory card day, no data from cliff before battery change, people in bathrobes at ~20:30
21/05/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cement	Clear, cloud	10	01hr 02min	Most activity occurs on lowest part (weathered) of surface
22/05/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Cloud, overcast, cloud	17	00hr 43min	N/A
23/05/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear, cloud, overcast, rain	9	00hr 24min	Bank Holiday Monday - few visits made to the site
24/05/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Cement	Cliff	Rain showers, overcast, cloud, clear	0	00hr 00min	N/A
25/05/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear, cloud, clear	10	00hr 31min	N/A
26/05/2022	Thursday	3	Cliff, cement, graffiti	04:00/21:59	Cement	Graffiti	Cloud, clear, cloud, clear, waves	0	00hr 00min	Waves only on already weathered part of surface
27/05/2022	Friday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Cloud	2	00hr 03min	N/A
28/05/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Overcast, raining, waves	10	00hr 17min	Waves only on already weathered part of surface, large group studying rocks in rain - geologists?
29/05/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Rain, overcast, cloud, clear, waves	5	00hr 14min	Waves only on already weathered part of surface
30/05/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear, cloud, overcast	20	00hr 32min	Between 19:30 and 20:00 group run across surface
31/05/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Cliff	Cement	Overcast, cloud, overcast, cloud, overcast, rain, waves	0	00hr 00min	Waves in the evening cover the eroded lowest part of surface
01/06/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Cliff	Cement	Rain, overcast, rain, waves	0	00hr 00min	Waves only on already weathered part of surface

02/06/2022	Thursday	3	Cliff, cement, graffiti	04:00/21:59	Cement	Cliff	Rain, waves	0	00hr 00min	Waves mostly on weathered part of surface, few larger waves in the evening but none that reach the fossils
03/06/2022	Friday	3	Cliff, cement, graffiti	04:00/21:59	Cliff	Cement	Overcast, cloud, overcast, rain, cloud, waves	0	00hr 00min	Waves only on already weathered part of surface
04/06/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cliff	Overcast, rain, overcast, cloud, clear, waves	2	00hr 02min	Waves only on already weathered part of surface
05/06/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, waves	1	00hr 02min	Waves only on already weathered part of surface
06/06/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Cliff	Cement	Overcast, cloud	0	00hr 00min	N/A
07/06/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Clear, cloud, overcast, clear	0	00hr 00min	N/A
08/06/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cement	Clear	3	00hr 13min	N/A
09/06/2022	Thursday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Overcast, cloud	8	00hr 24min	N/A
10/06/2022	Friday	3	Cliff, cement, graffiti	04:00/21:59	Cliff	Cement	Rain	0	00hr 00min	N/A
11/06/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Cement	Graffiti	Rain, overcast, clear	3	00hr 07min	N/A
12/06/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Cloud, overcast, cloud, clear	10	00hr 33min	N/A
13/06/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cement	Clear, waves	0	00hr 00min	Waves only on already weathered part of surface
14/06/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear, overcast, waves	5	00hr 05min	Waves only on already weathered part of surface
15/06/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cement	Overcast, cloud, clear, waves	2	00hr 12min	Waves only on already weathered part of surface, mature photoshoot at 05:30am

16/06/2022	Thursday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear	~55	06hr 55min	Fieldwork day, school prom photoshoot in the PM
17/06/2022	Friday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Overcast, clear	15	05hr 45min	Fieldwork day with pressure washer
18/06/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Clear, cloud, mist, overcast, rain, overcast	13	01hr 07min	Most activity occurs on lowest part (weathered) of surface
19/06/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, cloud	3	00hr 45min	Most activity occurs on the lowest part of the surface, activities include meditation(?) and exercise
20/06/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Overcast, rain showers, mist	3	00hr 18min	Mist hanging around for most of the afternoon and evening
21/06/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Mist, rain, overcast, rain showers	8	00hr 42min	Frame taken of kids inspecting cameras
22/06/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	Cliff	Overcast, cloud, clear	25	04hr 46min	Kids alter Cliff angle, fieldwork day, prom photos (two separate occasions)
23/06/2022	Thursday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Overcast, cloud, overcast, cloud, overcast	22	03hr 56min	Most activity occurs on lowest part (weathered) of surface
24/06/2022	Friday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, cloud, clear	7	01hr 22min	Most activity occurs on lowest part (weathered) of surface
25/06/2022	Saturday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, rain showers	6	00hr 15min	N/A
26/06/2022	Sunday	3	Cliff, cement, graffiti	04:00/21:59	Graffiti	N/A	Rain, overcast, cloud, clear, cloud	3	00hr 09min	N/A
27/06/2022	Monday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, cloud, clear, cloud	5	00hr 38min	Most activity occurs on lowest part (weathered) of surface
28/06/2022	Tuesday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, cloud	5	00hr 22 min	N/A
29/06/2022	Wednesday	3	Cliff, cement, graffiti	04:00/21:59	Cement	N/A	Overcast, rain, overcast,	6	01hr 06min	Most activity occurs on lowest part (weathered) of surface

							rain, cloud, clear, waves			
30/06/ 2022	Thursday	3	Cliff, cement, graffiti	04:00/ 21:59	Graffiti	N/A	Overcast, cloud, overcast, rain	23	00hr 27min	School group of about 18 individuals visit the site for 3 minutes just before 2pm
01/07/ 2022	Friday	3	Cliff, cement, graffiti	04:00/ 21:59	Graffiti	N/A	Rain, overcast, cloud, overcast, cloud, overcast	1	00hr 04min	N/A
02/07/ 2022	Saturday	3*	Cliff*, cement, graffiti	04:00/ 21:59	Graffiti	Cement	Cloud, clear, cloud, overcast	31	01hr 08min	Wedding group photos on surface just before 4pm, *Cliff runs out of battery
03/07/ 2022	Sunday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Rain, overcast, cloud, overcast	10	03hr 39min	Most activity occurs on lowest part (weathered) of surface
04/07/ 2022	Monday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Overcast, cloud, clear periods	12	03hr 08min	Picnic on main fossiliferous location in PM
05/07/ 2022	Tuesday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Clear, cloud, clear	6	01hr 15min	Most activity occurs on lowest part (weathered) of surface
06/07/ 2022	Wednesday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Clear, cloud, overcast, rain shower	7	00hr 40min	Most activity occurs on lowest part (weathered) of surface
07/07/ 2022	Thursday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Rain, overcast, cloud, rain	3	01hr 00min	Most activity involved sitting on surface
08/07/ 2022	Friday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Cloud, clear, cloud, clear	13	01hr 32min	Most activity occurs on lowest part (weathered) of surface
09/07/ 2022	Saturday	2	Cement, graffiti	04:00/ 21:59	Graffiti	Cement	Cloud	30	01hr 35min	Wedding couple photos at 15:20 and group photos at 16:35
10/07/ 2022	Sunday	5	Cliff, cement, graffiti	04:00/ 21:29 (overlap)	Graffiti	Cement	Clear	15	03hr 26min	Battery/memory card day, researchers visit site
11/07/ 2022	Monday	3	Cliff, cement, graffiti	04:30/ 21:29	Graffiti	N/A	Clear, cloud	15	02hr 15min	Activity across all of surface
12/07/ 2022	Tuesday	3	Cliff, cement, graffiti	04:30/ 21:29	Graffiti	N/A	Cloud, clear	6	00hr 30min	Activity across all of surface, including people searching for fossils
13/07/ 2022	Wednesday	3	Cliff, cement, graffiti	04:30/ 21:29	Graffiti	N/A	Overcast, cloud, clear, cloud	12	01hr 21min	Most activity occurs on lowest part (weathered) of surface

14/07/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	N/A	Overcast, clear, cloud	3	00hr 02min	N/A
15/07/2022	Friday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, cloud, clear	18	00hr 37min	Large amount of mist in morning and early afternoon
16/07/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	N/A	Overcast, clear	8	00hr 45min	Most activity occurs on lowest part (weathered) of surface
17/07/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Clear, cloud	16	00hr 35min	Most activity occurs on lowest part (weathered) of surface
18/07/2022	Monday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Cloud, clear, cloud, overcast	15	00hr 36min	Odd device wheeled onto surface just before 11am
19/07/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	N/A	Rain, overcast, rain	5	00hr 19min	Most activity occurs on lowest part (weathered) of surface
20/07/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	N/A	Rain, overcast, cloud, overcast, rain	6	00hr 30min	Group of people looking at fossils in the am
21/07/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, cloud, clear	~74	04hr 49min	A lot of activity on the lowest (weathered) part of the surface - footfall number taken from averaging out Graffiti (72) and Cement (76)
22/07/2022	Friday	3	Cliff, cement, graffiti	04:30/21:29	Cement	Graffiti	Clear	27	02hr 08min	Most activity occurs on lowest part (weathered) of surface
23/07/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:29	Cement	Graffiti	Mist, overcast, clear	24	00hr 47min	Wedding photos just before 11am (grooms party, all on weathered part of surface), most activity of lowest surface
24/07/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Clear	17	00hr 37min	Activity across surface
25/07/2022	Monday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Cloud, overcast	17	01hr 19min	Boat next to surface at ~16:30, picnic just after 18:00
26/07/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, rain showers	18	01hr 06min	Most activity occurs on lowest part (weathered) of surface
27/07/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Mist, overcast, rain, overcast, cloud, clear	8	00hr 26min	Activity across surface

28/07/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, cloud, clear, rain, clear, overcast, waves	19	01hr 00min	Waves on lowest part of surface, 9:30-10:30 unknown research group visits site
29/07/2022	Friday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, cloud, overcast	26	01hr 15min	Activity across surface
30/07/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Rain, overcast, rain showers	20	00hr 53min	Most activity occurs on lowest part (weathered) of surface
31/07/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Clear	28	02hr 38min	Most activity occurs on lowest part (weathered) of surface
01/08/2022	Monday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Clear, cloud	21	00hr 24min	Activity across surface
02/08/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Cloud, clear, cloud, clear	18	00hr 20min	Most activity occurs on lowest part (weathered) of surface
03/08/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Cloud, overcast, rain, overcast, cloud	11	00hr 32min	Activity across surface, but majority on lower areas
04/08/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Rain, overcast, cloud, clear	6	00hr 12min	Activity across surface, regatta day in St. John's (might explain low footfall)
05/08/2022	Friday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Clear	6	00hr 16min	Most activity occurs on lowest part (weathered) of surface
06/08/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:29	Cement	Graffiti	Overcast, cloud, clear	20	00hr 48min	Wedding photos at 17:30, but only taken on lower (weathered) surface
07/08/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Cloud	15	01hr 22min	At 21:22 flashlights on the rocks, most activity on the lowest (weathered) part of the surface
08/08/2022	Monday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, rain showers, overcast, cloud, waves	6	00hr 13min	Waves only on the lowest portion of the weathered surface
09/08/2022	Tuesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cliff	Overcast, rain, overcast, waves	1	00hr 01min	Waves only on the lowest portion of the weathered surface
10/08/2022	Wednesday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, waves	3	00hr 05min	Waves only on the lowest portion of the weathered surface

11/08/2022	Thursday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, cloud, waves	2	00hr 07min	Waves only on the lowest portion of the weathered surface
12/08/2022	Friday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, waves	13	00hr 26min	Waves only on the lowest portion of the weathered surface
13/08/2022	Saturday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Rain, overcast, cloud, clear, overcast, waves	9	00hr 29min	Waves only on the lowest portion of the weathered surface
14/08/2022	Sunday	3	Cliff, cement, graffiti	04:30/21:29	Graffiti	Cement	Overcast, rain, overcast, cloud, clear, overcast	19	00hr 44min	Activity across surface
15/08/2022	Monday	3	Cliff, cement, graffiti	04:30/21:29	Cement	Graffiti	Overcast, rain, cloud	20	01hr 01min	Most activity occurs on lowest part (weathered) of surface
16/08/2022	Tuesday	5*	Cliff, cement, graffiti*	04:30/21:29 (overlap)	Graffiti	Cement	Overcast, rain	4	00hr 16min	Battery/memory card day, *Graffiti did not start recording
17/08/2022	Wednesday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Overcast, rain showers	3	00hr 02min	N/A
18/08/2022	Thursday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Rain, overcast, rain, waves	1	00hr 02min	Waves only on the lowest portion of the weathered surface
19/08/2022	Friday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Rain, overcast, cloud, clear, cloud	10	00hr 25min	N/A
20/08/2022	Saturday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Cloud, overcast, rain showers	3	00hr 08min	N/A
21/08/2022	Sunday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Overcast, cloud	6	00hr 19min	N/A
22/08/2022	Monday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Overcast, cloud, clear	7	00hr 32min	N/A
23/08/2022	Tuesday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Clear, cloud, overcast	18	01hr 25min	~18:55 fish net dragged across lowest part of surface, already weathered so no damage to fossils - most activity on lower surface
24/08/2022	Wednesday	2	Cliff, cement	04:30/21:29	Cliff	Cement	Rain, cloud, overcast	2	2hr 12min	Couple spend 132 minutes sitting at edge of surface (weathered part) - lighting meant this was easier to record from Cliff
25/08/2022	Thursday	2	Cliff, cement	04:30/21:29	Cement	Cliff	Clear, cloud, overcast	12	00hr 41min	Most activity occurs on lowest part (weathered) of surface

26/08/2022	Friday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, cloud, clear, cloud	19	00hr 53min	Activity across surface, but majority on lower areas
27/08/2022	Saturday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Cloud, clear, cloud	2	00hr 10min	N/A
28/08/2022	Sunday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Clear	10	00hr 30min	Activity across surface
29/08/2022	Monday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Cloud	11	00hr 26min	Activity across surface
30/08/2022	Tuesday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Cloud	3	00hr 07min	N/A
31/08/2022	Wednesday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, clear, cloud	3	00hr 02min	N/A
01/09/2022	Thursday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Clear, overcast	10	00hr 31min	Most activity occurs on lowest part (weathered) of surface
02/09/2022	Friday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Rain, overcast, cloud	4	00hr 08min	N/A
03/09/2022	Saturday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Clear, overcast, clear, waves	10	00hr 23min	Waves only on the lowest portion of the weathered surface
04/09/2022	Sunday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Mist, overcast, cloud, clear	8	00hr 37min	Most activity occurs on lowest part (weathered) of surface
05/09/2022	Monday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast	2	00hr 08min	N/A
06/09/2022	Tuesday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, waves	0	00hr 00min	Waves only on the weathered surface
07/09/2022	Wednesday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, cloud, waves	2	00hr 16min	Waves only on the weathered surface
08/09/2022	Thursday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, cloud, clear, waves	8	00hr 26min	Waves begin lapping closer to fossiliferous surface, activity across the surface
09/09/2022	Friday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Cloud, waves	8	00hr 16min	Waves only on the weathered surface
10/09/2022	Saturday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Storm, waves	0	00hr 00min	Waves across entire surface
11/09/2022	Sunday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Storm, waves	0	00hr 00min	Waves across entire surface
12/09/2022	Monday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, rain, waves	0	00hr 00min	Waves on lower part of fossiliferous surface, with a few covering the entirety of the surface
13/09/2022	Tuesday	2	Cliff, cement	04:30/ 21:29	Cement	Cliff	Overcast, waves	5	00hr 19min	Waves on lower portion of fossiliferous surface in the AM

14/09/2022	Wednesday	5*	Cliff*, cement, graffiti	04:30/20:29	Cement	Graffiti	Cloudy, overcast, clear, waves	12	01hr 03min	Battery/memory card day, *Cliff memory card corrupted with no data salvageable for rest of study. Waves only on weathered surface
15/09/2022	Thursday	2	Cement, graffiti	05:30/20:29	Cement	Graffiti	Rain, overcast, cloud, clear, waves	6	00hr 21min	Waves only on the weathered surface
16/09/2022	Friday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Overcast, rain showers, cloud, waves	1	00hr 02min	Waves only on the weathered surface
17/09/2022	Saturday	2	Cement, graffiti	05:30/20:29	Cement	Graffiti	Overcast, cloud, overcast, cloud, rain showers	0	00hr 00min	N/A
18/09/2022	Sunday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Clear, cloud, rain, cloud, clear	4	00hr 10min	N/A
19/09/2022	Monday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Clear, cloud, clear, cloud, waves	8	03hr 06min	Researchers visit the site and laser scan surface, waves only on weathered surface
20/09/2022	Tuesday	2	Cement, graffiti	05:30/20:29	Cement	Graffiti	Cloud, overcast, cloud, clear, waves	0	00hr 00min	Waves only on the weathered surface
21/09/2022	Wednesday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Clear, cloud	6	00hr 46min	Nearly all activity on top of the fossiliferous surface
22/09/2022	Thursday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Rain, overcast	2	00hr 01min	N/A
23/09/2022	Friday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Cloud, clear, cloud	2	00hr 40min	Most activity occurs on lowest part (weathered) of surface
24/09/2022	Saturday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Cloud, clear, cloud, clear, waves	13	00hr 40min	Waves only on the weathered surface, activity across entire surface
25/09/2022	Sunday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Cloud, rain, overcast, cloud, clear	6	00hr 12min	N/A
26/09/2022	Monday	2	Cement, graffiti	05:30/20:29	Graffiti	Cement	Cloud	3	00hr 05min	N/A
27/09/2022	Tuesday	2	Cement, graffiti	05:30/20:29	Cement	N/A	Overcast, cloud	0	00hr 00min	N/A
28/09/2022	Wednesday	2	Cement, graffiti	05:30/20:29	Cement	N/A	Rain	0	00hr 00min	N/A

29/09/2022	Thursday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, waves	1	00hr 03min	Waves only on the weathered surface
30/09/2022	Friday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, cloud, clear	5	00hr 21min	N/A
01/10/2022	Saturday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	3	00hr 07min	For a few days/week now there has been significant water running across the surface (x3 frames taken from Cement)
02/10/2022	Sunday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, cloud, overcast, cloud	7	00hr 25min	N/A
03/10/2022	Monday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, cloud, clear, waves	5	00hr 08min	Waves only on the weathered surface
04/10/2022	Tuesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	1	00hr 01min	N/A
05/10/2022	Wednesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	3	00hr 13min	N/A
06/10/2022	Thursday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, clear	2	00hr 15min	N/A
07/10/2022	Friday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Rain, overcast, cloud, overcast, waves	2	00hr 02min	Waves only on the weathered surface
08/10/2022	Saturday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast	7	00hr 30min	N/A
09/10/2022	Sunday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, cloud, overcast, clear	19	00hr 45min	Rained overnight, activity largely on the fossiliferous surface (people looking at the fossils)
10/10/2022	Monday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, cloud, clear	6	00hr 09min	N/A
11/10/2022	Tuesday	2	Cement, graffiti	05:30/ 20:29	Cement	Graffiti	Clear, cloud, clear, waves	0	00hr 00min	Waves only on the weathered surface
12/10/2022	Wednesday	2	Cement, graffiti	05:30/ 20:29	Cement	Graffiti	Clear, cloud, clear, waves	0	00hr 00min	Waves only on the weathered surface
13/10/2022	Thursday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	11	00hr 35min	Activity across surface
14/10/2022	Friday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, cloud, clear	4	00hr 07min	N/A
15/10/2022	Saturday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast (fog), cloud	1	00hr 32min	N/A
16/10/2022	Sunday	2	Cement, graffiti	05:30/ 20:29	Cement	N/A	Overcast, waves	0	00hr 00min	Waves only on the weathered surface

17/10/2022	Monday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Rain, overcast, waves	6	00hr 11min	Waves only on the weathered surface
18/10/2022	Tuesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, rain, overcast, waves	4	00hr 44min	Waves only on the weathered surface, activity across entire surface
19/10/2022	Wednesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Rain, clear, overcast, cloud, clear	3	00hr 22 min	N/A
20/10/2022	Thursday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, waves	0	00hr 00min	Waves only on the weathered surface
21/10/2022	Friday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Cloud, waves	6	00hr 21min	Waves only on the weathered surface
22/10/2022	Saturday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, cloud, clear	2	00hr 12min	N/A
23/10/2022	Sunday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	2	00hr 04min	N/A
24/10/2022	Monday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Cloud	4	00hr 20min	Researchers photographing Charnia at ~12:40
25/10/2022	Tuesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear	2	00hr 02min	N/A
26/10/2022	Wednesday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, cloud, overcast, waves	5	01hr 09min	Waves only on the weathered surface, small group across entire surface in the PM
27/10/2022	Thursday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Overcast, rain, waves	4	00hr 08min	Waves only on the weathered surface
28/10/2022	Friday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Cloud, clear, waves	7	01hr 03min	Waves only on the weathered surface, activity across entire surface
29/10/2022	Saturday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, waves	5	00hr 47min	Waves only on the weathered surface, activity across entire surface
30/10/2022	Sunday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, cloud	4	00hr 06min	N/A
31/10/2022	Monday	2	Cement, graffiti	05:30/ 20:29	Graffiti	Cement	Clear, waves	5	00hr 05min	Waves only on the weathered surface, Trick-or-Treat'ers on the surface at ~17:50

Table C.2 – Event number and duration of ice cover events.

Event no.	Start	Finish	Total no. of days
1	05/12/2021	05/12/2021	1
2	06/12/2021	06/12/2021	1
3	10/12/2021	12/12/2021	3
4	15/12/2021	27/12/2021	13
5	04/01/2022	06/01/2021	3
6	07/01/2022	07/01/2022	1
7	09/01/2022	15/01/2022	7
8	16/01/2022	30/01/2022	15
9	01/02/2022	12/02/2022	12
10	14/02/2022	17/02/2022	4
11	20/02/2022	20/02/2022	1
12	21/02/2022	23/02/2022	3
13	25/02/2022	13/03/2022	17
14	14/03/2022	19/03/2022	6
15	20/03/2022	22/03/2022	3
16	23/03/2022	23/03/2022	1
17	24/03/2022	24/03/2022	1

Table C.3 – Event number and dates of high energy waves covering fossils.

Event no.	Date
1	09/11/2021
2	10/11/2021
3	11/11/2021
4	12/11/2021
5	13/11/2021
6	09/12/2021
7	10/12/2021
8	23/12/2021
9	25/12/2021
10	26/12/2021
11	27/12/2021
12	28/12/2021
13	29/12/2021
14	30/12/2021
15	03/01/2021
16	04/01/2021
17	13/04/2021
18	14/04/2021
19	10/09/2021
20	11/09/2021
21	12/09/2021
22	13/09/2021

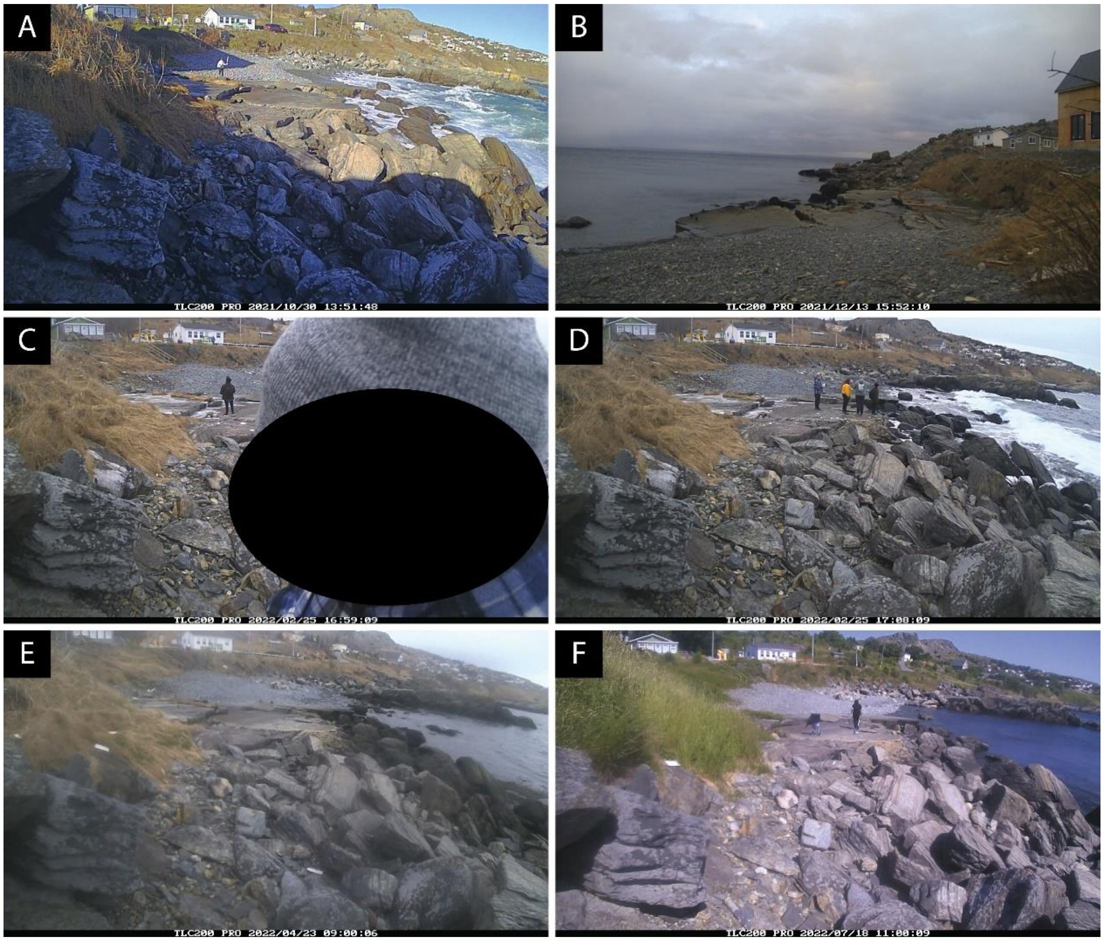


Fig. C.1 – Additional camera footage highlighting the anthropic risks to the fossils preserved on the Allison Surface. A, on the day of camera setup (and outside of study period) an individual was seen wielding a baseball bat on the fossiliferous surface, hitting rocks across the surface and into the ocean. B, debris (wooden plank) laying on the upper fossiliferous surface containing *Aspidella* specimens, wooden plank fell onto the surface on the 3rd December 2021 and was removed on the 13th December 2021. C, individual trying to obscure the camera while others throw blocks of ice across the fossiliferous surface. D, aftermath of blocks of ice being thrown onto the fossiliferous surface, white shards around the individual's feet and across the surface are the remnants of the blocks of ice. E, anthropic debris and litter surrounding the fossiliferous surface. Precise dates and times are in the timestamps on the photographs (time zone UTC-3:30).