

# The Stratigraphical Context of the Ediacaran Biota of Eastern Newfoundland

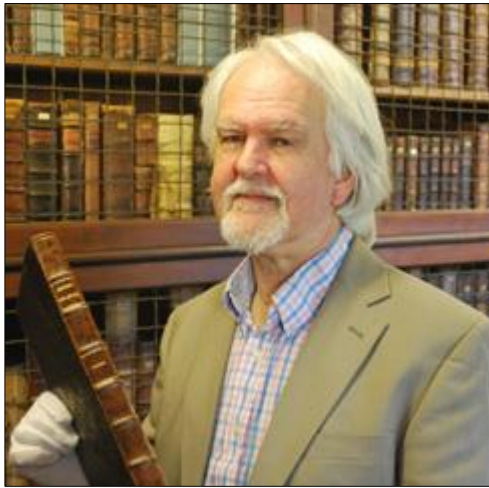
JACK J. MATTHEWS  
UNIVERSITY COLLEGE

**Submitted for consideration for the degree of Doctor of Philosophy**

**Michaelmas Term 2015**

**Department of Earth Sciences, University of Oxford**





*In Memory of Prof. Martin D. Brasier*

*1947-2014*

*Supervisor, Mentor, Friend*

# Contents

---

<b>List of Figures</b> .....	i
<b>Abstract</b> .....	vii
<b>Extended Abstract</b> .....	ix
<b>Acknowledgements</b> .....	xiii
<b>Chapter 1:</b>	
Introduction .....	1-1
<b>Chapter 2:</b>	
Stratigraphy of the Mistaken Point Ecological Reserve and Catalina Dome .....	2-1
<b>Chapter 3:</b>	
Sedimentology of the Mistaken Point Ecological Reserve and Catalina Dome.....	3-1
<b>Chapter 4:</b>	
Geochronology of the Mistaken Point Ecological Reserve and Catalina Dome .....	4-1
<b>Chapter 5:</b>	
Towards a Stratigraphic Framework for the Ediacaran of Avalonia.....	5-1
<b>Chapter 6:</b>	
Post-Fossilisation Processes and their implications for understanding Ediacaran macrofossil assemblages.....	6-1
<b>Chapter 7:</b>	
Fieldwork and Fossil Protection: A Review of the Avalonian Ediacaran Experience...	7-1
<b>Chapter 8:</b>	
Conclusions .....	8-1

# List of Figures

---

## CHAPTER 1

- Figure 1.1: Examples of the Ediacara biota from Newfoundland ..... 1-3
- Figure 1.2: Palaeogeographic reconstructions for Avalonia during the Ediacaran ..... 1-5
- Figure 1.3: Map of Eastern Newfoundland, showing geology and localities..... 1-7

## CHAPTER 2

- Figure 2.1: Map of the Mistaken Point Ecological Reserve ..... 2-4
- Figure 2.2: Map of the Catalina Dome area ..... 2-5
- Figure 2.3: Slabbed section of the Drook Formation ..... 2-10
- Figure 2.4: Photographs of the Drook Formation in outcrop ..... 2-11
- Figure 2.5: Supplementary photographs of the Drook Formation..... 2-12
- Figure 2.6: Thin sections from the Drook and Briscal formations..... 2-14
- Figure 2.7: Summary log from the base of the Drook Formation ..... 2-15
- Figure 2.8: Photographs of the Briscal Formation in outcrop ..... 2-20
- Figure 2.8: Supplementary photographs of the Briscal Formation ..... 2-21
- Figure 2.9: Sedimentary log through a section of the Briscal Formation..... 2-22
- Figure 2.11: Slabbed section of the Briscal Formation ..... 2-24
- Figure 2.12: Photographs of the Mistaken Point Formation in outcrop ..... 2-28

Figure 2.13: Supplementary photographs of the Mistaken Point Formation .....	2-29
Figure 2.14: Sedimentary log through a section of the Mistaken Point Formation.....	2-30
Figure 2.14: Revised sedimentary log of the upper Mistaken Point Formation.....	2-31
Figure 2.15: Thin sections from the Mistaken Point Formation.....	2-33
Figure 2.16: Slabbed section through the ‘D’ Surface, Mistaken Point Formation .....	2-34
Figure 2.17: Slabbed section through the ‘E’ Surface, Mistaken Point Formation.....	2-35
Figure 2.18: Photographs of the Trepassey Formation in outcrop .....	2-39
Figure 2.19: Supplementary photographs of the Trepassey Formation.....	2-40
Figure 2.20: Revised sedimentary log of part of the Trepassey Formation .....	2-41
Figure 2.21: Slabbed section of the Trepassey Formation .....	2-43
Figure 2.22: Thin sections of the Trepassey and Fermeuse formations .....	2-44
Figure 2.23: Photographs of the Fermeuse Formation in outcrop.....	2-47
Figure 2.24: Supplementary photographs of the Fermeuse Formation .....	2-48
Figure 2.25: Slabbed section of the Fermeuse Formation .....	2-50
Figure 2.26: Sedimentary log through a section of the Shepherd Point Formation .....	2-54
Figure 2.27: Photographs of the Shepherd Point Formation in outcrop.....	2-55
Figure 2.28: Supplementary photographs of the Shepherd Point Formation .....	2-56
Figure 2.29: Revised sedimentary log for the Shepherd Point, Murphy’s Cove, and Rowland Head formations .....	2-57

Figure 2.30: Slabbed section from the Shepherd Point Formation.....	2-58
Figure 2.31: Photographs of the Murphy’s Cove Formation.....	2-61
Figure 2.32: Supplementary photographs of the Murphy’s Cove Formation.....	2-62
Figure 2.33: Slabbed section from the Murphy’s Cove Formation.....	2-63
Figure 2.34: Sedimentary log through a section of the Rowland Head Formation .....	2-66
Figure 2.35: Photographs of the Rowland Head Formation in outcrop.....	2-67
Figure 2.36: Supplementary photographs of the Rowland Head Formation .....	2-68
Figure 2.37: Slabbed section from the Rowland Head Formation .....	2-70
Figure 2.38: Photographs of the Port Union Formation in outcrop.....	2-72
Figure 2.39: Supplementary photographs of the Port Union Formation .....	2-73
Figure 2.40: Sedimentary log through a section of the Port Union Formation .....	2-74
Figure 2.41: Revised log through the Port Union Formation .....	2-75
Figure 2.42: Thin section from the Port Union Formation.....	2-77
Figure 2.43: Photographs of the Little Catalina Formation in outcrop .....	2-79
Figure 2.44: Supplementary photographs of the Little Catalina Formation.....	2-80
Figure 2.45: Revised log through the bottom of the Little Catalina Formation .....	2-81
Figure 2.46: Stratigraphy of the Chance Cove Supergroup.....	2-84
Figure 2.47: Stratigraphic thickness comparison and relationship hypotheses between the Catalina Dome and MPER sections.....	2-92

Figure 2.48: Stratigraphy of the Chance Cove Supergroup.....	2-94
--	------

### **CHAPTER 3**

Figure 3.1: Slabbed section of the DRK-10 tuffite.....	3-4
Figure 3.2: Slabbed section of the DRK-1 tuffite .....	3-6
Figure 3.3: Slabbed section of the MP-14 tuffite .....	3-8
Figure 3.4: Slabbed section of the LC-1 tuffite.....	3-9
Figure 3.5: Slabbed section of the SH-2 tuffite .....	3-11
Figure 3.6: Images of laminated layer underlying fossil horizons .....	3-15
Figure 3.7: Hummocky Cross Stratification of Retallack from Catalina Dome .....	3-21
Figure 3.8: Ripples from the Chance Cove Supergroup.....	3-23

### **CHAPTER 4**

Figure 4.1: Map of geochronological samples from MPER.....	4-9
Figure 4.2: Summary of geochronological analyses from MPER .....	4-10
Figure 4.3: Map of geochronological samples from the Catalina Dome.....	4-12
Figure 4.4: Summary of geochronological analyses from the Catalina Dome.....	4-13
Figure 4.5: Age model for the rocks of MPER.....	4-16
Figure 4.6: Chronostratigraphic correlation between MPER and the Catalina Dome ...	4-22

### **CHAPTER 5**

Figure 5.1: Stratigraphic correlation of Avalonian Ediacaran successions.....	5-3
---	-----

Figure 5.2: Stratigraphic distribution of taxa in the Catalina Dome area.....	5-15
Figure 5.3: Stratigraphic distribution of taxa in Mistaken Point Ecological Reserve ....	5-16
Figure 5.4: Chronostratigraphic distribution of shared taxa from Charnwood Forest, MPER, and the Catalina Dome.....	5-19
Figure 5.5: Graphic correlation of the MPER and Catalina Dome sections.....	5-22

## **CHAPTER 6**

Figure 6.1: Map of Newfoundland with Mistaken Point marked.....	6-5
Figure 6.2: The Yale outcrops of the ‘E’ Surface at Mistaken Point .....	6-6
Figure 6.3: Sedimentology of the ‘E’ Surface.....	6-8
Figure 6.4: Comparison of observed palaeocommunities at ‘E’ Surface localities.....	6-10
Figure 6.5: The ‘E’ Surface at Watern Cove West.....	6-12
Figure 6.6: The ‘E’ Surface at Watern Cove East .....	6-13
Figure 6.7: The ‘E’ Surface at The Stumps .....	6-15
Figure 6.8: The ‘E’ Surface at Cape Race .....	6-16
Figure 6.9: Preservation and differential exposure of fossils by abrasion and spalling .	6-25
Figure 6.10: Abrasion on the Yale ‘E’ Surface outcrop.....	6-30

## **CHAPTER 7**

Figure 7.1: Map of the Mistaken Point Ecological Reserve.....	7-4
Figure 7.2: Map of the conservation designations for the Charnwood Forest area.....	7-5

Figure 7.3: Map of the conservation designations for the Long Mynd area ..... 7-6

Figure 7.4: Map of Significant Paleontological Sites in the Trinity Bay North area ..... 7-7

Figure 7.5: Examples of conservation signage, fossil removal, and attempted theft ..... 7-11

Figure 7.6: Geoconservation legislative frameworks for Newfoundland and England . 7-18

**BACK COVER INSERT**

Map 1: Geological Map of the Mistaken Point Ecological Reserve and Cape Race Region

Map 2: Geological Map of the Catalina Dome

# Abstract

---

Detailed geological mapping and improved understanding of the geological evolution of the siliciclastic late Ediacaran rocks of the Mistaken Point Ecological Reserve (MPER) and the Catalina Dome, both of Newfoundland, provide a new framework for improved lithostratigraphic subdivision of the successions. The lithostratigraphic correlation of the Catalina Dome with the succession at MPER is found to be incorrect, prompting the erection of the Trinity Bay North Group to classify the rocks of the Catalina Dome.

U-Pb (zircon) ages from the successions provide essential temporal constraints on the rise and fall of the Ediacara biota, and show that the Catalina Dome sections are up to 5 Myr older than previously thought. Both the MPER and Catalina Dome successions show an early fossil assemblage characterised by the presence of *Trepassia* and *Vinlandia*; a taxonomic radiation ~575 Ma; the emergence of evidence for animals ~565 Ma; and the sudden disappearance of most forms within post-565 Ma slumped slope deposits. These points provide the basis of discussion around the potential for a biostratigraphy for the Ediacaran of Avalonia, and support the ‘Ediacaran Explosion’ hypothesis.

Previous research using sedimentary structures and geochemical proxies to assign a non-marine deposition environment to the MPER and Catalina Dome sections is found to be flawed and without merit. There is no evidence for shallow marine or sub-aerial depositional environments. All known Avalonian rangeomorphs are found in deep-marine facies. The environmental controls on the stratigraphic distribution of taxa remain poorly constrained.

Analysis of tuffites within MPER suggests they were deposited by ashy turbidity currents, rather than as ash-falls. This prompts caution when using these tuffites for

geochronological analysis, and requires the re-evaluation of the traditional taphonomic model for rangeomorph fossilisation.

‘Post-fossilisation processes’ are shown to bias fossil census studies, most notably through differing mechanisms of tuffite weathering and erosion. The impacts on palaeoecological studies, and geoconservation efforts are considered. The geoconservation legislative frameworks for Newfoundland and England are compared and contrasted, and recommendations made.

# Extended Abstract

---

The Ediacaran Period is widely regarded as the cradle for the origins of the animal phyla, but the extent to which the succession of macrofossil forms within this period is evolutionarily, ecologically, or environmentally controlled is yet to be established. Highly resolved lithostratigraphic and temporal constraints are vital in this endeavour, and will also assist the important work of subdividing the Ediacaran Period.

Chapter 1 introduces the thesis, outlining the Ediacaran Period and its biota, as well as the geological history of eastern Newfoundland.

Chapter 2 describes a new framework for an improved lithostratigraphic subdivision of the late Ediacaran rocks of the Mistaken Point Ecological Reserve (MPER), through detailed geological mapping and an improved understanding of the geological evolution of the siliciclastic succession. MPER is situated on the Avalon Peninsula of Newfoundland, and records a diverse and exceptionally well preserved late Ediacaran rangeomorph-dominated assemblage. The Catalina Dome, 200 km north on the Bonavista Peninsula, Newfoundland, is also well known for a rangeomorph-dominated fossil assemblage. Analysis of the Catalina Dome section reveals that pre-existing lithostratigraphic correlations with MPER are found to be incorrect, which has significant implications for the stratigraphic ranges of many taxa. The Trinity Bay North Group is created to classify the succession at the Catalina Dome. The Chance Cove Supergroup is created to encompass the late Ediacaran siliciclastic successions at MPER and the Catalina Dome. The rocks of the Catalina Dome are suggested to have been deposited in a sub-basin peripheral to that in which the MPER succession was deposited in, or alternatively the Catalina Dome section is the thinner lateral equivalent of the MPER deposits, within a sediment wedge.

Chapter 3 reviews the sedimentology of the MPER and Catalina Dome successions. Close examination of the sedimentology of tuffaceous horizons, thought to have smothered and cast the Ediacaran palaeocommunities, reveals they were deposited by ashy turbidity currents. This not only has significant potential to improve the taphonomic understanding of the Ediacaran assemblage, but also requires any geochronological data yielded therefrom to be scrutinised in detail due to the implied resedimentation. The Ediacaran fossils of the Mistaken Point Ecological Reserve, and the Catalina Dome have been reconstructed by some as having lived and died in terrestrial and shallow marine environments. Critical analysis of both these siliciclastic successions reveals no evidence for shallow marine or sub-aerial deposition, and geochemical proxies are found to have been used outside the parameters of their methodology in proposing non-marine depositional environments. Reanalysis shows these successions were most likely deposited in deep marine environments, excluding photoautotrophic affinities for the Ediacara Biota present. The stratigraphic succession exposed in the Mistaken Point Ecological Reserve evidences the initial rifting, spreading, and mature phases of an Ediacaran backarc basin. The Catalina Dome succession shows deposition within similar environments to the Mistaken Point Ecological Reserve, revealing similar depositional processes. More research is required to better understand the precise depositional environments of specific formations within Catalina Dome succession.

Chapter 4 provides new high-precision chronostratigraphic constraints on the MPER and Catalina Dome successions. New U-Pb (zircon) ages from key stratigraphic volcanogenic horizons within the ~2300 m thick Ediacaran succession in and around the Mistaken Point Ecological Reserve (MPER) provide an improved chronostratigraphic framework for the Ediacaran macro- and trace-fossil assemblage. This provides an essential temporal constraint for comparison and correlation with other broadly contemporaneous

fossiliferous successions worldwide in order to understand evolutionary and ecological development. Furthermore, U-Pb (zircon) ages from two horizons in the Catalina Dome, Bonavista Peninsula allow development of the chronostratigraphic framework for the macrofossil assemblage present in this succession, and demonstrate that much of the Catalina Dome is older than previously envisaged through lithostratigraphic correlation with the rocks at Mistaken Point. This new chronostratigraphic framework permits the integration of lithostratigraphic and palaeontological datasets for the first time, and provides valuable constraints on the rise of the Ediacara biota.

Chapter 5 reviews the state of Avalonian Ediacaran stratigraphy, combining previous lithostratigraphic and chronostratigraphic constraints with those presented in the previous chapters. The Newfoundland sections at Mistaken Point and the Catalina Dome both show an earliest fossil assemblage containing the rangeomorphs *Vinlandia* and *Trepassia*. Shortly after, around 575 Ma there is a rapid increase in taxonomic diversity, suggesting an ‘Ediacaran Explosion’. Evidence for metazoan behaviour first appears at both Mistaken Point and the Catalina Dome ~565 Ma. The interval from 545 – 565 Ma, containing the disappearance of rangeomorphs across Avalonia, remains poorly constrained chronostratigraphically. All known Ediacaran rangeomorphs are found in deep-marine deposits. Potential exists for the creation of several Avalonian biostratigraphic zones, though further investigation is required.

Chapter 6 presents the concept of ‘post-fossilisation processes’, and how they can bias interpretation of fossil census data. The Ediacaran fossil assemblages at Mistaken Point Ecological Reserve are some of the oldest known examples of the enigmatic Ediacara biota, and provide some of the earliest evidence for animal life in the rock record. Because of the abundance of fossils, and their exposure on large bedding planes, these assemblages have been the subject of numerous studies of fossil census data. This study demonstrates

that a first order control on the observed fossil assemblage is the method by which the overlying crystal tuff is eroded and weathered. Weathering and erosion – along with the biases associated with tectonics, metamorphism, and discovery – are generally overlooked within the wider field of taphonomy, and are here grouped as ‘post-fossilisation processes’. Observed variability in fossil assemblages that has previously been used as evidence for palaeoecological interpretations, is considered herein to be subject to significant post-fossilisation bias, particularly through differential erosional and weathering processes. The recognition that post-fossilisation processes significantly influence fossil census data has significant implications for Ediacaran palaeoecology both in Newfoundland and beyond. It is further recognised that the study of post-fossilisation processes has significance to the field of geoconservation, and the continued sustainability of these world-famous fossil localities that are currently being considered as a potential UNESCO world heritage site.

Chapter 7 analyses the state of geoconservation mechanisms in Newfoundland and England. The increase in Ediacaran research over the past 50 years has been accompanied by an equal growth in interest from the general public; precipitating both a necessary development of geoconservation legislation and management frameworks. Various geoconservation laws, both in England and Newfoundland, are reviewed, focussing on access to localities, removal of material, and export of specimens. Examples of fossil theft and damage are provided as benchmarks against which to assess various approaches. Problems concerning ambiguity and contradiction in legislation are highlighted, as well as the overall complexity of both jurisdictions’ structures. The current issues are discussed, including the importance of community involvement, and recommendations for the future proposed.

# Acknowledgements

---

This research would have been much more difficult, and less enjoyable, without the help and support of the local communities in Newfoundland. Thanks go to the people of Portugal Cove South, Trepassey, Ferryland, Upper Island Cove, Trinity Bay North, and Bonavista. Your kindness and hospitality is unrivalled. Special mention should go to Mary and Jerome of the Trepassey Motel for taking me in, no matter how busy they were, and Edith Samson of the Coaker Foundation for all her help and support. Richard Thomas of the Mistaken Point Ecological Reserve is thanked for his assistance and good humour in the field.

Funding from NERC, NIGFSC, and the University of Oxford Department of Earth Sciences Burdett Coutts Fund are gratefully acknowledged.

Tom Hearing is thanked for his work as a cheery and perpetually engaged field assistant - you couldn't ask for better. I am indebted to Alex Liu for opening my eyes to the Ediacaran in 2008 when he offered me the opportunity to field assist for him. Your support, friendship, guidance, and ability to withstand my rants in the field is greatly appreciated. Leila Battison, Latha Menon, Russell Garwood, and Liam Herringshaw are also thanked for their friendship, thoughts, and ideas.

These projects aren't possible without the support of a Department, and all the people that are part of that community. I want to especially thank Emma and Elaine for their never ending supply of answers to postgraduate questions. Jeremy is thanked for his help in preparing difficult samples. Adrian is likewise thanked for his guidance in sample preparation at the NERC Isotope Geosciences Laboratories.

Well placed guidance is essential if one is to survive the journey that is DPhil life. Duncan McIlroy, Bruce Levell, and Dan Condon all stepped up to fill the gap when needed, and I am immensely grateful for all the help and support they have provided. I would also like to thank my college advisor, Tamsin Mather, and also David Pyle, for the support they have given, especially over the past year.

Finally I must express my thanks to Martin Brasier, without whom this entire enterprise would never have begun. While field assistant to Alex in 2008, Martin was incredibly encouraging that I get involved in his research group, which led to future trips to Newfoundland, a Masters project, and then a DPhil. His insistence on the importance of field studies, and seeing as many outcrops as possible, in an age where the trend is to spend increasing amounts of time in the lab, has stood me in good stead. No outcrop was ever boring when Martin was there, and the cheery discussion would go on into the evening over a beer - whisky if you were lucky. He was so much more than a supervisor; he was a mentor and a friend. While there are many who have offered support since Martin's death, for which I am grateful, my ability to submit this thesis is in no small part down to the indelible lessons Martin taught, most memorably the democratic nature of science, the importance of parsimony, and that the wider geological context of a sample was essential. He lives on in what, and how, he taught us.

# Chapter 1: Introduction

---

The Ediacaran, 635–541 Ma is the youngest period of the Precambrian and its palaeontology documents the transition from the microbe-dominated Proterozoic to the metazoan ruled environments of the Phanerozoic.

The start of the Ediacaran is defined as the base of the Marinoan cap carbonate, with the Global Boundary Stratotype Section and Point (GSSP) situated in the Enorama Creek section of the Nuccaleena Formation, South Australia (Knoll et al., 2006). Underlying this horizon are the arkosic sandstones, siltstones and diamictites of the Elatina Formation, which are interpreted to be glacial and glacial marine deposits (Leitch, 1990). These glacial deposits are associated with the Marinoan (Lemon and Gostin, 1990), the last of the truly global glaciations, though the severity of these glaciations is debated (Hoffman et al., 1998; Kilner et al., 2005; Dobrzinski and Bahlburg, 2007; Allen and Etienne, 2008). The age of the end of the Marinoan glaciation is constrained in Namibia to be younger than  $635.5 \pm 1.2$  Ma (U-Pb zircon) (Hoffmann et al., 2004), and in China where it cap carbonate itself is dated to  $635.2 \pm 0.5$  Ma (U-Pb zircon) (Condon et al., 2005).

The top of the Ediacaran is the base of the Cambrian, with a GSSP at Fortune Head, Newfoundland, and the exact boundary being the lowest occurrence of the trace fossil *Phycodes pedum* (Brasier et al., 1994), and the onset of widespread vertical burrowing by metazoans.

The late Neoproterozoic is also a time of great palaeogeographical change, with the rifting apart of Rodinia (Li et al., 2008) and Pannotia (Scotese, 2009) taking place. Geochemical data, specifically stable carbon isotopes, reveal a number of large negative excursions. The Shuram excursion, the largest known in the geological record (Le Guerroue, 2010), occurs

within the Ediacaran, though its exact age and duration are still debated (Halverson et al., 2005; Bristow and Kennedy, 2008).

Life before the Ediacaran was widespread and varied, including examples of multicellularity (Butterfield, 2009), and eukaryotes (e.g. Bosak et al., 2011). The Lantian biota, tentatively given a date of ~600 Ma, contains algal fossils a few centimetres in size (Yuan et al., 2011), however it is not until ~579 Ma with the Avalon biotic assemblage (Waggoner, 2003) that “life got big” (Narbonne and Gehling, 2003).

The Ediacaran therefore constitutes an important transitional interval in geological history, from the end of the ‘Snowball Earth’ glaciations (Hoffman et al., 1998) to the ‘Cambrian Explosion’ biological radiation. The Ediacara biota is consequently of importance to our understanding of the origins of animal life, since it directly precedes the Cambrian biota from which all subsequent animal life evolved (Brasier, 2009).

Ediacaran fossils have been described from a total of 109 localities (Liu and Brasier, 2012), in rocks deposited in a variety of marine environments. The Avalon biotic assemblage appears in Newfoundland and the United Kingdom shortly after the Gaskiers glacial event (Eyles and Eyles, 1989). The assemblage is dominated by the rangeomorphs, a clade of soft-bodied organisms comprising one or more fractal-like ‘fronds’, sometimes with an associated stem or holdfast disk (Narbonne, 2004; Brasier et al., 2012). The Ediacara biota in Avalonia, studied herein in Newfoundland and the United Kingdom, have been interpreted to include examples of algae (Ford, 1958), a now extinct phyla (Seilacher, 1992), lichens (Retallack, 1994), fungi (Peterson et al., 2003), and protists (Seilacher et al., 2003). The assemblage also contains evidence for horizontal locomotion (Liu et al., 2010), and a muscular cnidarian-like organism (Liu et al., 2014). Examples of the Ediacara biota from Newfoundland are given in Figure 1.1.

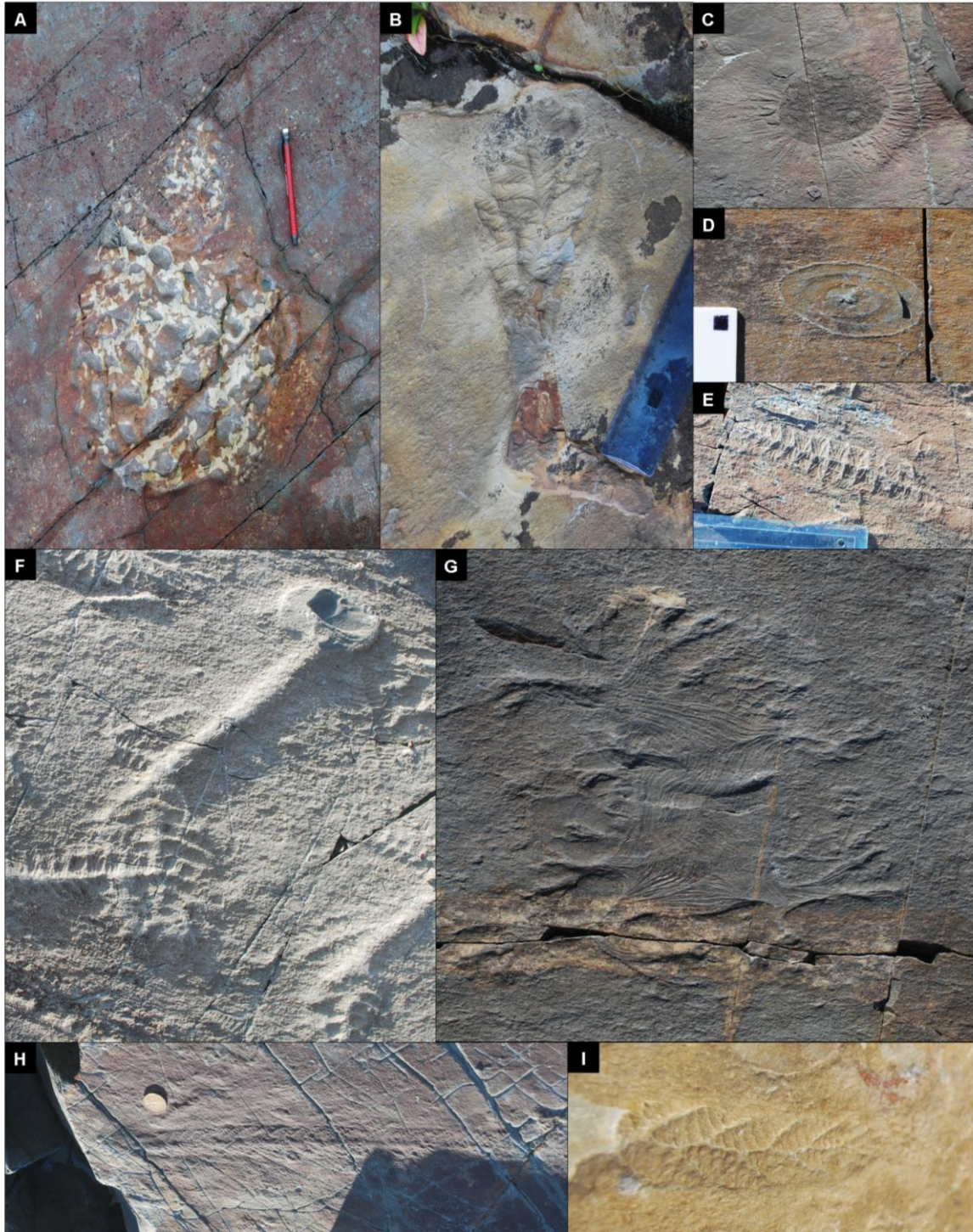


FIGURE 1.1. Examples of the Ediacara biota from Newfoundland. A) An ivesheadiomorph, thought to be the decayed remains of an organism. Known colloquially as a 'pizza disk' B) The frondose form *Beothukis*. C) *Heimalora*, a discoidal form with 'rays'. D) The basic discoidal form *Aspidella*. E) The spindle form *Fractofusus*. F) *Charniodiscus* from the Mistaken Point E-Surface. G) *Haootia* - a muscle-bearing stauromedusan-like organism. H) The lower part of a *Trepassia* specimen. I) A small specimen of *Charnia*.

The palaeo-microcontinent of Avalonia developed as part of a volcanic arc off the northern active margin of Gondwana (Nance et al., 2002), and comprises what is now modern day Southern Britain, the Low Countries, Eastern Newfoundland, Nova Scotia, and New Brunswick. Avalonia is thought to have had a latitude of roughly 60° south during the late Ediacaran (Pisarevsky et al., 2008), but alternative scenarios with palaeo-latitudes of 40–65° have also been calculated (Torsvik, 2003; Samson et al., 2005; Thompson et al., 2007; Li et al., 2008). Calculation of Avalonia's palaeo-latitude is further complicated by debate as to whether the Earth's magnetic field during the late Neoproterozoic may have been distinctly non-uniformitarian (Abrajevitch and Van der Voo, 2010). There appears to be agreement that Avalonia was located close to the Amazonian and West African cratons of Gondwana during the late Ediacaran, but the precise distribution of the peri-Gondwanan palaeocontinents is a matter of ongoing debate (Figure 1.2; Nance et al., 2002; Murphy et al., 2004; Linnemann, 2007; Pollock et al., 2009).

Avalonia developed into a platformal environment during the Cambrian (Nance et al., 2002), and then accreted to Laurentia where it was affected by the Appalachian-Caledonide orogeny (Keppie et al., 1991). This placed Avalonia at the centre of Pangea. Eastern (modern European) Avalonia and Western (modern North American) Avalonia are then separated in the Mesozoic by the opening of the North Atlantic.

The Avalon Peninsula of Newfoundland has a >7.5 km thick volcano-sedimentary succession of late Neoproterozoic rocks. The stratigraphic succession shows a gradual net-shallowing-upwards trend from deep-marine basin-floor facies, to shallow-marine and fluvial siliciclastic units. These rocks, most notably in the area around Mistaken Point, contain the earliest diverse communities of Ediacaran macro-organisms in the fossil record (Liu et al., 2011). Mistaken Point is located within the Mistaken Point Ecological Reserve, a candidate UNESCO World Heritage Site, on the southern shore of the Avalon Peninsula.

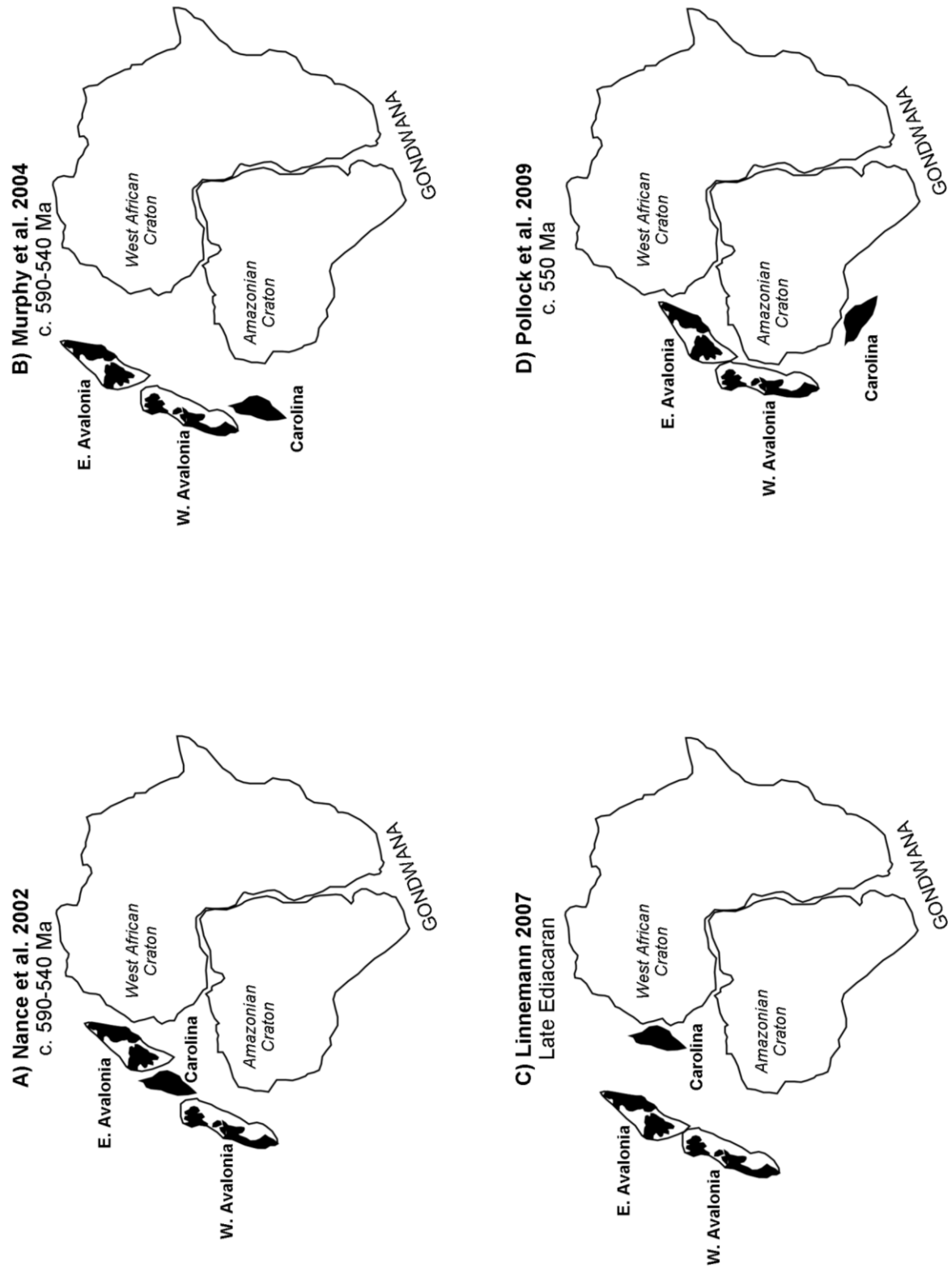


FIGURE 1.2. Various palaeogeographic reconstructions for the peri-Gondwanan terranes of Eastern Avalonia (modern Southern Britain and the Low Countries), Western Avalonia (modern Eastern Newfoundland, Nova Scotia, and New Brunswick), and Carolina (modern North and South Carolina). A) Reconstruction from Nance et al. (2002). B) Reconstruction from Murphy et al. (2004). C) Reconstruction from Linnemann (2007). D) Reconstruction from Pollock et al. (2009).

A similar assemblage of Ediacaran fossils is also found on the east of the Bonavista Peninsula of Newfoundland, preserved in a sedimentary succession of late Neoproterozoic rocks that show a gradual shallowing upwards trend (O'Brien and King, 2005). These fossiliferous outcrops occur within the Catalina Dome, a NNE trending elliptical anticlinal dome, centred on the town of Trinity Bay North. The Avalon Zone of Newfoundland (Myrow, 1995), being that part of the island to the east of the Hermitage Bay – Dover Fault, is dominated by Ediacaran geology. Though the Avalon Zone comprises very many different Ediacaran lithologies from various depositional environments, examples of the Ediacara biota have so far only been described from what is herein classified as the Chance Cove Supergroup – the siliciclastic succession that dominates the eastern part of the Avalon Zone. A summary of the geology and geography of Eastern Newfoundland is given in Figure 1.3.

Together, the Mistaken Point Ecological Reserve and the Catalina Dome form the focus of Ediacaran palaeontological studies within Newfoundland, due to the high-fidelity of preservation and taxonomic diversity observed (Liu et al., 2015). Both successions are believed to have been deposited in a tectonically active basin associated with island-arc volcanism (Myrow, 1995) prior to Avalonia separating from Gondwana (Nance et al., 2002; Wood et al., 2003).

The Ediacaran fossils at Mistaken Point were first discovered in 1967, with publication following the next year (Anderson and Misra, 1968). Since then, as has become custom in Ediacaran field studies in Newfoundland, many of the fossiliferous horizons have been named. Initially, the most prominent surfaces within the Mistaken Point area were given identifications in alphabetical order up through the section (Benus, 1988). This is the origin of the name 'E' Surface for the horizon at Mistaken Point famed for its many thousands of fossilised forms. Many more fossiliferous horizons have since been

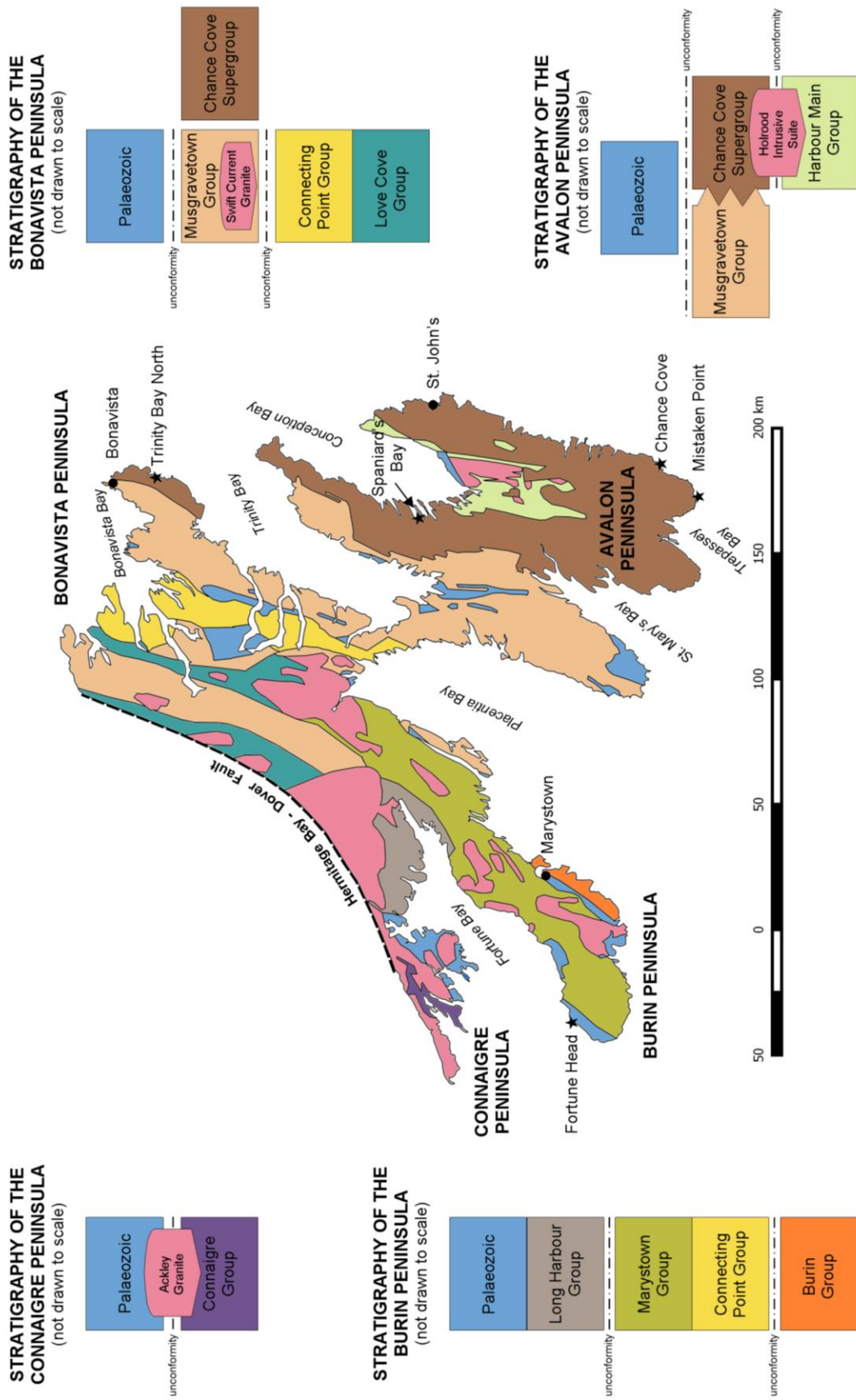


FIGURE 1.3. Geological map of Eastern Newfoundland, with stratigraphic columns for each major peninsula. Based on data from multiple sources (Blackwood, 1984; O'Brien, 1984; King et al., 1988; O'Brien et al., 1990; Dec et al., 1992; O'Brien and King, 2005; Normore, 2010) .

discovered below the 'E' Surface, on top of 'A', 'B', 'C', and 'D' surfaces, though the names still persist in the literature.

The discovery of multiple outcrops of the 'E' Surface gave rise to the naming of individual outcrops, as well as horizons, often after the geographical location of that outcrop, or after a University with a history of Ediacaran research. Thus individual outcrops of the 'E' Surface have been named the 'Yale', 'Harvard', and 'Watern Cove West' outcrops (Clapham et al., 2003). Other informal names such as the 'Pizza Disk Bed' (also known as the 'A' Surface) and 'The Pizzeria' (a fossiliferous horizon in the Trepassy Formation) are also in use.

Ediacaran fossils were first documented in the Catalina dome by survey geologists O'Brien and King (2004). The fossiliferous outcrops were documented in much more detail by the late Hans J. Hofmann (2008), who numbered all the surfaces he found. Thus, many fossiliferous localities in the Catalina Dome are referred to by the number he assigned, e.g. 'Hofmann 14' or 'HF14'. Similarly to the Mistaken Point Ecological Reserve, a number of surfaces have also acquired other names, including the 'Discovery', 'Johnson' and 'MUN' surfaces.

While the Ediacara biota of Newfoundland has now been the subject of scientific inquiry for nearly half a century, these studies have often focused primarily on the organisms, their palaeoecology, and evolution (e.g. Clapham et al., 2003; Narbonne, 2004; Gehling and Narbonne, 2007; Darroch et al., 2013). Where research has considered the wider stratigraphic and sedimentological contexts on the Ediacara biota, the studies have often been geographically restricted to particular fossiliferous localities (e.g. Wood et al., 2003; Ichaso et al., 2007; Mason et al., 2013). The Ediacara biota of Newfoundland continues to provide valuable insights into key biotic innovations such as locomotion (Liu et al., 2010),

musculature (Liu et al., 2014), and stolon-like reproduction (Mitchell et al., 2015), though the wider context of these significant discoveries is hampered by lack of a high-precision, peer-reviewed chronostratigraphic framework.

This thesis, based on extensive field studies in the Mistaken Point Ecological Reserve and at the Catalina Dome, seeks to critically assess the stratigraphic relationships between these two globally significant fossiliferous localities. The research provides both a rigorous lithostratigraphy on which current and future discoveries can be mapped, as well as a new chronostratigraphy between the two sections, allowing accurate regional and global correlation for the first time. This thesis also assesses the environments under which the sediments were deposited – and therefore in which the Ediacaran organisms lived and died.

Chapter 2 examines the stratigraphy of the most prominent Ediacaran fossil locality in the world, the Mistaken Point Ecological Reserve, Newfoundland, as well as that of the Catalina Dome on the Bonavista Peninsula. Geological mapping and stratigraphic analysis offers new insights into the validity of lithostratigraphic correlation between the two sections. Theories for the geological relationship of these two significant palaeontological sites are suggested and tested.

Chapter 3 examines the sedimentology of the rocks of the Mistaken Point Ecological Reserve and the Catalina Dome. The method by which tuffites were deposited at these localities is examined, and its impact on taphonomy and geochronological studies considered. The depositional environments of the sediments of the Mistaken Point Ecological Reserve and the Catalina Dome are critically assessed.

Chapter 4 presents new geochronological data for the Mistaken Point Ecological Reserve and the Catalina Dome. Two previous horizons from the Mistaken Point Ecological

Reserve are re-examined, and four supplementary horizons are analysed to provide a robust, high-precision chronostratigraphic framework for this globally significant palaeontological locality. Two new dates from the Catalina Dome are given, providing the basis for the first chronostratigraphic correlation with the Mistaken Point Ecological Reserve succession. The new geochronological data is used to assess ideas around stratigraphic relationships proposed in Chapter 2.

Chapter 5 reviews the stratigraphy of Ediacaran outcrops across Newfoundland and the United Kingdom, bringing together previous chronostratigraphic data with those presented in the previous chapter. The stratigraphic distributions of the various taxa are examined, and possibility of erecting biostratigraphic units assessed.

Chapter 6 investigates the processes fossils undergo once they have entered the geological record, up to and including discovery. Examples of the mechanisms by which fossils become exposed are studied at Mistaken Point Ecological Reserve, and the biases these may cause in fossil population datasets are considered.

Chapter 7 reviews the geoconservation frameworks, legislative and otherwise, that are used to protect geologically significant localities in Newfoundland and England. The two systems are compared, and the roles of government, local communities, and researchers are considered.

## **REFERENCES**

- Abrajevitch, A., and Van der Voo, R., 2010, Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis: *Earth and Planetary Science Letters*, v. 293, no. 1–2, p. 164–170, doi: 10.1016/j.epsl.2010.02.038.
- Allen, P.A., and Etienne, J.L., 2008, Sedimentary challenge to Snowball Earth: *Nature Geoscience*, v. 1, no. 12, p. 817–825, doi: 10.1038/ngeo355.

- Anderson, M.M., and Misra, S.B., 1968, Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland: *Nature*, v. 220, no. 5168, p. 680–681, doi: 10.1038/220680a0.
- Benus, A.P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland): Trace Fossils, Small Shelly Fossils and the Precambrian Cambrian Boundary: *Proceedings, 1987, Memorial University (New York State Museum and Geological Survey Bulletin)*, p. 8–9.
- Blackwood, R.F., 1984, Geology of the west half of the Dolland Brook map area (11P/15), southern Newfoundland: Newfoundland Department of Mines and Energy, Mineral Development Division, Rep, , no. 84–1, p. 198–210.
- Bosak, T., Lahr, D.J.G., Pruss, S.B., Macdonald, F.A., Dalton, L., and Matys, E., 2011, Agglutinated tests in post-Sturtian cap carbonates of Namibia and Mongolia: *Earth and Planetary Science Letters*, v. 308, no. 1–2, p. 29–40, doi: 10.1016/j.epsl.2011.05.030.
- Brasier, M.D., 2009, *Darwin’s lost world : the hidden history of animal life*: Oxford University Press, Oxford.
- Brasier, M.D., Antcliffe, J.B., and Liu, A.G., 2012, The architecture of Ediacaran Fronds: *Palaeontology*, v. 55, no. 5, p. 1105–1124, doi: 10.1111/j.1475-4983.2012.01164.x.
- Brasier, M., Cowie, J., and Taylor, M., 1994, Decision on the Precambrian-Cambrian boundary stratotype: *Episodes-News magazine of the International Union of Geological Sciences*, v. 17, no. 1, p. 3–8.
- Bristow, T.F., and Kennedy, M.J., 2008, Carbon isotope excursions and the oxidant budget of the Ediacaran atmosphere and ocean: *Geology*, v. 36, no. 11, p. 863–866.
- Butterfield, N.J., 2009, Modes of pre-Ediacaran multicellularity: *Precambrian Research*, v. 173, no. 1–4, p. 201–211.
- Clapham, M.E., Narbonne, G.M., and Gehling, J.G., 2003, Paleocology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland: *Paleobiology*, v. 29, no. 4, p. 527–544, doi: 10.1666/0094-8373(2003)029<0527:POTOKA>2.0.CO;2.
- Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A., and Jin, Y., 2005, U-Pb Ages from the Neoproterozoic Doushantuo Formation, China: *Science*, v. 308, no. 5718, p. 95–98, doi: 10.1126/science.1107765.
- Darroch, S.A.F., Laflamme, M., and Clapham, M.E., 2013, Population structure of the oldest known macroscopic communities from Mistaken Point, Newfoundland: *Paleobiology*, v. 39, no. 4, p. 591–608, doi: 10.1666/12051.
- Dec, T., O’Brien, S.J., and Knight, I., 1992, Late precambrian volcanoclastic deposits of the Avalonian eastport basin (Newfoundland Appalachians): petrofacies, detrital clinopyroxene geochemistry and palaeotectonic implications: *Precambrian Research*, v. 59, no. 3, p. 243–262, doi: 10.1016/0301-9268(92)90059-W.

- Dobrzinski, N., and Bahlburg, H., 2007, Sedimentology and environmental significance of the Cryogenian successions of the Yangtze Platform, South China block: *Palaeogeography Palaeoclimatology Palaeoecology*, v. 254, p. 100–+.
- Eyles, N., and Eyles, C.H., 1989, Glacially-influenced deep-marine sedimentation of the Late Precambrian Gaskiers Formation, Newfoundland, Canada: *Sedimentology*, v. 36, no. 4, p. 601–620, doi: 10.1111/j.1365-3091.1989.tb02088.x.
- Ford, T.E., 1958, Precambrian fossils from Charnwood Forest: *Proceedings of the Yorkshire Geological Society*, v. 31, p. 211–217.
- 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*, v. 44, no. 3, p. 367–387, doi: 10.1139/E07-003.
- Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: *Geological Society of America Bulletin*, v. 117, no. 9–10, p. 1181–1207, doi: 10.1130/B25630.1.
- Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic Snowball Earth: *Science*, v. 281, no. 5381, p. 1342–1346, doi: 10.1126/science.281.5381.1342.
- Hoffmann, K.H., Condon, D.J., Bowring, S.A., and Crowley, J.L., 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation: *Geology*, v. 32, no. 9, p. 817–820.
- Hofmann, H.J., O'Brien, S.J., and King, A.E., 2008, Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada: *Journal of Paleontology*, v. 82, no. 1, p. 1–36, doi: 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*, v. 44, no. 1, p. 25–41.
- Keppie, J.D., Nance, R.D., Murphy, J.B., and Dostal, J., 1991, Northern Appalachians: Avalon and Meguma Terranes, *in* Dallmeyer, D.R.D. and Lécorché, D.J.P. eds., *The West African Orogens and Circum-Atlantic Correlatives*, IGCP-Project 233, Springer Berlin Heidelberg, p. 315–333.
- Kilner, B., Niocaill, C., and Brasier, M., 2005, Low-latitude glaciation in the Neoproterozoic of Oman: *Geology*, v. 33, no. 5, p. 413–416, doi: 10.1130/G21227.1.
- King, A.F., Colman-Sadd, S.P., Hayes, J.P., and Division, N.M.D., 1988, Geology of the Avalon Peninsula, Newfoundland:(parts of 1K, 1L, 1M, and 2C): Mineral Development Div., Dept. of Mines, Government of Newfoundland and Labrador.
- Knoll, A.H., Walter, M.R., Narbonne, G.M., and Christie-Blick, N., 2006, The Ediacaran Period: a new addition to the geologic time scale: *Lethaia*, v. 39, no. 1, p. 13–30, doi: 10.1080/00241160500409223.

- Le Guerroue, E., 2010, Duration and synchronicity of the largest negative carbon isotope excursion on Earth: The Shuram/Wonoka anomaly: *Comptes Rendus Geoscience*, v. 342, no. 3, p. 204–214, doi: 10.1016/j.crte.2009.12.008.
- Leitch, E.C., 1990, *The Adelaide Geosyncline: Late proterozoic stratigraphy, sedimentation, palaeontology and tectonics*: Elsevier.
- Lemon, N.M., and Gostin, V.A., 1990, Glacigenic sediments of the late Proterozoic Elatina Formation and equivalents, Adelaide Geosyncline, South Australia: *The Evolution of a Late Precambrian—Early Paleozoic Rift Complex: the Adelaide Geosyncline*, v. 16, p. 149–163.
- Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., et al., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: *Precambrian Research*, v. 160, no. 1–2, p. 179–210, doi: 10.1016/j.precamres.2007.04.021.
- Linnemann, U., 2007, Ediacaran rocks from the Cadomian basement of the Saxo-Thuringian Zone (NE Bohemian Massif, Germany): age constraints, geotectonic setting and basin development: *Geological Society, London, Special Publications*, v. 286, no. 1, p. 35–51, doi: 10.1144/SP286.4.
- Liu, A.G., and Brasier, M.D., 2012, A Global Comparative Analysis of Ediacaran fossil localities.:
- Liu, A.G., Kenchington, C.G., and Mitchell, E.G., 2015, Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota: *Gondwana Research*, v. 27, no. 4, p. 1355–1380, doi: 10.1016/j.gr.2014.11.002.
- Liu, A.G., Matthews, J.J., Menon, L.R., McIlroy, D., and Brasier, M.D., 2014, *Hootia quadriformis* n. gen., n. sp., interpreted as a muscular cnidarian impression from the Late Ediacaran period (approx. 560 Ma): *Proceedings of the Royal Society of London B: Biological Sciences*, v. 281, no. 1793, p. 20141202, doi: 10.1098/rspb.2014.1202.
- 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 microfossil record: *Palaeontology*, v. 54, no. 3, p. 607–630, doi: 10.1111/j.1475-4983.2010.01024.x.
- 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*, v. 38, no. 2, p. 123–126.
- Mason, S.J., Narbonne, G.M., Dalrymple, R.W., and O'Brien, S.J., 2013, Paleoenvironmental analysis of Ediacaran strata in the Catalina Dome, Bonavista Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 50, no. 2, p. 197–212, doi: 10.1139/cjes-2012-0099.
- 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*, v. 524, no. 7565, p. 343–346, doi: 10.1038/nature14646.

- 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*, v. 93, no. 5, p. 659–682, doi: 10.1007/s00531-004-0412-9.
- Myrow, P.M., 1995, Neoproterozoic Rocks of the Newfoundland Avalon Zone: *Precambrian Research*, v. 73, no. 1–4, p. 123–136.
- Nance, R.D., Murphy, J.B., and Keppie, J.D., 2002, A Cordilleran model for the evolution of Avalonia: *Tectonophysics*, v. 352, no. 1–2, p. 11–31.
- Narbonne, G.M., 2004, Modular construction of early ediacaran complex life forms: *Science*, v. 305, no. 5687, p. 1141–1144, doi: 10.1126/science.1099727.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: *Geology*, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- Normore, L.S., 2010, Geology of the Bonavista map-area (NTS 2C/11), Newfoundland: Current Research Report, p. 10–1.
- O'Brien, S.J., 1984, Geology of the Terrenceville (1M/10) and Gisborne Lake (1M/15) map areas, southeast Newfoundland: Mineral Development Division, Department of Mines and Energy.
- 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 Report, p. 4–1.
- O'Brien, S.J., and King, A.F., 2005, Late Neoproterozoic (Ediacaran) stratigraphy of Avalon Zone sedimentary rocks, Bonavista Peninsula, Newfoundland: Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, p. 6–1.
- O'Brien, S.J., Strong, D.F., and King, A.F., 1990, The Avalon zone type area: southeastern Newfoundland Appalachians: Avalonian and Cadomian geology of the North Atlantic: Blackie, p. 166–194.
- Peterson, K.J., Waggoner, B., and Hagadorn, J.W., 2003, A fungal analog for Newfoundland Ediacaran fossils? *Integrative and Comparative Biology*, v. 43, no. 1, p. 127–136, doi: 10.1093/icb/43.1.127.
- Pisarevsky, S.A., Murphy, J.B., Cawood, P.A., and Collins, A.S., 2008, Late Neoproterozoic and Early Cambrian palaeogeography: models and problems: Geological Society, London, Special Publications, v. 294, no. 1, p. 9.
- 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*, v. 166, no. 3, p. 501–515, doi: 10.1144/0016-76492008-088.

- Retallack, G.J., 1994, Were the Ediacaran Fossils Lichens: *Paleobiology*, v. 20, no. 4, p. 523–544.
- Samson, S.D., D’Lemos, R.S., Miller, B.V., and Hamilton, M.A., 2005, Neoproterozoic palaeogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages: *Journal of the Geological Society*, v. 162, no. 1, p. 65–71, doi: 10.1144/0016-764904-003.
- Scotese, C.R., 2009, Late Proterozoic plate tectonics and palaeogeography: a tale of two supercontinents, Rodinia and Pannotia: Geological Society, London, Special Publications, v. 326, no. 1, p. 67–83, doi: 10.1144/SP326.4.
- Seilacher, A., 1992, Vendobionta and Psammocorallia - Lost Constructions of Precambrian Evolution: *Journal of the Geological Society*, v. 149, p. 607–613.
- Seilacher, A., Grazhdankin, D., and Legouta, A., 2003, Ediacaran biota: The dawn of animal life in the shadow of giant protists: *Paleontological Research*, v. 7, no. 1, p. 43–54, doi: 10.2517/prpsj.7.43.
- Thompson, M.D., Grunow, A.M., and Ramezani, J., 2007, Late Neoproterozoic paleogeography of the Southeastern New England Avalon Zone: Insights from U–Pb geochronology and paleomagnetism: *Geological Society of America Bulletin*, v. 119, no. 5–6, p. 681–696, doi: 10.1130/B26014.1.
- Torsvik, T.H., 2003, The Rodinia Jigsaw Puzzle: *Science*, v. 300, no. 5624, p. 1379–1381, doi: 10.1126/science.1083469.
- Waggoner, B., 2003, The Ediacaran biotas in space and time: *Integrative and Comparative Biology*, v. 43, no. 1, p. 104–113, doi: 10.1093/icb/43.1.104.
- 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 Trepassy formations, southeastern Newfoundland: *Canadian Journal of Earth Sciences*, v. 40, no. 10, p. 1375–1391.
- Yuan, X., Chen, Z., Xiao, S., Zhou, C., and Hua, H., 2011, An early Ediacaran assemblage of macroscopic and morphologically differentiated eukaryotes: *Nature*, v. 470, no. 7334, p. 390–393, doi: 10.1038/nature09810.

# Chapter 2: Stratigraphy of the Mistaken Point Ecological Reserve and Catalina Dome

---

## **ABSTRACT**

Detailed geological mapping and an improved understanding of the geological evolution of the siliciclastic late Ediacaran rocks of the Mistaken Point Ecological Reserve (MPER) provide a new framework for an improved lithostratigraphic subdivision of the succession. Unit descriptions for the formations within MPER are brought up to date, and the accuracy of formation thicknesses is improved through enhanced understanding of the structural geology. Reevaluation of the siliciclastic succession at the Catalina Dome, Bonavista Peninsula, shows it has been incorrectly lithostratigraphically correlated with the rocks of MPER. The Trinity Bay North Group, comprising five formations is created to characterise the rocks of the Catalina Dome – a globally significant palaeontological site in late Ediacaran research. This decoupled lithostratigraphy removes the bias implicit in correlation, and allows an independent framework on which palaeontological and other data can be compared and contrasted. The Chance Cove Supergroup is created comprising the late Ediacaran fossiliferous siliciclastic successions of the Avalon and Bonavista peninsulas. The rocks of the Catalina Dome are suggested to have been deposited in a sub-basin peripheral to that in which the MPER succession was deposited in, or alternatively the Catalina Dome section is the thinner lateral equivalent of the MPER deposits, within a sediment wedge. Further research is required to constrain the lateral variability in the Chance Cove Supergroup.

## INTRODUCTION

The oldest rocks in the Avalon region are the interdigitated volcanoclastic and sedimentary lithologies of the Harbour Main Group (Rose, 1952), which forms a north-south trending belt across the central part of the Avalon Peninsula. The Harbour Main Group comprises pyroclastic flows and ignimbrites, as well as volcanoclastic sediments (Papezik, 1970). The oldest stratigraphic unit on the Avalon Peninsula, found in the centre of the Holyrood Horst is the Hawke Hills Tuff, which has been dated at  $729 \pm 7$  Ma (Israel, 1998). A granodiorite from the Horse Cove Complex, near Bauline, has been dated to  $625 \pm 1.4$  Ma (Skipton et al., 2013), but most of the dates for the Harbour Main Group cluster between 578 Ma and 582 Ma. The dates come from a variety of volcanic sources including rhyolites, andesites, feldspar porphyry, and pumiceous tuff beds (Sparkes et al., 2005; Skipton et al., 2013).

The Harbour Main Group is intruded by the Holyrood Intrusive Suite, comprising medium grained, massive, pink to grey granite with dates of  $620 +2.2/-1.7$  Ma (Krogh et al., 1983) and  $622.5 \pm 1.3$  Ma (Sparkes et al., 2005).

The rocks of the Conception Group lie unconformably on these igneous-dominated deposits, with the lowest unit being the Mall Bay Formation, consisting of siliceous siltstones, thickly bedded quartzose sandstones and occasional tuffs. It is only known from the south of the Avalon Peninsula within the western limb of the Colinet Passage Syncline, and the Crossing Place and Point La Haye Anticlines. The base of this formation is not exposed. The Mall Bay Formation is interpreted to have been deposited within the middle to lower part of small submarine fans (Gardiner and Hiscott, 1988).

Above the Mall Bay Formation are the unsorted diamictites of the Gaskiers Formation that are separated by thin horizons of grey to green siltstones, sandstones and conglomerates.

The conformable base of the Gaskiers Formations is defined by the first appearance of the diamictites. The unit is exposed in the south of the Avalon Peninsula around the Crossing place and Point La Haye Anticlines, Great Colinet Island, and a few smaller outcrops around Harbour Main in Conception Bay. The Gaskiers Formation has been interpreted as having been deposited by debris flows transported marginal marine glacial sediments from shallower depths to the deep basin floor (Eyles and Eyles, 1989).

The Drook, Briscal, Mistaken Point, Trepassey, and Fermeuse Formations described in detail herein from studies in and around the Mistaken Point Ecological Reserve (MPER) (Figure 1), lie above the Gaskiers Formation, although this contact is not visible within the direct area of study.

Outside the study area, the delta front sediments of the Renew's Head and Cappahayden Formations overlie the offshore shelf to slope siltstones and sandstones of the Fermeuse Formation (Matthews, 2011).

The shallowing-upwards succession continues through the light-grey wave rippled interbedded sandstones and siltstones of the Gibbett Hill Formation, comprising delta plain deposits (Matthews, 2011). The overlying Ferryland Head Formation and successive red sandstones and conglomerates of the Signal Hill Group represent successively more fluvial and terrestrial depositional environments (Williams and King, 1979; Matthews, 2011).

The rocks of the Catalina Dome, Bonavista Peninsula (Figure 2), have most recently been lithostratigraphically correlated with the formations found in and around the Mistaken Point Ecological Reserve (MPER) (O'Brien and King, 2005; Hofmann et al., 2008; Mason et al., 2013). This assertion has the effect of extending Mistaken Point-based palaeoenvironmental and chronostratigraphic interpretations over a distance of 200 km without independent supporting evidence. The rocks of the Catalina Dome, their

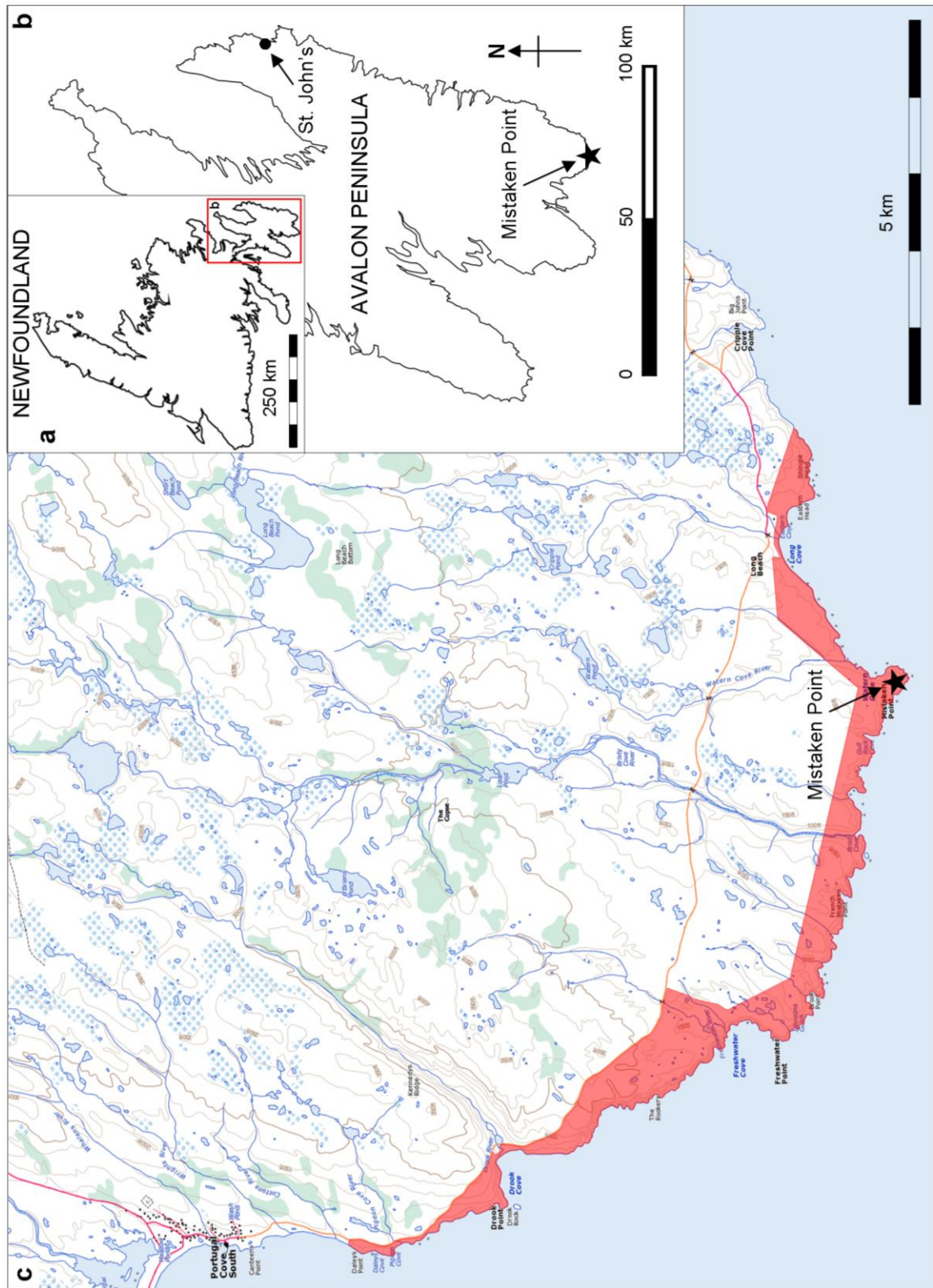


FIGURE 2.1. Locality map of the Mistaken Point Ecological Reserve. A) Map of Newfoundland. B) Map of the Avalon Peninsula showing the position of Mistaken Point and the provincial capital St. John's. C) Map of Mistaken Point region, with the Mistaken Point Ecological Reserve highlighted in red.

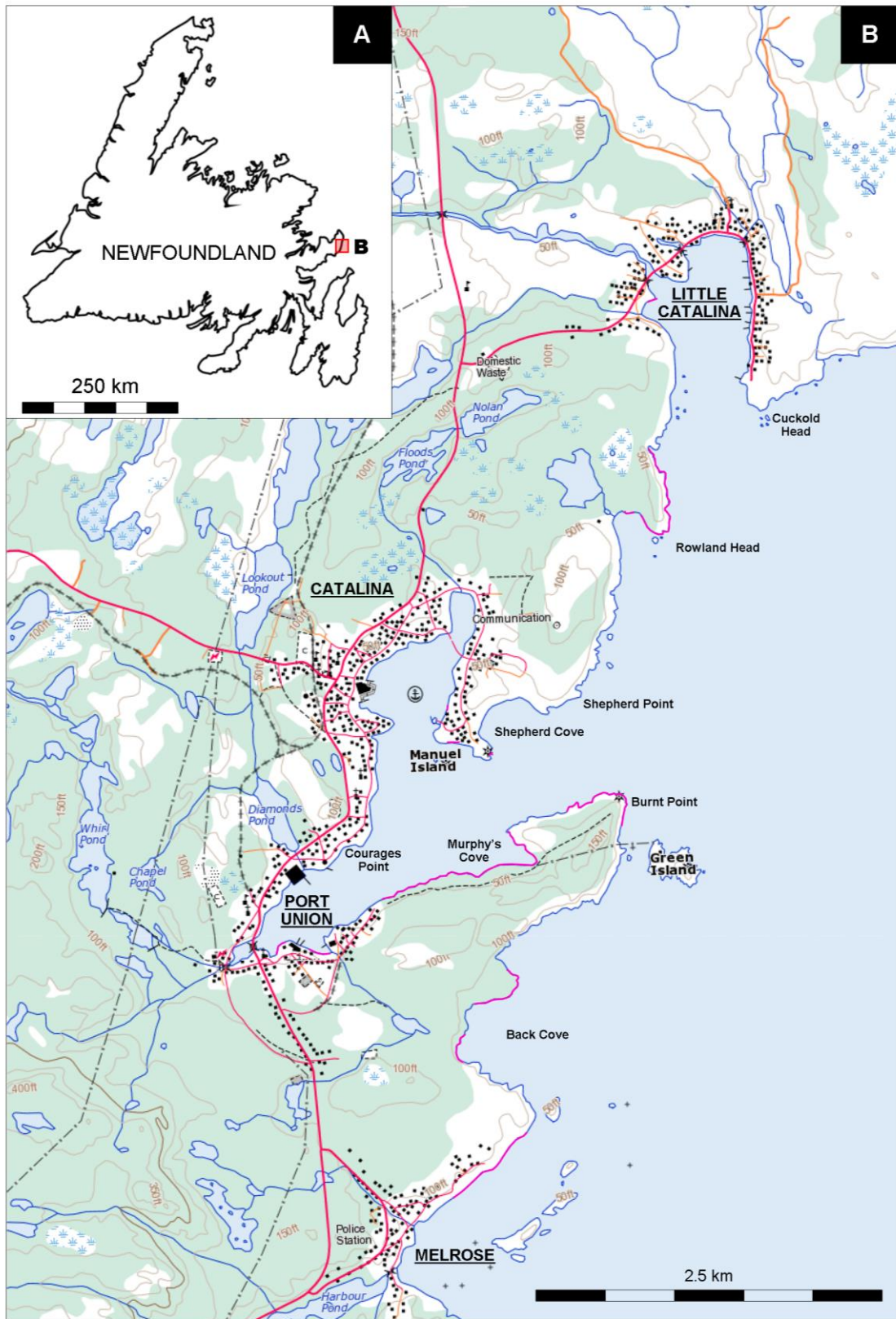


FIGURE 2.2. Locality map of the Trinity Bay North town area, formed of the settlements of Melrose, Port Union, Catalina, and Little Catalina.

subdivision and classification, and their relationship to the rocks of MPER are herein critically assessed and discussed.

## **METHODS**

The sediments of the Mistaken Point Ecological Reserve and surrounding area were mapped and studied in the field seasons from 2011-2014 (Map 1). The sediments of the Catalina Dome and surrounding area were mapped and studied in the 2011-2014 field seasons (Map 2). To assist in understanding the regional context of the succession in and around both areas, other key localities from the Avalon and Bonavista Peninsulas were also studied. GPS co-ordinates are not published for fossiliferous sites, in line with the conditions of MPER Research Permits. Bed thicknesses are described using the commonly used scheme of Ingram (1954). Bed thickness has been used as part of stratigraphic descriptions for some time (Bokman, 1957), and continues to be used as a character with which to identify stratigraphic units (e.g Mackie and Smallwood, 1987; McLoughlin and Drinnan, 1997; Hathway and Lomas, 1998; Brett and Baird, 2002; Moreno et al., 2015). Extensive fieldwork across the two areas has shown bed thickness to be useful as one among many characteristics to distinguish the units described.

The sedimentary features and depositional environments of the formations described below are detailed in Chapter 2. The geochronology of the Catalina Dome and MPER sections is discussed in Chapter 3.

## **LITHOSTRATIGRAPHY OF THE MISTAKEN POINT ECOLOGICAL RESERVE**

*Statement of Intent:* The following is an attempt to revise the Drook, Briscal, Mistaken Point, Trepassey, and Fermeuse Formations of Williams and King (1979). As this is an

unpublished DPhil thesis, the following does not constitute a formal revision, as defined by the International Stratigraphic Guide (Salvador, 1994).

### **Drook Formation**

*Name:* Drook Formation, designated after the historic settlement of Drook, which also lends its name to the nearby beach and headland, all on the Avalon Peninsula, Newfoundland.

*Type Locality and Stratotypes:* The type locality is Drook, 3 miles southeast of Portugal Cove South (Misra, 1971). The lectostratotype is defined as those rocks south of Drook Cove, between Drook Cove itself (N: 46°40'18.4" W: 053°14'34.2") and The Rookery (N: 46°39'11.60 W: 053°13'55.76"). The rocks of Pigeon Cove are designated a parastratotype, representing the more tuffaceous deposits at the top of the succession.

*Distribution, Thickness, and Boundaries:* The Drook Formation is of unknown total thickness within the Mistaken Point Ecological Reserve as the lower boundary of the formation does not crop out. The Drook Formation crops out across much of the Avalon Peninsula, and its base is best examined in the Gaskiers area. Examination of this contact shows dm-scale beds of the Drook Formation lying directly upon the Gaskiers diamictite. Only a relatively small exposure could be examined, but the contact appeared conformable.

The Drook Formation has previously been estimated to be 1500 m thick (Williams and King, 1979), though only around 770 m of this is visible in the area of the Mistaken Point Ecological Reserve (Section 1, Map 1). The base of the unit is defined as the top of the diamictite containing dropstones and striated clasts known as the Gaskiers Formation. Elsewhere the Drook Formation unconformably overlies the Harbour Main Group and

Holyrood Intrusive Suite Group, where a boulder conglomerate directly overlies the contact (O'Brien et al., 2001). The top of the formation is defined as the base of the overlying Briscal Formation, with which there is a conformable contact.

In areas of the central Avalon Peninsula, the Drook Formation is intruded by the Whalesback Gabbro, a fine to coarse-grained massive (pyroxene-plagioclase) gabbro (Williams and King, 1979). The age of this intrusion is not known, though it is not known to intrude any other formation.

*Historical Background:* The rocks now comprising the Drook Formation were first described by Joseph Beete Jukes (1843) as 'The St. John's slate', which by virtue of being mapped from Trepassy Bay to Cape Race, must have contained at least everything from the modern Drook Formation to the Fermeuse Formation. This was revised by Alexander Murray (1881), to the 'Green red and purple slates in frequent alternations' of his 'series c', within the 'Intermediate System'. Within his description of 'series c', Murray states:

*The texture of these slates is generally extremely fine, and in some cases they approach in hardness to jasper or chert.*

It is likely that this mention of chert-like rocks is in reference to rocks now within the Drook Formation. Charles Walcott (1899), while retaining the wider description of Murray's 'series c' (and therefore its extent) revised the unit to the 'Torbay slates', noting:

*It covers a great extent of country in its broad extension from cape Saint Francis to cape Race, Saint Marys bay, and across to Conception bay.*

Misra (1971), in mapping the Biscay Bay-Cape Race area erected the Drook and Freshwater Point Formations to describe the green siliceous argillites, cherts, and subordinate sandstones outcropping from Daly's Point to Big Cove. Williams and King

(1979) abandoned the Freshwater Point Formation, merging it within the Drook Formation to produce a more regionally mappable unit (Table 2.1).

*Sedimentological Description:* The Drook Formation comprises thinly to medium bedded green, grey, and pink siliceous siltstones and sandstones, with local thickly bedded sandstones. The variegated nature of the unit is characteristic (Figure 2.3; Figure 2.4A; Figure 2.5), along with white weathered surfaces, and a cherty appearance with some conchoidal fractures on fresh surfaces. The rocks are often very well indurated and difficult to break with a hammer.

Beds often exhibit normal grading, and locally shale clasts can also be found (Figure 2.3; Figure 2.4D). The lectostratotype contains a number of metre-scale silt-rich sandstone beds containing abundant rafts of reworked Drook-like material, with thicknesses representing the cm – dm thickness of the original source bed, and lengths of rafts up to 1.5 m (Figure 2.4B). These tabular rafts are sometime bent or deformed, and the ends are angular in appearance.

In places, the Drook Formation contains carbonate nodules, weathering with a distinctive punctate pattern preferential to the host lithology. Some rippled horizons are found within the lectostratotype, as well as erosional grooves (Figure 2.4C). A number of horizons showing either asymmetric ripples or erosional grooves give flow directions to the east and south east, contrary to the north easterly and south easterly flow directions suggested by Wood et al. (2003). However, only four horizons were observed and measured, compared to the 47 measurements of Wood et al. (2003) – though these are from near the base of what is a relatively thick formation.

Typical beds have a lithic arenite/greywacke composition. Quartz grains dominate, with abundant polycrystalline grains; most of volcanic origin, though some appear to originate

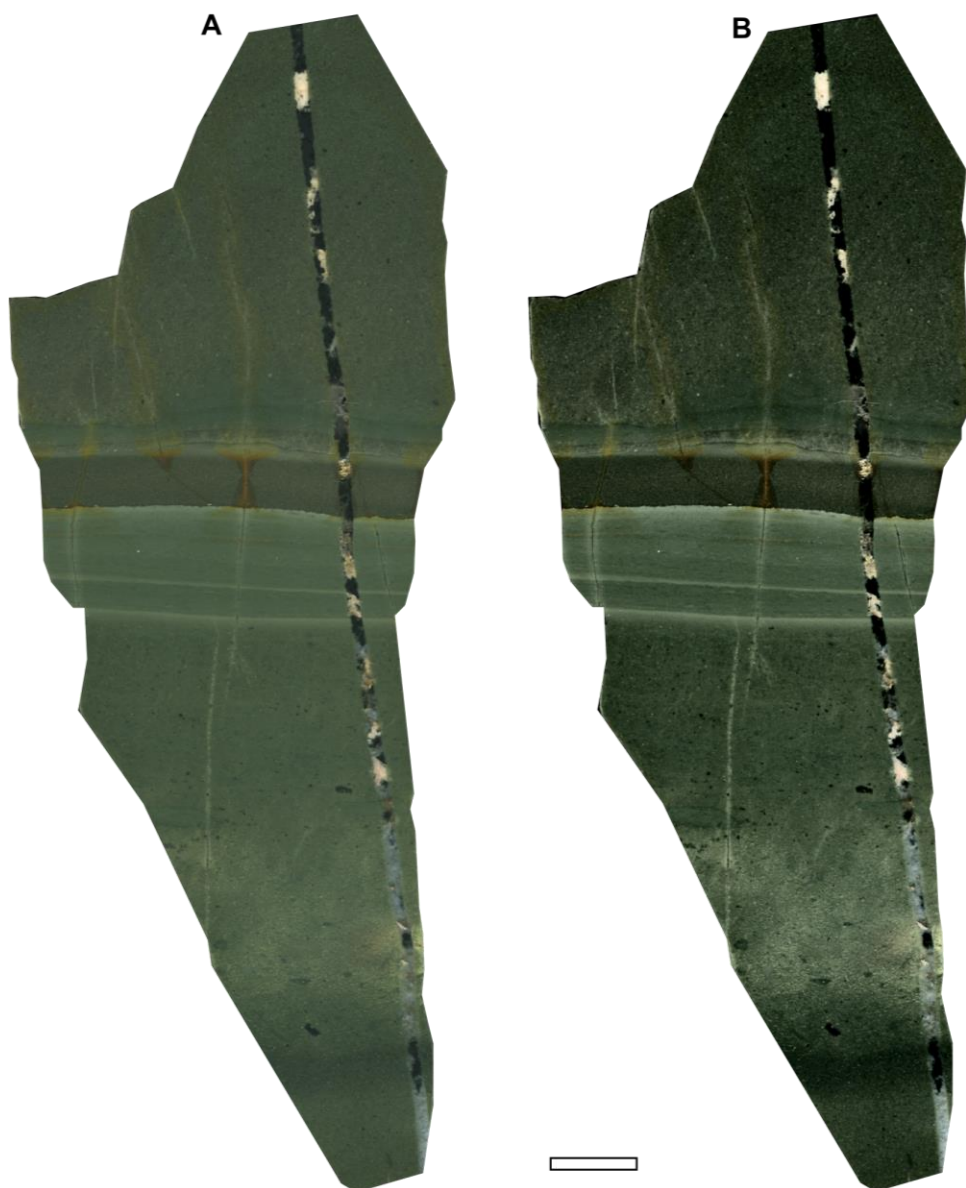


FIGURE 2.3. Slabbed section from the Drook Formation. A) True colour scan, showing variegated colours of the formation. This section is dominated by cherty sandstones and siltstones, with some rounded mud clasts. Note mineral filled fracture running vertically. B) False colour image to emphasis internal structures within the unit. Scale bar is 1 cm.

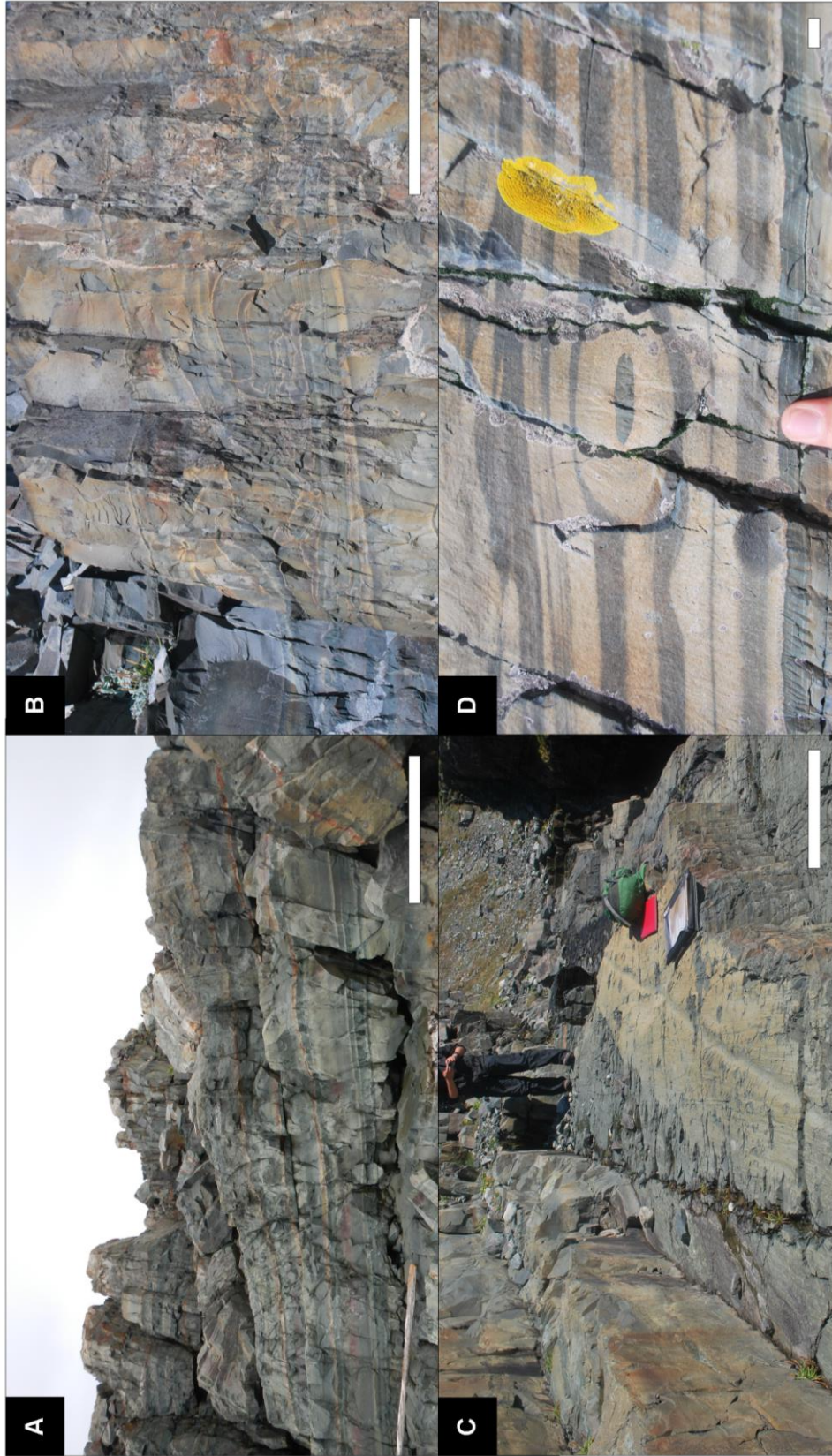


FIGURE 2.4. Drook Formation. A) Typical variegated beds of the Drook Formation from south of Pigeon Cove. Scale bar 50 cm. B) Large rafted clasts in a debris flow, Drook. Scale bar 50 cm. C) Large erosional groove, on surface covered in smaller erosion grooves, sub-parallel to the larger example. Scale bar 50 cm. D) Isolated shale clast in the Drook Formation at Drook with alteration halo. Scale bar 1 cm.

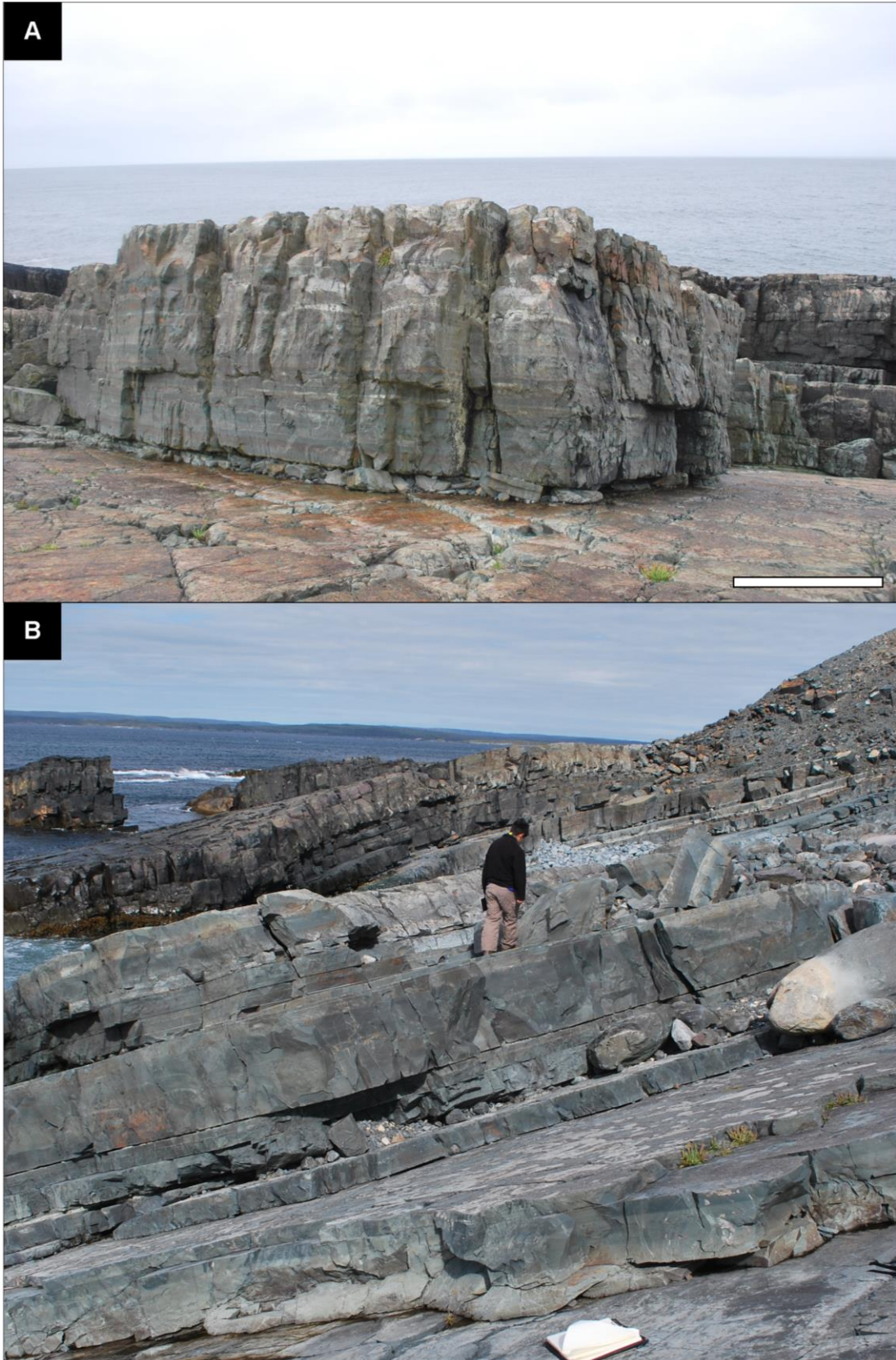


FIGURE 2.5. Supplementary photographs of the Drook Formation. A) Typical Drook Formation from the coastal outcrops to the south-east of Drook. Scale bar is 1 m. B) Typical Drook Formation south of Pigeon Cove. Note palaeontologist for scale.

from a schist (Figure 2.6A). Prismatic feldspar laths are found locally within strata, as are disperse clusters of pyrite framboids.

Fossiliferous bedding planes, limited to the top of the formation, often exhibit a rusty appearance, as do the laminations which can be observed in places. These rusty surfaces are caused by the weathering of pyrite framboids, which are ubiquitous on the fossiliferous surfaces.

The top of the unit is the most tuffaceous, with some ashy beds, identified by their buff and light green colours and cleaved nature, over 30 cm thick. The green colour is attributed to the common chloritic cement of these units. The majority of the tuffites comprise silt to mud-grade material, however several contain lapilli.

Examination of a slabbed and polished section of a representative sample of the Drook Formation shows normally graded sandstones and siltstones containing angular lithic and rounded shale clasts (Figure 2.3). The mineral-filled fracture passing vertically through the sample, and how it breaks through the shale clast, is indicative of the very well indurated nature of the rock. The red horizon in the middle of the sample effervesces when HCl is applied, indicating a carbonate cement.

A summary log from Gardiner and Hiscott (1988) for the base of the Drook Formation is given in Figure 2.7.

*Palaeontology:* The Drook Formation is host to the first complex macroscopic life, following the Neoproterozoic glaciations and associated biogeochemical perturbations (Shen et al., 2008). The fossils are restricted to the upper ~150 m of the formation, and include *Trepassia wardae* (Narbonne and Gehling, 2003), *Vinlandia antecessans* (Brasier et al., 2012), and a unique horizon with the earliest examples of juvenile

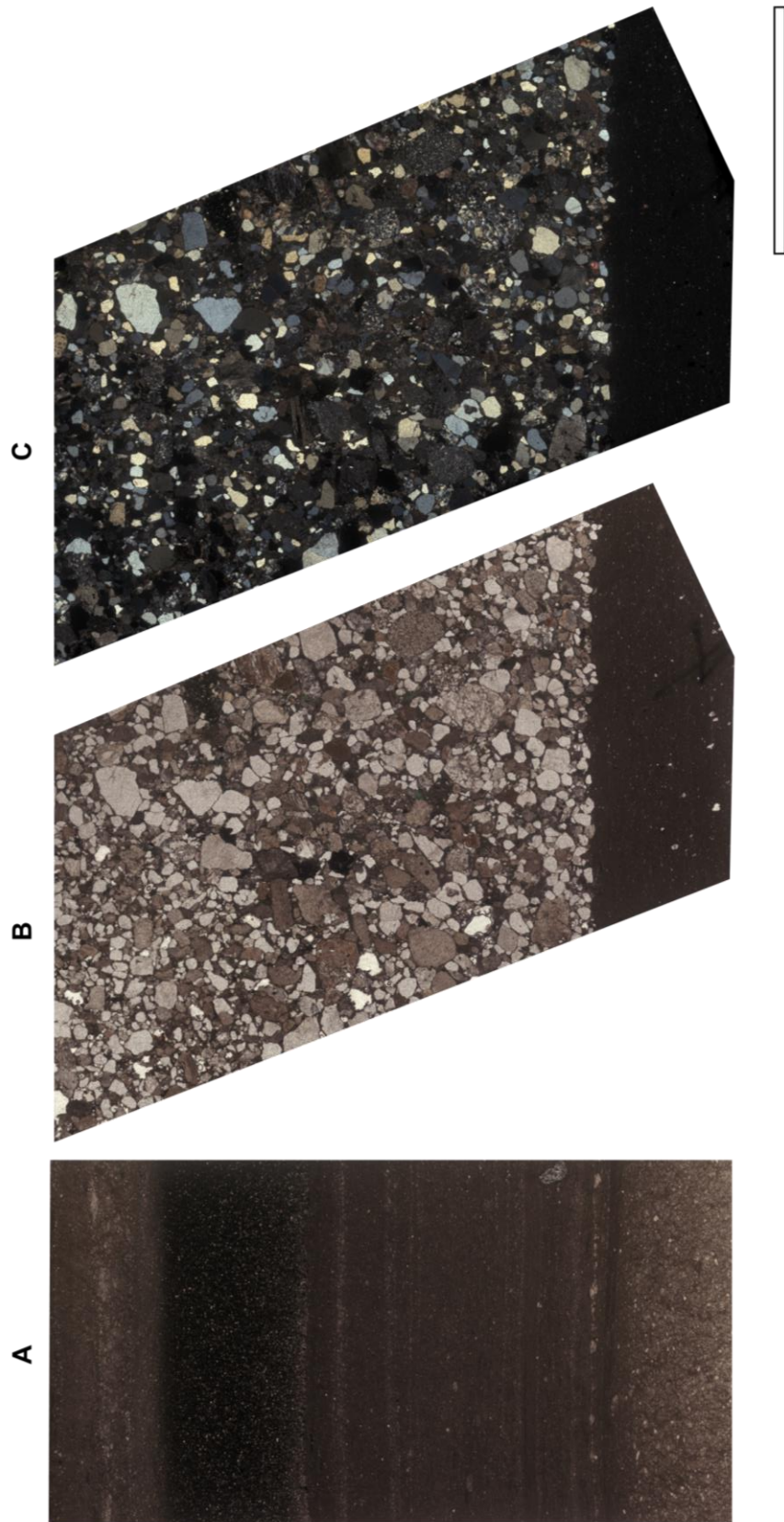


FIGURE 2.6. A) Thin section of the siltstones and fine sandstones of the Drook Formation. Plane polarized light. B) Thin section of the coarse, immature, poorly sorted, sandstones of the Briscol Formation. C) As (B) but under Cross-Polarized Light. Scale bar is 1cm.

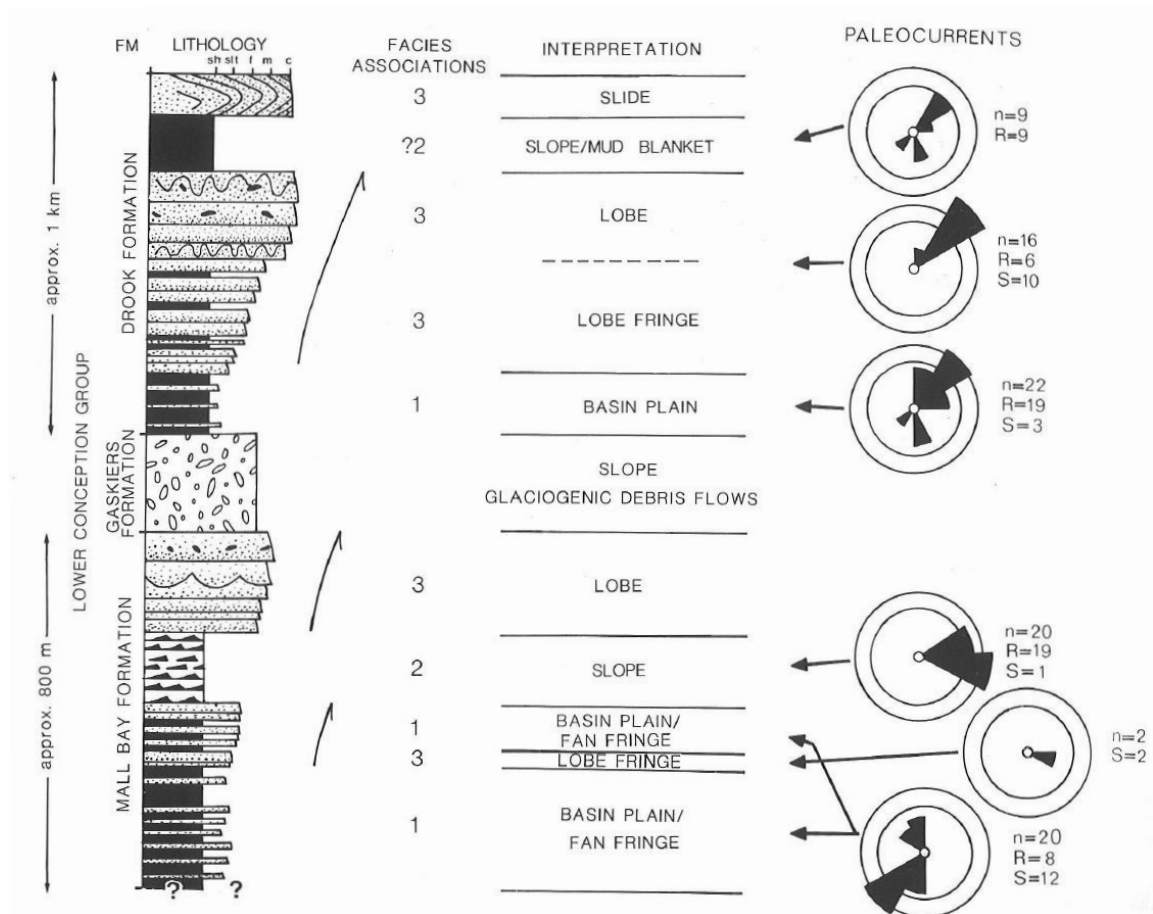


FIGURE 2.7. Summary of the stratigraphy of the lower Conception Group, reproduced from Gardiner and Hiscott (1988). Note that the section of Drook Formation show is stratigraphically below any of the Drook Formation that crops out in and around the Mistaken Point Ecological Reserve.

rangeomorphs that also exhibits the first example of secondary community succession (Liu et al., 2012).

Furthermore, this surface hosts the more notable examples of ivesheadiomorphs, thought to be the decayed remains of frondose organisms (Liu et al., 2011).

Jukes (1843)	Murray (1881)	Walcott (1899)	Misra (1971)	Williams and King (1979)	Herein
St. John's slate	'Series d'	Momable Slates	St. John's Formation	Fermeuse Formation	Fermeuse Formation
	'Series c'	Torbay Slates	Cape Cove Formation	Trepassey Formation	Trepassey Formation
				Mistaken Point Formation	Mistaken Point Formation
				Briscal Formation	Briscal Formation
			Freshwater Point Formation	Drook Formation	Drook Formation
			Drook Formation		

TABLE 2.1. Comparison of stratigraphic classifications used for the rocks of Mistaken Point Ecological Reserve. Not drawn to scale.

### **Briscal Formation**

*Name:* Briscal Formation, named after the historic fishing community of Briscal Harbour.

The settlement no longer exists, and the area is now more commonly referred to as Bristy Cove.

*Type Locality and Stratotypes:* The type locality, while not referenced in detail by Williams and King (1979) is given in the Lexicon of Canadian Geological Names (2015) as:

*Briscal Harbour (abandoned settlement), from Gull Island Point to Cape Cove, Trepassey area, southeastern Avalon Peninsula, Newfoundland.*

This type locality is problematic as it references localities that cannot be located on provincial maps within the suggested area. Confusion is likely as Gull Island Point is known from the St. Schott's area, which is also mapped as Briscal Formation (Williams and King, 1979). Cape Cove provides further problems as this name is best known from near Cape Race, where it lent its name to a formation in an earlier stratigraphic model (Misra, 1971). It is therefore proposed that the type locality for the Briscal Formation be revised to: Bristy Cove, Avalon Peninsula, Newfoundland.

The lectostratotype is designated as those rocks comprising the coastal outcrops on the western side of Bristy Cove, Avalon Peninsula, Newfoundland (N: 46°37'49.2" W: 053°11'23.4").

*Distribution, Thickness, and Boundaries:* The Briscal Formation is 310 m thick within the Mistaken Point Ecological Reserve (MPER). This is considerably thinner than the 1200 m previously cited by Williams and King (1979), likely due to the recognition of a number of folds leading to repeated section. For the purpose of the thickness calculation, it has been assumed that the throw on the fault at French Mistaken Point was 0 m, as no evidence to calculate the true throw could be obtained. Within the mapping area, the formation crops out again just north of Cape Race, where it is thinner than within MPER, and also on the northwestern side of the Freshwater Anticline (Williams and King, 1979), where its top was not observed. Outside the mapping area, the Briscal Formation crops out around the

Biscay Bay, St. Schott's, and Gull Island Synclines's. Save for a small 100 m thick section in Aquaforte Harbour (Williams and King, 1979), the formation is not known anywhere outside of the south coast of the Avalon Peninsula.

The base of the Briscal Formation is here defined as the first occurrence of sustained m-scale sandstones or grits in the succession. The top of the formation is defined as the base of the overlying, conformable, Mistaken Point Formation, with which it has a gradational contact.

*History within the Southern Avalon Peninsula:* The rocks now comprising the Briscal Formation were first described by Joseph Beete Jukes (1843) as 'The St. John's slate', which by virtue of being mapped from Trepassey Bay to Cape Race, must have contained at least everything from the modern Drook Formation to the Fermeuse Formation. This was revised by Alexander Murray (1881), first Director of the Geological Survey of Newfoundland, to the 'Green red and purple slates in frequent alternations' of his 'series c', within the 'Intermediate System'. Murray describes:

*The slate (c of section) keeps the coast exclusively to the southward of Cape Race, and round to the westward to Trepassey.*

'Series c' therefore comprises the Briscal Formation, and likely most of the Drook, Mistaken Point, and Trepassey Formations of the modern day. Charles Walcott (1899), while retaining the wider description of Murray's 'series c' (and therefore its extent) revised the unit to the 'Torbay slates', noting:

*It covers a great extent of country in its broad extension from cape Saint Francis to cape Race, Saint Marys bay, and across to Conception bay.*

Misra (1971), in mapping the Biscay Bay-Cape Race area erected the Cape Cove Formation, which would comprise all of what is now referred to as the Briscal, Mistaken

Point, and Trepassey Formations. Williams and King (1979) abandoned the Cape Cove Formation, splitting it into three formations and erecting the Briscal Formation (Table 1).

*Sedimentological Description:* The Briscal Formation is characterised by thickly and very thickly bedded, normally graded grey green and pink coarse sandstones and grits, to grey siltstones (Figure 2.8A; Figure 2.9). The base of these beds may show features such as load and flame structures and flute marks (Figure 2.8B). These diagnostic thickly bedded sandstones are interspersed among normally graded medium bedded grey to light grey fine sandstones and siltstones (Figure 2.8C; Figure 2.10). The formation contains a number of fossiliferous horizons, as well as a few highly prominent light grey-green thickly bedded tuffaceous horizons (Figure 2.8D).

Like the Drook Formation, the units of the Briscal Formation tend to have lithic arenite compositions. Grains are generally rounded to sub-rounded, and moderately to poorly sorted. Quartz grains dominate, with many exhibiting undulose extinction, deformation lamellae and kink bands. Polycrystalline quartzite grains show dynamically recrystallized fabrics, and irregular migrated grain boundaries. These deformation fabrics are indicative of quartz with a deformed, metamorphic origin – the random orientation of these fabrics within samples excludes an authigenic origin. Feldspars exhibiting deformation twinning are also present.

Rounded lithic fragments are common, and estimated to comprise ~40 % of the rock in places. The provenance of these is mixed, some as mentioned above appear to have a tectonic origin, others have a clear igneous origin, with prismatic feldspar laths abundant within an altered chlorite matrix. Sedimentary lithics are also present, including fine-grained quartzites and examples of a laminated carbonate (Figure 2.6B,C).

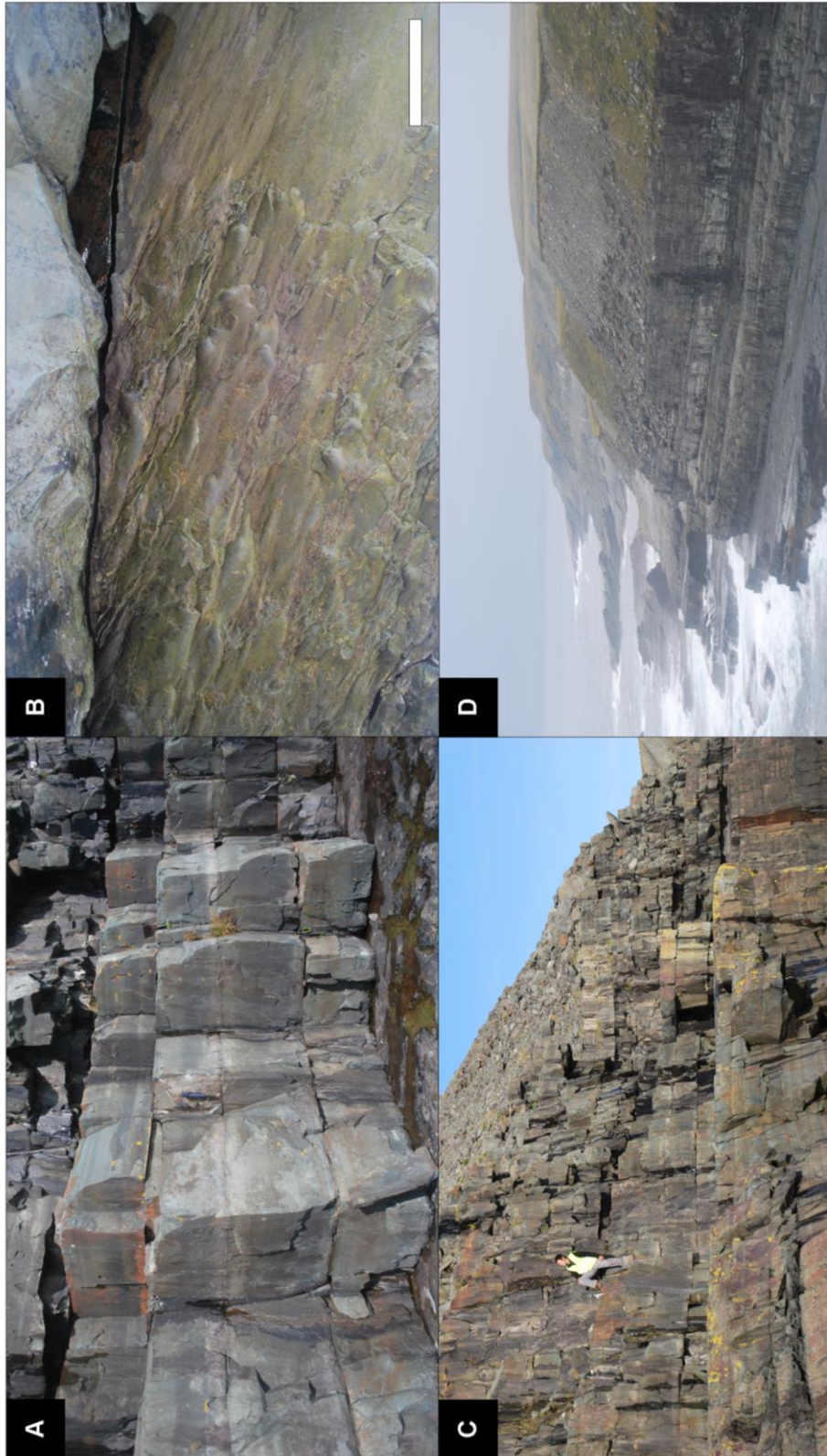


FIGURE 2.8. Briscal Formation at French Mistaken Point. A) Typical thickly-bedded normally graded sandstones of the Briscal Formation. Note geological hammer in centre for scale. B) Flute marks on the underside of a sandstone bed. Scale bar 5 cm. C) Typical exposure of Briscal Formation. Note palaeontologist for scale. D) Cliff exposure of Briscal Formation with light-grey tuffaceous horizons. Note palaeontologist in hi-vis vest for scale.

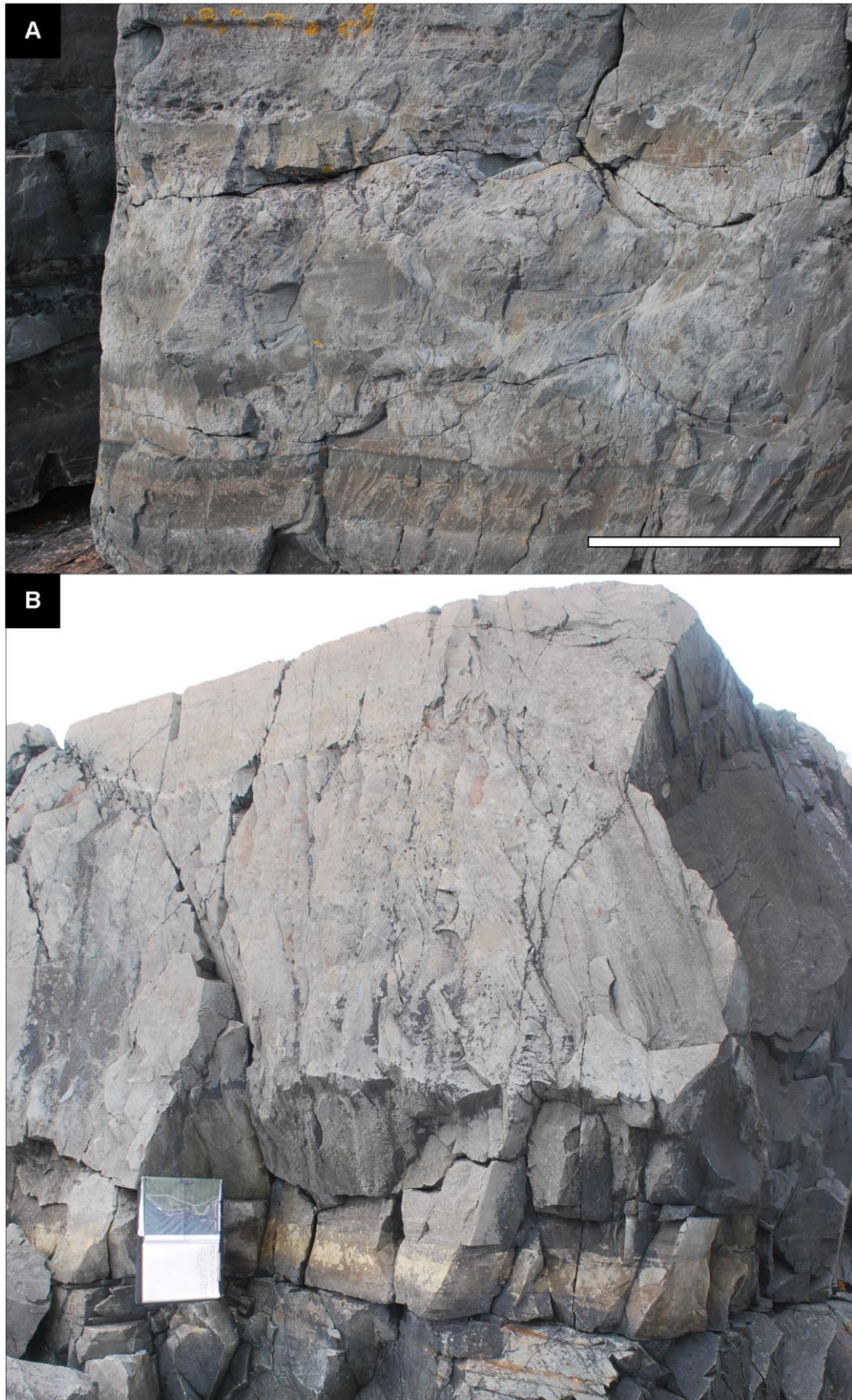


FIGURE 2.9. Supplementary photographs of the Briscal Formation. A) Typical beds of the Briscal Formation from near French Mistaken Point. Scale bar is 50 cm. B) Large, massive sandstone bed near the base of the Briscal Formation, to the north of Pigeon Cove. Note A3 clipboard (long axis is 49.5 cm) for scale.

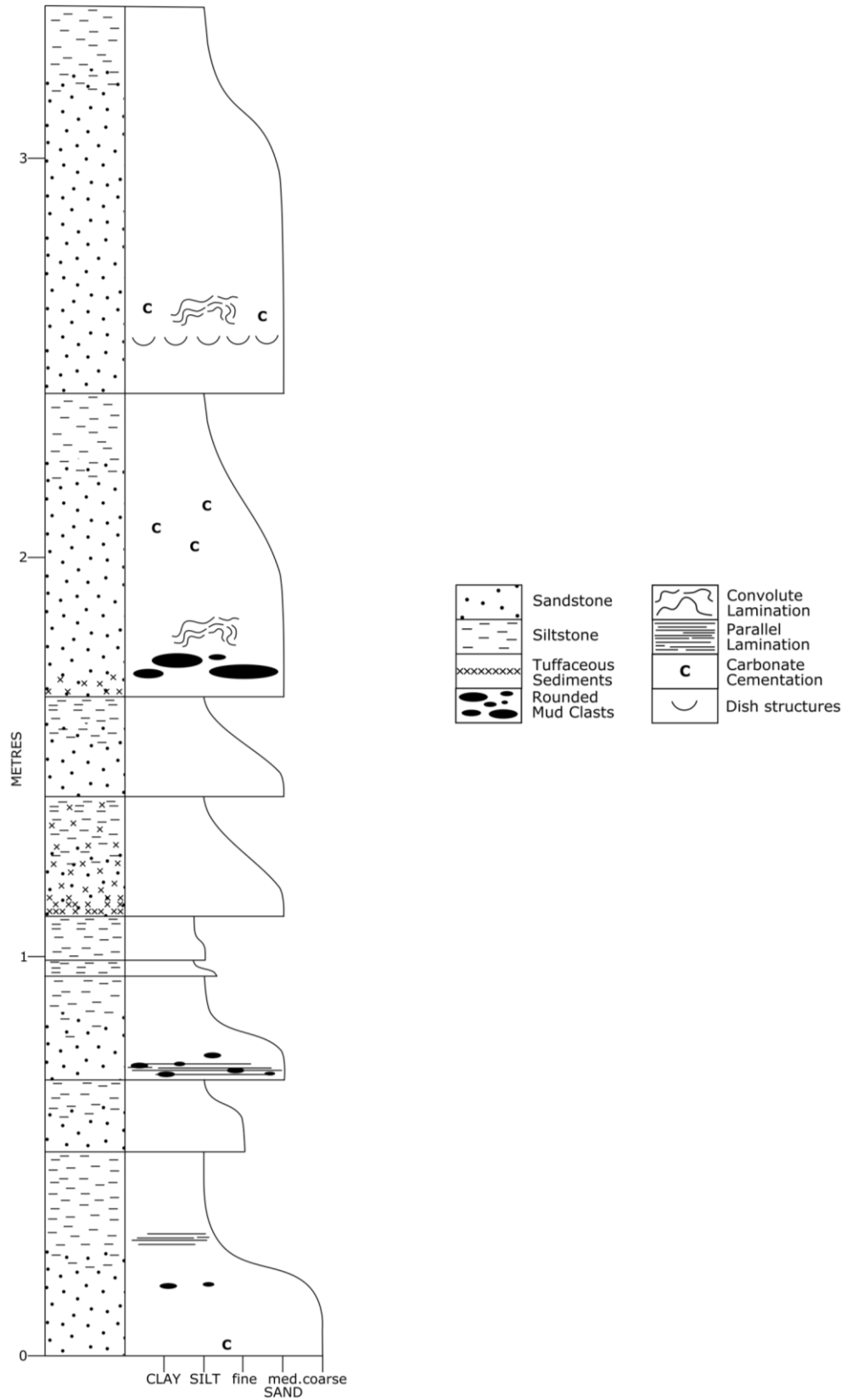


FIGURE 2.10. Sedimentary log through a section of the Briscal Formation at French Mistaken Point. The section is dominated by thickly-bedded, normally-graded light-green and grey sandstones. These sandstones often show zones of parallel lamination, carbonate cementation, rounded shale clasts, and dewatering structures and convolute lamination. There are occasional thinly and medium-bedded siltstones.

Cements vary, but include chlorite and carbonate. Pyrite framboids are commonly found within the matrix between grains. Inter-grain concavo-convex boundaries indicate post deposition pressure solution, representative of burial metamorphism.

A 55 cm thick slabbed section through a representative bed of the Briscal Formation shows a basal ~2 cm thick parallel laminated medium sandstone that is overlain by a 28 cm thick zone of coarse, moderately sorted sandstone that is normally graded (Figure 2.11). The upper ~10 cm of this zone is a fine sandstone, with 2 – 5 mm diameter rounded shale clasts, the alignment of which, in addition to the clear laminations at the very top of the zone, suggest cross-lamination. This is overlain by a 21 cm thick coarse siltstone that transitions to a fine siltstone ~12 cm from the base of this zone. The base of this siltstone contains a number of discontinuous and broken interbeds between the siltstone and the underlying sandstone. Load and dish structures are seen in this interbedded zone. The coarse siltstone is mostly homogenous, save for dish and dewatering structures highlighted by their sandier composition. The fine siltstone at the top is mostly without structure, but is peppered by many white fine sand grains. These dispersed white grains persist into the top 4 cm of the bed, comprising a very finely laminated dark green mudstone, with occasional collections of silt-grade material highlighting particular lamellae. A number of *Aspidella* specimens are found preserved on top of this laminated green mudstone layer. Flute marks from the base of this unit suggest a north-westerly flow direction. Noting this is a measurement from one horizon, this is in contrast to the north-easterly direction given by Narbonne et al. (2001), from an unknown number of measurements.

*Palaeontology:* The Briscal Formation has been considered to be mostly unfossiliferous, with specimens of *Charnia*, *Fronndophyllas*, *Fractofusus*, *Aspidella*, *Beothukis* and *Bradgatia* being described from a limited number of small bedding planes isolated to



FIGURE 2.11. Slabbed section from the Briscal Formation. A) Section showing normally graded sandstones with shale clasts, dewatering structures, and possible amalgamation surface. B) False colour image to emphasise features. Scale bar is 10 cm.

Bristy Cove (Clapham et al., 2003; Gehling and Narbonne, 2007; Flude and Narbonne, 2008; Bamforth and Narbonne, 2009). However, over the course of this study, and during the fieldwork of Liu (2011), a number of new fossil-bearing surfaces have been discovered throughout the formation, greatly extending the known stratigraphic range of taxa including *Fractofusus*, *Charniodiscus*, *Primocandelabrum*, and *Culmofrons*.

### **Mistaken Point Formation**

*Name:* Mistaken Point Formation, named after the small promontory on the south eastern coast of the Avalon Peninsula of Newfoundland. The headland's name recognises how sailors would confuse it with Cape Race, thereby turning north toward St. John's too soon, and foundering on the rocks.

*Type Locality and Stratotypes:* The type locality, while not referenced specifically in Williams and King (1979) is in the Lexicon of Canadian Geological Names (2015) as:

*Mistaken Point to about 1 km west in coastal cliffs of Trepassey Bay, southern Avalon Peninsula, Newfoundland.*

This type locality, while more specific than that given in the original publication, is now unsatisfactory due to the presence of Trepassey Formation within this section, as seen in the new map of the area (Map 1). It is therefore proposed that the type locality for the Mistaken Point Formation be revised to: The coastal cliffs on the south-west side of the Mistaken Point promontory, Avalon Peninsula, Newfoundland.

The lectostratotype is defined as those rocks from the head of Laurentian Gulch (a small cove that contains a fault that separates Mistaken Point from the mainland, N: 46°37'40.7" W: 053° 09'56.9"W) to the Mistaken Point F-Surface (Benus, 1988) (Map 1).

*Distribution, Thickness, and Boundaries:* The Mistaken Point Formation is 290 m thick within the Mistaken Point Ecological Reserve, and also underlies a strip of land to Cape Cove (Map 1), just north of Cape Race, where it is thinner than in MPER. Outside of the Mistaken Point Ecological Reserve, the Mistaken Point Formation is also known to outcrop at the back of the Trepassey Bay, and also in a syncline centred around St. Shott's. There are also several confirmed outcrops from the eastern coast of the Avalon Peninsula, as far north as Tor Bay (King, 1990). While the Mistaken Point Formation has also been mapped as outcropping on the Bay de Verde and Bonavista Peninsulas, this will be discussed in a later chapter.

The base of the formation is defined as the transition to medium bedded sandstones and siltstones, from the dominant thickly and very thickly bedded sandstones of the underlying Briscal Formation. The boundary is gradational. The top of the formation corresponds to the base of the overlying Trepassey Formations, with which there is a conformable and gradational boundary.

*History within the Southern Avalon Peninsula:* The rocks now comprising the Mistaken Point Formation were first described by Joseph Beete Jukes (1843) as The St. John's slate, which by being mapped from Trepassey Bay to Cape Race, must have contained at least everything from the modern Drook Formation to the Fermeuse Formation. This was revised by Alexander Murray (1881), first Director of the Geological Survey of Newfoundland, to the 'Green red and purple slates in frequent alternations' of his 'series c', within the 'Intermediate System'. Murray describes:

*The slate (c of section) keeps the coast exclusively to the southward of Cape Race, and round to the westward to Trepassey.*

‘Series c’ therefore comprises the Mistaken Point Formation, and likely most of the Drook, Briscal and Trepassey Formations of the modern day. Murray’s description of *Oldhamia* from these rocks was rejected in subsequent years as likely representing concretions (Weston, 1892).

Charles Walcott (1899), while retaining the wider description of Murray’s ‘series c’ (and therefore its extent) revised the unit to the ‘Torbay slates’, noting:

*It covers a great extent of country in its broad extension from cape Saint Francis to cape Race, Saint Marys bay, and across to Conception bay.*

Misra (1971), in mapping the Biscay Bay-Cape Race area erected the Cape Cove Formation, which would comprise all of what is now referred to as the Briscal, Mistaken Point, and Trepassey Formations. Williams and King (1979) abandoned the Cape Cove Formation, splitting into three formations, including the Mistaken Point Formation (Table 1).

*Sedimentological Description:* The Mistaken Point Formation comprises thick beds of graded, sometimes convolute, turbiditic medium to fine purple, green and grey sandstones graded into grey-green siltstones (Figure 2.12; Figure 2.13; Figure 2.14). While these units are most diagnostic, it is dominated by thin to medium bedded grey, green and occasionally purple graded siltstones. Many bedding planes are coated in light grey-green tuffaceous material, which is often preferentially cleaved compared to the surrounding beds. Rounded shale clasts are locally present in the thicker beds. The top of the formation, and the base overlying Trepassey Formation, contain a number of large m-scale beds containing angular cobble-sized clasts of tuffaceous material (Figure 2.11B). Zones of carbonate cementation are common throughout the Mistaken Point Formation. A log from Wood et al. (2003) is modified in Figure 2.15.

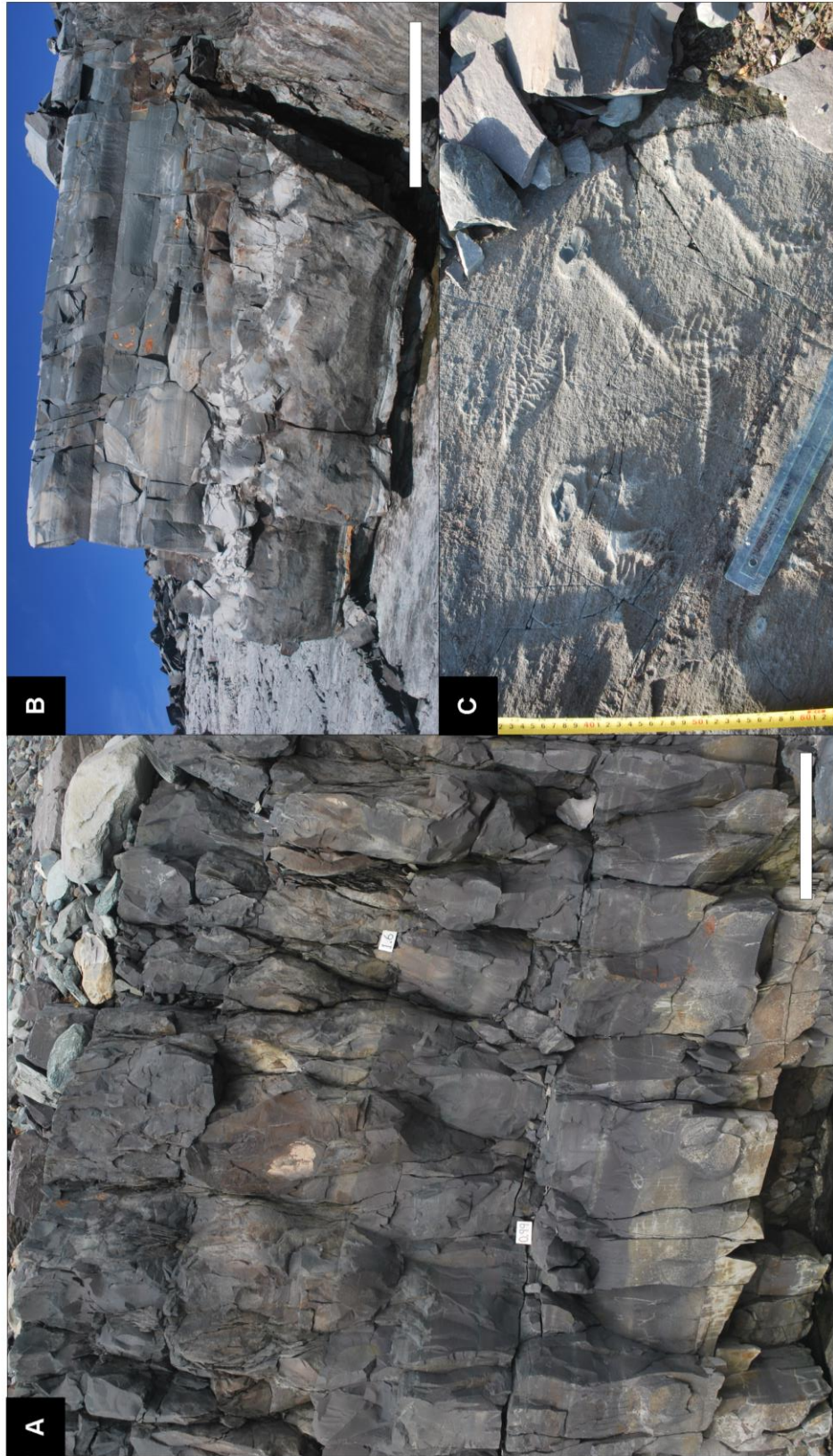


FIGURE 2.12. Mistaken Point Formation at Mistaken Point. A) Typical beds of the Mistaken Point Formation, between the D- and E- fossiliferous surfaces. Scale bar is 50 cm. B) Isolated linked-debrite deposit containing angular cobble-sized clasts of tuffite. Scale bar is 50 cm. C) Example of the E-Surface fossil horizon in the Mistaken Point Formation. Note ruler and tape measure with 1 cm gradations.



FIGURE 2.13. Supplementary photographs of the Mistaken Point Formation. A) Typical beds of the upper Mistaken Point Formation with debrite at the top. From north-east of Watern Cove. Scale bar is 50 cm. B) Typical beds of the Mistaken Point Formation from around the 'B' Surface. Note buff coloured tuffite, and deformed bedding due to a fault. Note geochemist for scale.

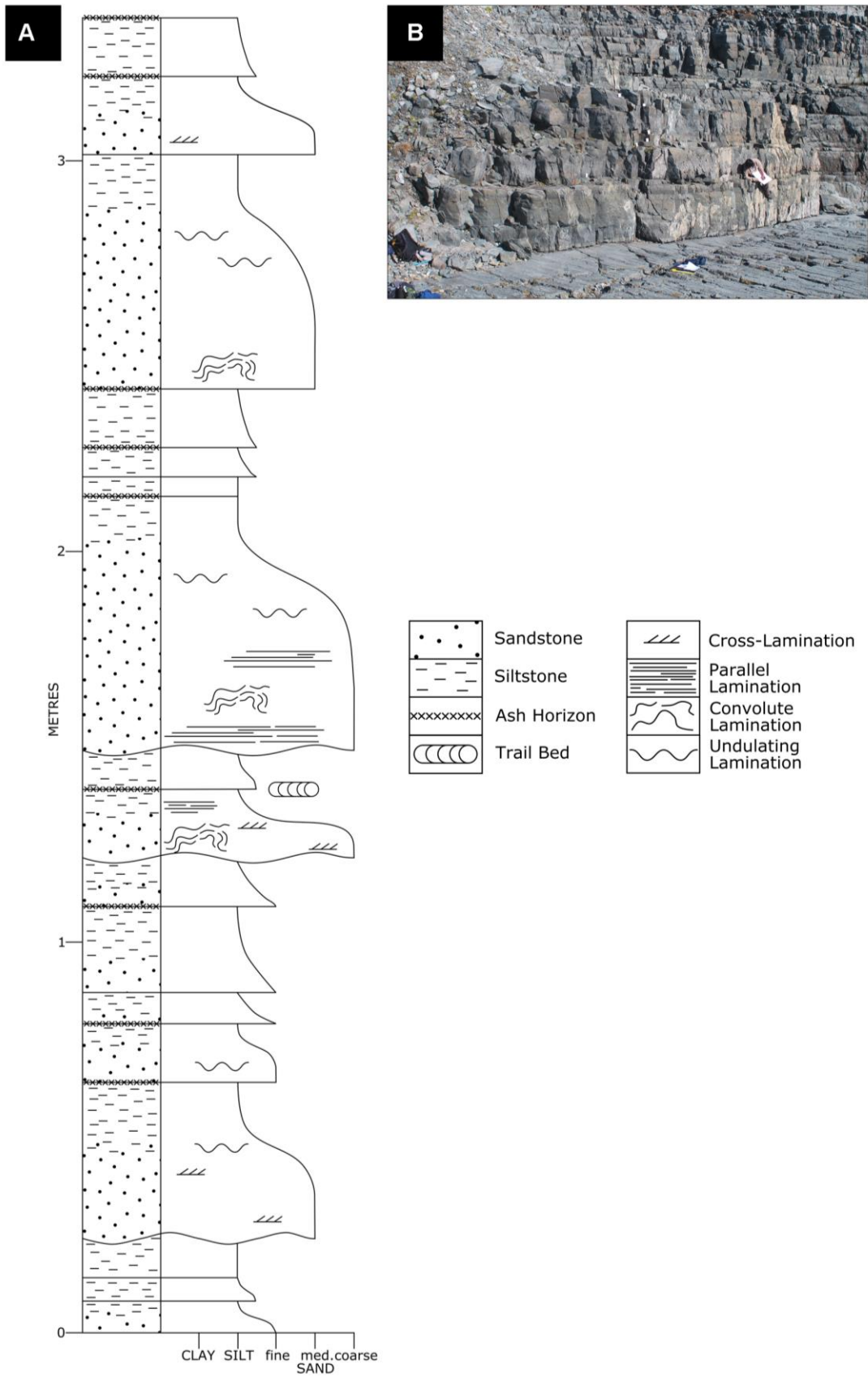


FIGURE 2.14. A) Log through part of the upper Mistaken Point Formation at Mistaken Point, including the trail-bearing horizon described in Liu et al. (2014). B) Photograph of the section logged in (A). Note diminutive palaeontologist for scale, sitting on the trace fossil horizon.

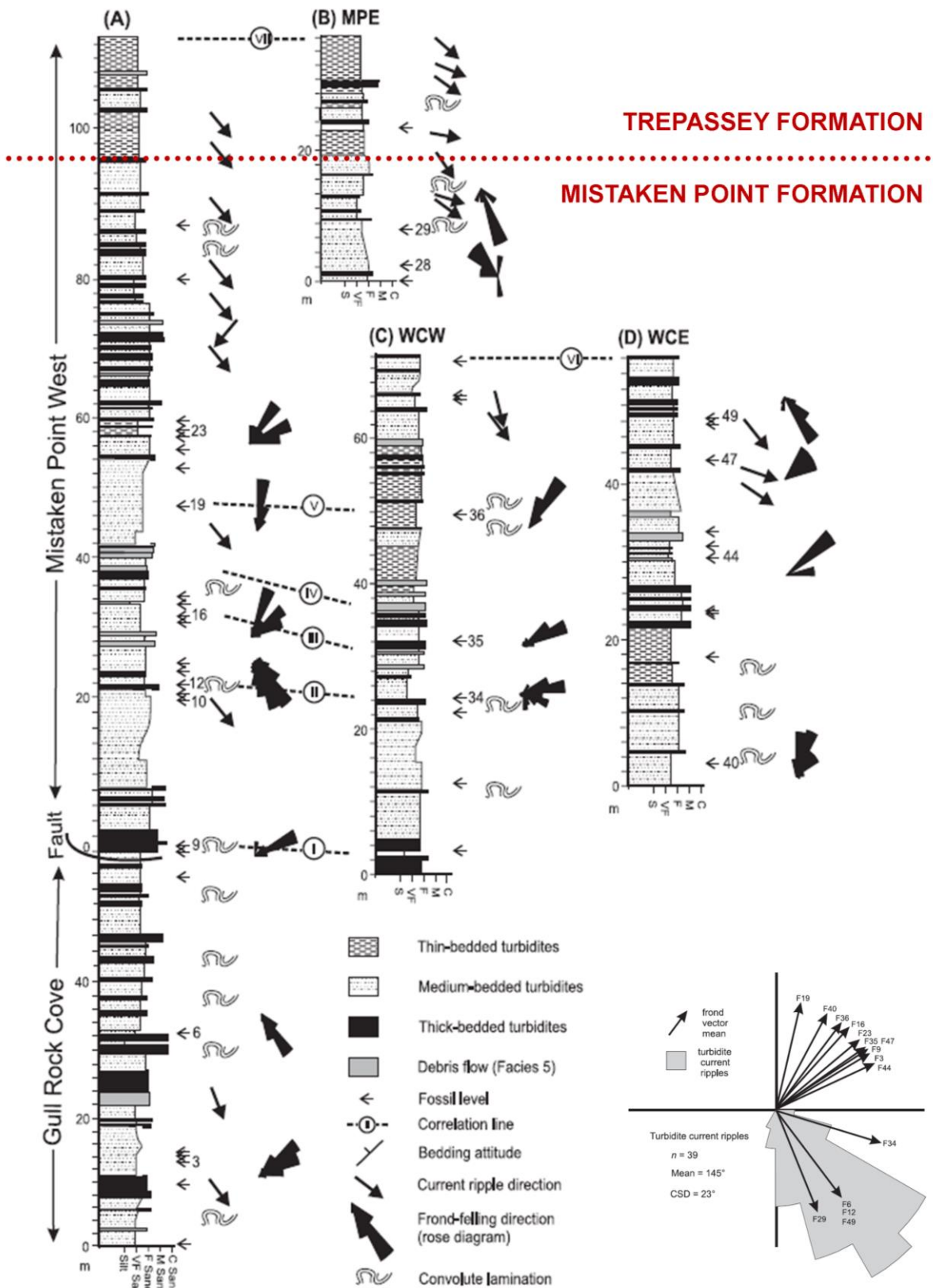


FIGURE 2.14. Log of the upper Mistaken Point Formation reproduced from Wood et al. (2003). Revisions to boundaries are shown in red. Frond alignment directions and turbidite current flow directions from Wood et al. (2003) for the Mistaken Point are given in the rose diagram. A) Mistaken Point West, B) Mistaken Point East. C) Watn Cove West. D) Watn Cove East. Scale in metres.

The Mistaken Point Formation has a more sublithic arenite composition than the underlying formations. Dominated by sub-rounded quartz, there are minor amounts of rounded lithic fragments and feldspars (Figure 2.15A). The cement is a mixture of chlorite and silica. Pyrite framboids can be found locally.

A slabbed section from directly below the Mistaken Point 'Yale' Outcrop of the fossiliferous 'D' Surface records typical beds within the Mistaken Point Formation (Figure 2.16). 15 cm thick, the bottom 5 cm shows a purple, parallel laminated fine sandstone, with an area rich in muddy wisps at the top of this zone. These wisps may represent compacted, elongate shale clasts. Above this is a 3 cm thick zone of cross-laminated fine to very fine sandstone. This is overlain by a 5.5 cm thick normally graded purple siltstone with parallel laminations at the base. The unit is capped by a 1.5 cm thick olive green layer of very thinly laminated mudstone with a local isolated and some collections of silt-grade clasts. It is on top of this olive green layer that the fossils or the 'D' Surface are preserved.

A similar succession is seen in the rocks immediately below the 'E' Surface at the same locality (Figure 2.17). The 30 cm thick slabbed section records two beds. The lower, ~16 cm thick unit has an ~6 cm thick purple normally graded fine sandstone base which is overlain by ~8 cm thick purple normally graded siltstone with thin parallel laminations at the bottom. The boundary between the sandstone and siltstone is notably stepped in one place, with the space left by the creation of this step filled in by non-laminated siltstone, and the beds above remaining non-stepped. This is suggestive of a syn-depositional deformation of some kind. The ~16 cm thick lower bed is capped by a 2 cm thick layer of olive green very thinly laminated mudstone with local isolated and some agglomerations of silt grains. The upper 14 cm thick bed comprises purple parallel laminated fine sands normally graded into a purple siltstone. The top 1.5 cm of the bed is a very thinly



FIGURE 2.15. Thin sections from the Mistaken Point Formation. A) Cross-laminated sandstone from between the 'D' and 'E' Surfaces at Mistaken Point. B) Chloritic crystal-tuff that lies directly upon the fossiliferous 'E' Surface. Scale bars are 1 cm.

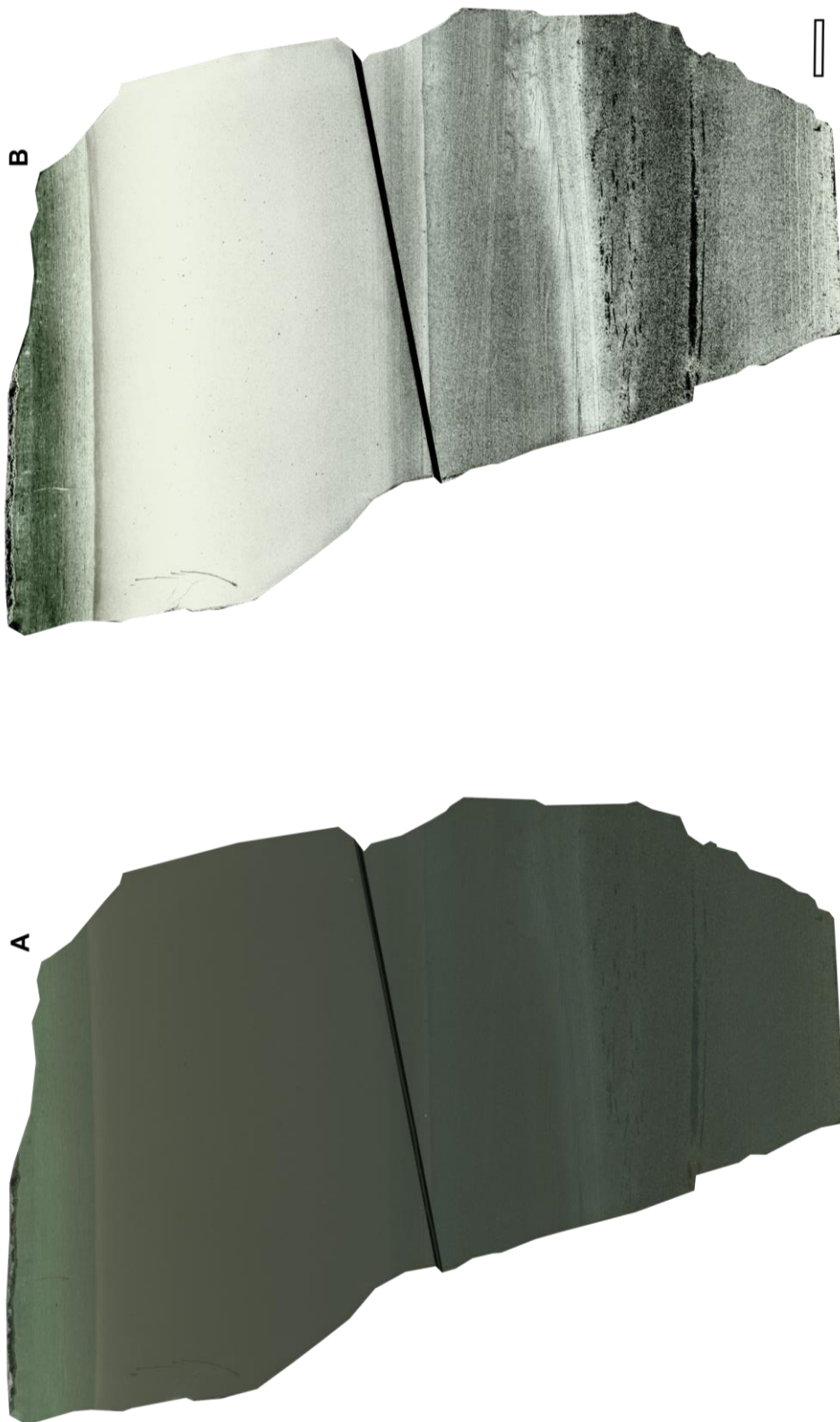


FIGURE 2.16. Slabbed and polished section of sediments underlying the 'D' Surface. A) True colour scan of the normally graded fine sandstone and siltstone turbidite directly underlying the fossiliferous 'D' Surface. Green layer at the top interpreted as a possible contourite deposit. B) False colour image to help emphasise internal structures within the horizons. Note mud clasts and cross-lamination. Scale bar is 1 cm.



FIGURE 2.17. Slabbed section of the sediments underlying the Mistaken Point 'E' Surface. A) True colour scan of the two turbidites underlying the fossil surface, each turbidite capped by a green possible contourite layer. B) False colour image to help emphasise internal structures. Scale bar is 1cm.

laminated olive green mudstone with local isolated and some agglomerations of silt grains. The fossils of the 'E' Surface lie directly on top of this layer.

*Palaeontology:* The Mistaken Point Formation is well known for its fossil-bearing bedding planes (Figure 2.12C). While the majority of the known fossiliferous outcrops are towards the top of the formation, they are known from throughout the unit. It is likely that this difference in density of fossil bearing surfaces is a product of accessibility. The Mistaken Point Formation is the most taxonomically diverse of all the formations described herein, containing *Aspidella*, *Hiemalora*, *Charnia*, *Vinlandia*, *Charniodiscus*, *Beothukis*, *Culmofrons*, *Trepassia*, *Fronidophyllas*, *Pectinifrons*, *Fractofusus*, *Hadryniscalca*, *Hapsidophyllas*, *Bradgatia*, and *Thectardis*, as well as the one of the oldest examples of locomotion from the Ediacaran (Liu et al., 2010).

### **Trepassey Formation**

*Nomenclature:* Designated after the historic fishing community of Trepassey on the southern shore of the Avalon Peninsula, Newfoundland, where the type section is to be found.

*Type Locality and Stratotypes:* The originator of the formation gave the designated type section as 'Trepassey Harbour' (Williams and King, 1979), with the Lexicon of Canadian Geological Names (2015) stating the type locality as:

*Powles Peninsula, southeast Trepassey Harbour, southern Avalon Peninsula, Newfoundland.*

The lectostratotype is defined as those rocks cropping out on the eastern and southern side of the Powles Peninsula, Trepassey Harbour (N: 46°42'03.6" W:053°23'19.1").

*Distribution, Thickness, and Boundaries:* The Trepassey Formation is 240 metres thick at its outcrop within Watern and Long Coves. It also crops out again within the mapping area, just north of Cape Race.

More broadly, the formation crops out in a number of places up the east coast of the Avalon Peninsula, as far north as Torbay. It has been suggested by some that the Trepassey Formation also crops out again on the Bay de Verde (Ichaso et al., 2007) and Bonavista (O'Brien and King, 2004) Peninsulas, but this will be examined in later chapters.

The base of the Trepassey Formation is defined by the transition from the thickly bedded deposits of the Mistaken Point Formation to thinly bedded units. This transition is gradational. The top of the formation is delineated as the base of the overlying Fermeuse Formation, which conformably lies above this unit.

*History within the Southern Avalon Peninsula:* The rocks now comprising the Trepassey Formation were first described by Joseph Beete Jukes (1843) as The St. John's slate, which by being mapped from Trepassey Bay to Cape Race, must have contained at least everything from the modern Drook Formation to the Fermeuse Formation. This was revised by Alexander Murray (1881), first Director of the Geological Survey of Newfoundland, to the 'Green red and purple slates in frequent alternations' of his 'series c', within the 'Intermediate System'. Murray describes:

*The slate (c of section) keeps the coast exclusively to the southward of Cape Race, and round to the westward to Trepassey.*

'Series c' therefore comprises the Trepassey Formation, and likely most of the Drook, Briscal and Mistaken Point Formations of the modern day. Murray's description of *Oldhamia* from these rocks was rejected in subsequent years as likely representing concretions (Weston, 1892).

Charles Walcott (1899), while retaining the wider description of Murray's 'series c' (and therefore its extent) revised the unit to the 'Torbay slates', noting:

*It covers a great extent of country in its broad extension from cape Saint Francis to cape Race, Saint Marys bay, and across to Conception bay.*

Misra (1971), in mapping the Biscay Bay-Cape Race area erected the Cape Cove Formation, which would comprise all of what is now referred to as the Briscal, Mistaken Point, and Trepassey Formations. Williams and King (1979) abandoned the Cape Cove Formation, splitting into three including the Trepassey Formation (Table 1).

*Sedimentological Description:* The Trepassey Formation is dominated by thinly bedded grey siltstones with occasional cross-laminated, carbonated cemented, starved ripple sandstones at the base of units (Figure 2.18; Figure 2.19). There is no abrupt change from the Mistaken Point Formation; it is a gradational thinning of beds and fining of sediment. The lower part of the formation contains a number of distinctive but rare thickly bedded debris flows. These are also known from the upper part of the Mistaken Point Formation, and are indicative of stratigraphic proximity to the Mistaken Point – Trepassey Formation boundary. Tuffite beds are less well known in the Trepassey Formation, than in the underlying Mistaken Point Formation. A revised log from Wood et al. (2003) is shown in Figure 2.20.

A slabbed section of beds from the Trepassey Formation, sampled from the outcrops around Cape Race, records a number of complete and partial 2 – 5 cm thick beds (Figure 2.19). It is important to note that this is at the thinner end of the thickness of bedding seen in the Trepassey Formation, and is more typical of the upper part of the formation. The sequence through the slab from base to top is as follows: greeny-purple siltstone of unknown complete thickness capped by 1 cm thick green very thinly parallel laminated



FIGURE 2.18. Trepassey Formation. A) Typical section of the Trepassey Formation from the Mistaken Point headland, showing thin beds of graded siltstone, with minor sandstone units. Note A3 clipboard for scale. B+C) 'Crinkly' carbonate layer (white arrows) with overlying convolute bedded sandstones with pyritic carbonate cementation used for lithostratigraphic correlation. (B) is from Mistaken Point, note pen for scale. (C) is from Long Cove, note A3 clipboard for scale.

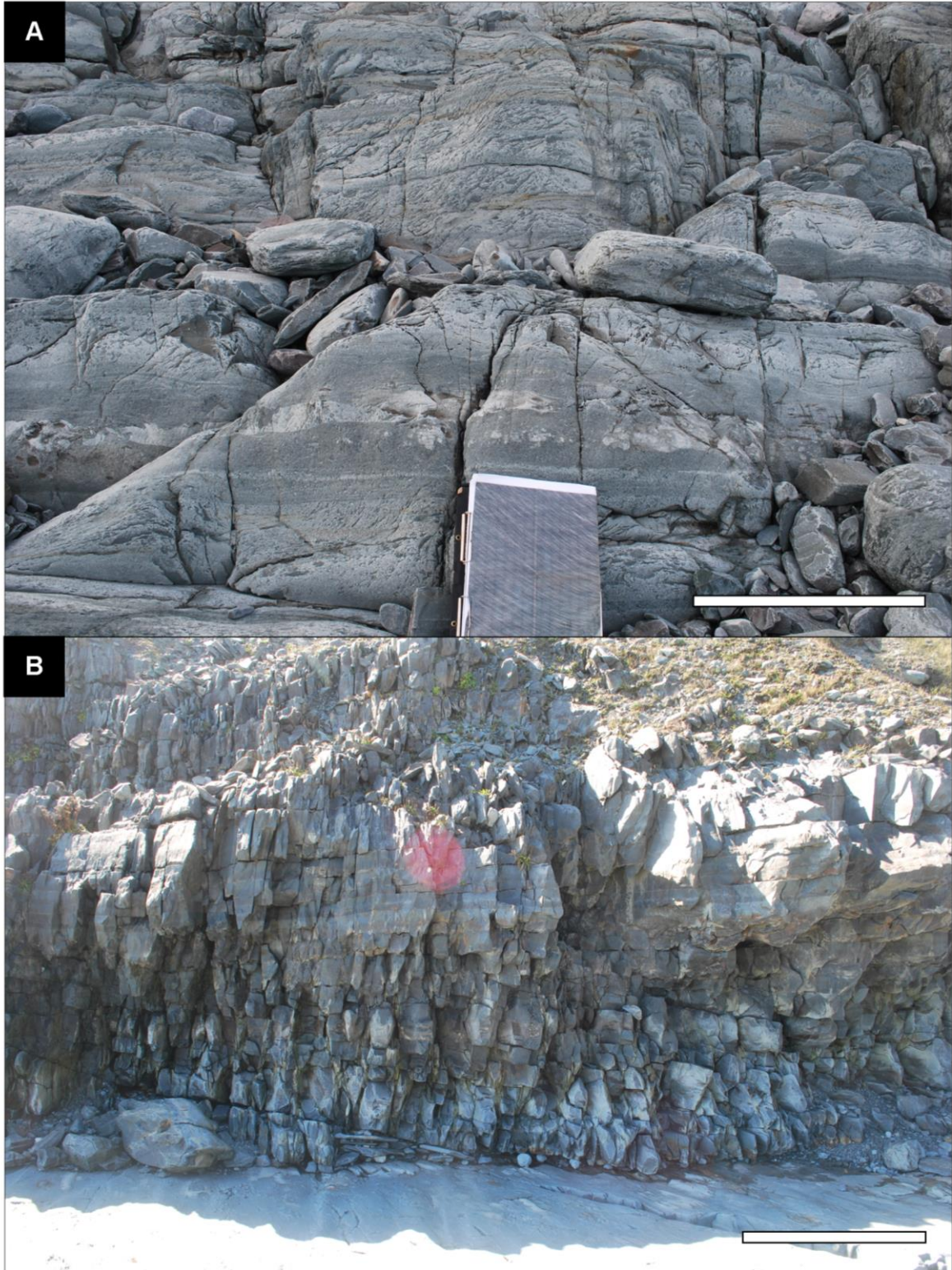


FIGURE 2.19. Supplementary photographs of the Trepassey Formation. A) Typical grey siltstones with minor sandstones from Long Cove. Scale bar is 50 cm. B) Cliff section of the Trepassey Formation from above the surface known as the 'Pizzeria'. Scale bar is 50 cm.

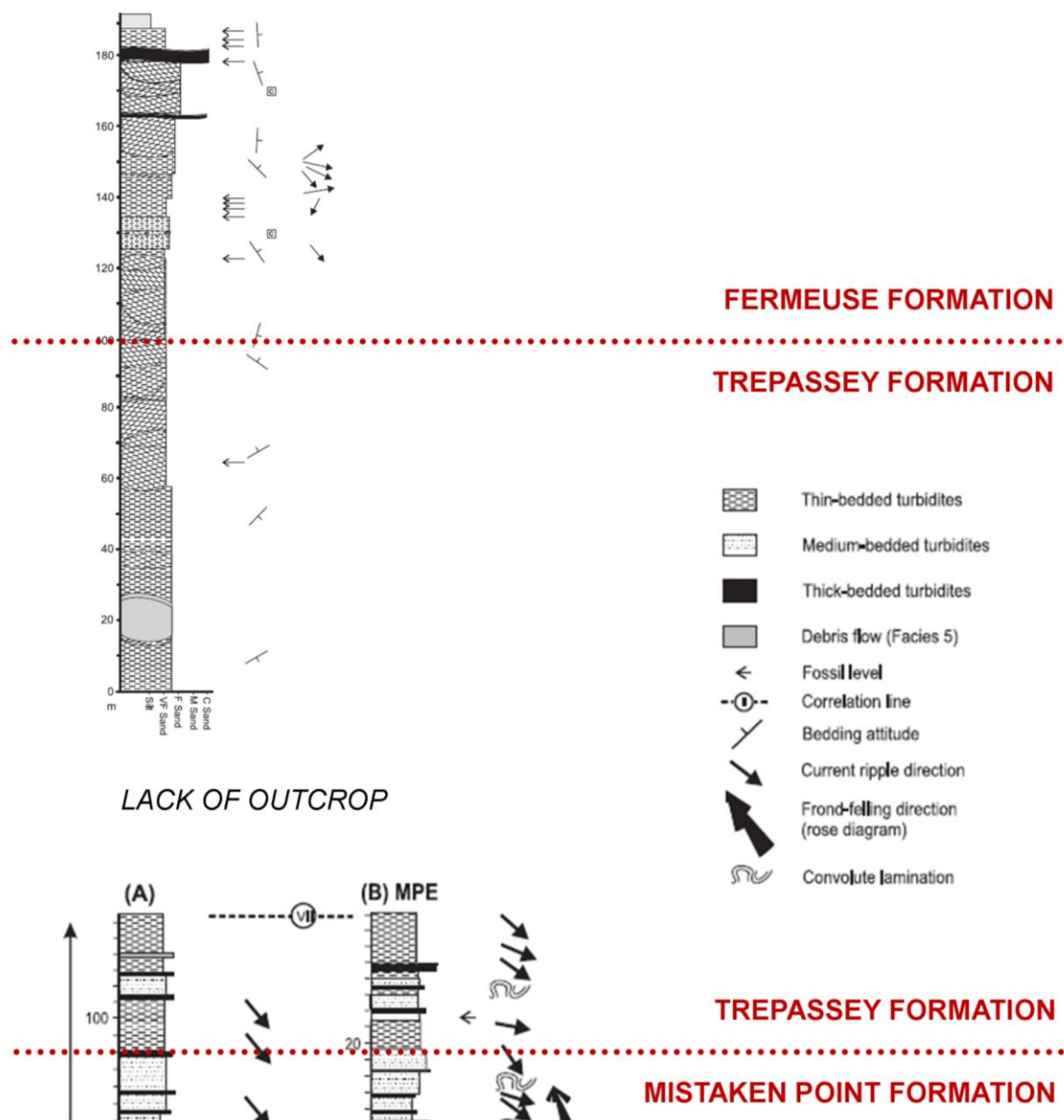


FIGURE 2.20. Logs through parts of the Trepassey and Fermeuse formations reproduced from Wood et al. (2003). Revisions to boundaries are shown in red. A) Mistaken Point West. B) Mistaken Point East. Scale in metres.

mudstone with isolated silt grains. 30 mm thick dark buff siltstone capped by 2 mm thick very thinly parallel laminated dark green mudstone with isolated silt grains. 18 mm thick normally graded fine sandstone to siltstone capped by a 3 mm thick olive green very thinly laminated mudstone with local isolated silt grains. A >4 cm thick greeny-purple normally graded fine sandstone to siltstone, pyritiferous at the base, with mm-scale load structures into the underlying mudstone.

Thin section analysis shows the siltstones and sandstones to have lithic subarkose composition, well sorted and dominated by sub-rounded quartz but with minor amounts of plagioclase and lithic fragments (Figure 2.22). Pyrite framboids are common.

A number of small toolmarks suggest a southerly down-slope flow direction, broadly consistent with that given by Wood et al. (2003).

*Palaeontology:* The Trepassy Formation in and around MPER has traditionally been seen as relatively sparse when it comes to fossils, with only one bedding plane with more than *Aspidella* being documented by Narbonne et al. (2005). However, as is described later, the process of remapping the area has revealed not only new fossiliferous bedding planes, but also that sections previously considered as Mistaken Point Formation, are indeed Trepassy Formation. The unit therefore also includes examples of *Hiemalora*, *Charnia*, *Vinlandia*, *Charniodiscus*, *Pectinifrons*, and *Primocandelabrum*. No fossils have been described from the upper part of the formation, although this is likely a product of the lack of outcrop around the Long Cove area.

### **Fermeuse Formation**

*Name:* Named after the township of Fermeuse, Avalon Peninsula, where the type section is located.

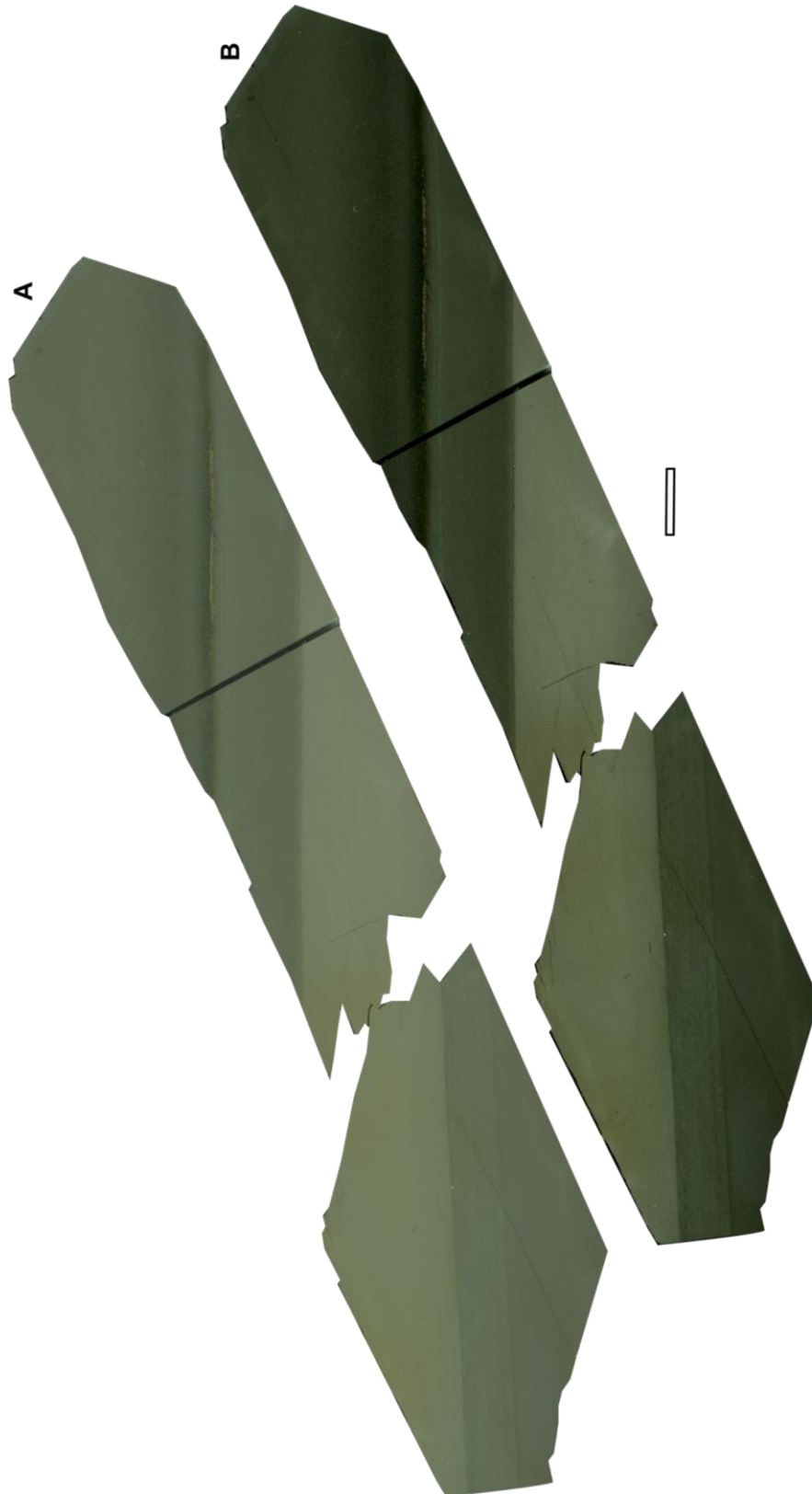
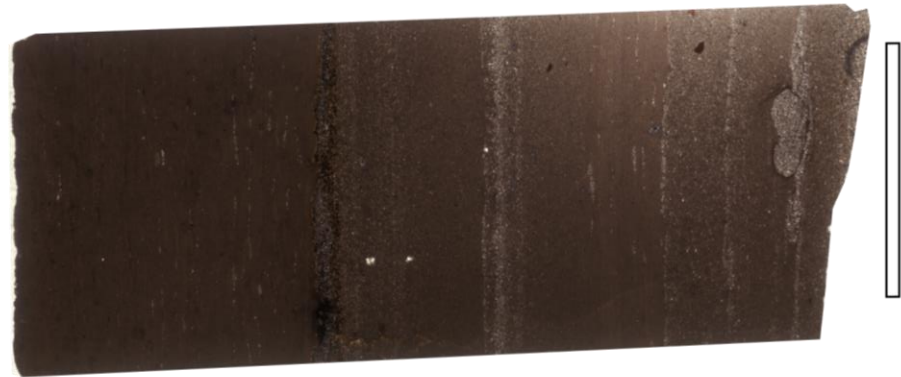


FIGURE 2.21. Slabbed section from the Trepassey Formation. A) True colour scan. At the base is the top of a siltstone turbidite unit, capped by a possible contourite green layer. Above this lies a light grey turbidite with possible capping contourite, and then the base of a sandstone with pyritiferous zone at its base. B) False colour images to help emphasise features. Scale bar is 1 cm.



B



A

FIGURE 2.22. A) Thin section from the Trepassey Formation. Sample shows ripple cross-laminated fine, normally graded, sandstone deposited on a possible contourite. B) Thin section from the Fermeuse Formation, showing typical dark grey siltstones and minor fine sandstones. Scale bars are 1 cm.

*Type Locality and Stratotypes:* The originators of the formation give the type section as ‘Fermeuse’ (Williams and King, 1979). The Lexicon of Canadian Geological Names (2015) lists the type locality as:

*Cliff section from about 200 m to 2 km west of Bear Cove Head, southeast Fermeuse Harbour, Trepassey area, southern Avalon Peninsula, southeastern Newfoundland. A reference section occurs between Middle Cove and Outer Cove, north of St. John’s.*

The type locality is therefore amended to: Fermeuse Harbour, Avalon Peninsula Newfoundland.

The lectostratotype is designated as: The ~2 km of coastal cliff section west of the mouth of the outflow of Bear Cove Pond, southern shore of Fermeuse Harbour, Newfoundland (N: 46°57'42.5" W: 052°54'55.3").

*Distribution, Thickness, and Boundaries:* The Fermeuse Formation is of unknown thickness within the mapping area, as the top of the formation does not outcrop. However, it is estimated that 720 m of the formation is present (Section 1, Map 1). In the local area, the Fermeuse Formation also crops out at the centre of the Biscay Bay and St. Schott’s Synclines.

The Fermeuse Formation crops out along much of the east coast of the Avalon Peninsula, including its type section at Fermeuse where it is estimated to be 1400 m thick (Williams and King, 1979). The formation underlies much of the cities of St. John’s and Mount Pearl, and crops out further north at Tor Bay. The Fermeuse Formation has also been described from the Bay de Verde (Ichaso et al., 2007) and Bonavista (O’Brien and King, 2004) Peninsulas, and this will be examined in later chapters.

The base of the formation is defined as the lowest occurrence of slumping within the grey siltstones and sandstones of the St. John’s Group. The top of the Fermeuse Formation, not

outcropping within the area of study, is defined as the base of the overlying Renew's Head Formation.

*History within the Southern Avalon Peninsula:* The rocks now comprising the Fermeuse Formation were first described by Joseph Beete Jukes (1843) as The St. John's slate, which by being mapped from Trepassey Bay to Cape Race, must have contained at least everything from the modern Drook Formation to the Fermeuse Formation. This was revised by Alexander Murray (1881), first Director of the Geological Survey of Newfoundland, to the 'Dark brown or blackish slates of St. John's' of his 'series d', within the 'Intermediate System'. It is likely this also includes the modern Renew's Head Formation. This unit included within it the 'aspidella slates' which were used for mapping of this unit in the field (Murray, 1881).

Charles Walcott (1899), while retaining the wider description of Murray's 'series d' (and therefore its extent) revised the unit to the 'Morable slates'.

Misra (1971), in mapping the Biscay Bay-Cape Race used the term St. John's Formation to classify the rocks from Shingle Head to Cape Race. These were revised by Williams and King (1979) to the Fermeuse Formation (Table 1).

*Sedimentological Description:* The Fermeuse Formation comprises thinly bedded dark grey and black siltstones, some with thin, cross-laminated and pyritiferous fine sandstones at the base of units (Figure 2.23A; Figure 2.24). Bedding is most frequently <5 cm thick. Metre-scale slump structures with internal convolute bedding are characteristic of the formation (Figure 2.23B,C), as are ~5 cm diameter blue-black phosphatic nodules. Carbonate cementation in sandy zones of units is common. Discrete tuffite units are rare within the Fermeuse Formation. A revised sedimentary log from Wood et al. (2003) for part of the Fermeuse Formation is given in Figure 2.20.

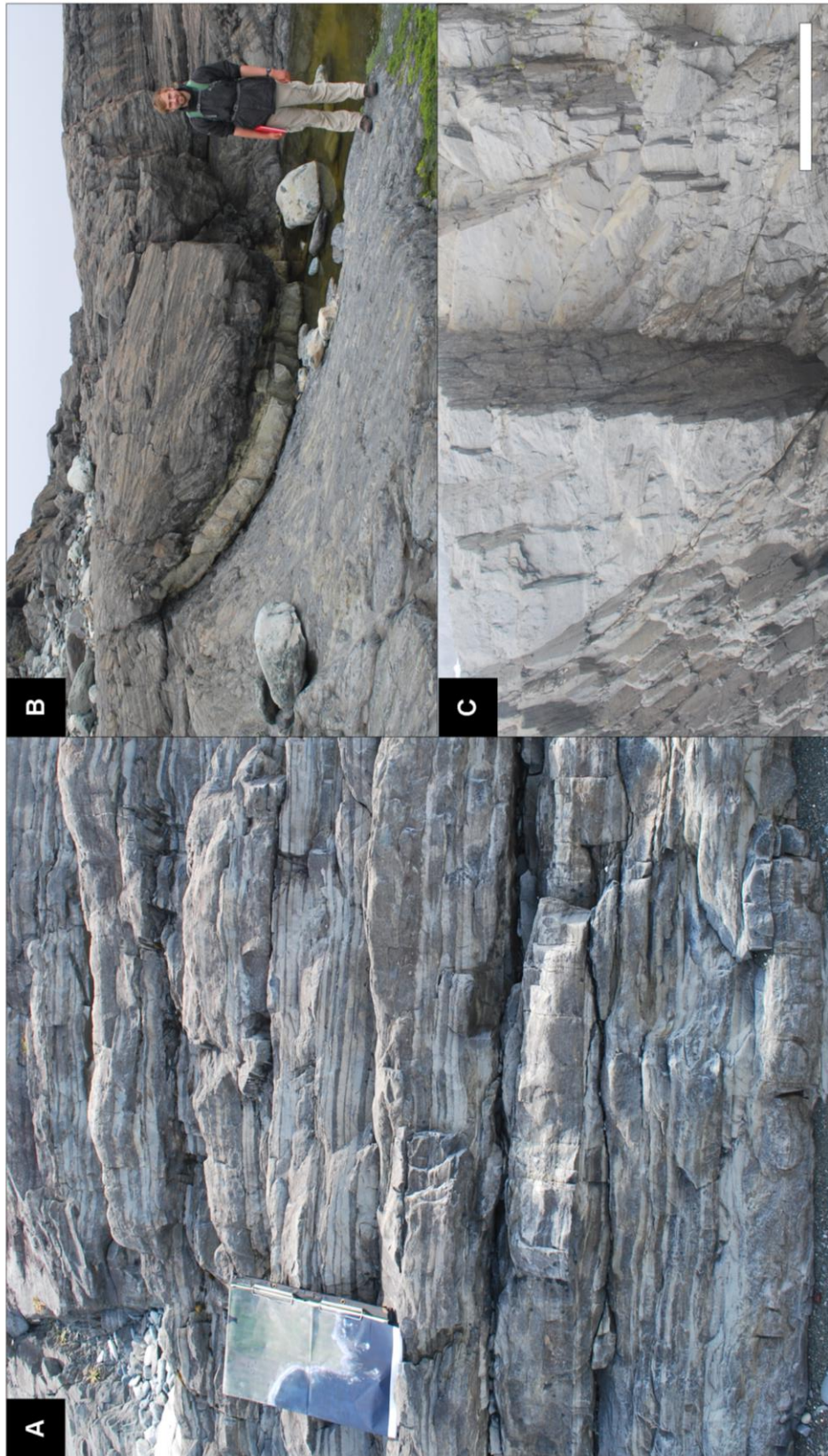


FIGURE 2.23. Fermeuse Formation. A) Typical thinly-bedded siltstones of the Fermeuse Formation at Shingle Head. Note A3 clipboard (long axis 43.5 cm) for scale. B) Slump at Shingle Head. Palaeontologist is standing on slump scar surface. Light green layer directly upon slump scar is SH-2 tuffite sampled for geochronologic analysis. C) Cliff exposure of Fermeuse Formation, note recumbent-folded bedding on left. Scale bar is 1 m.

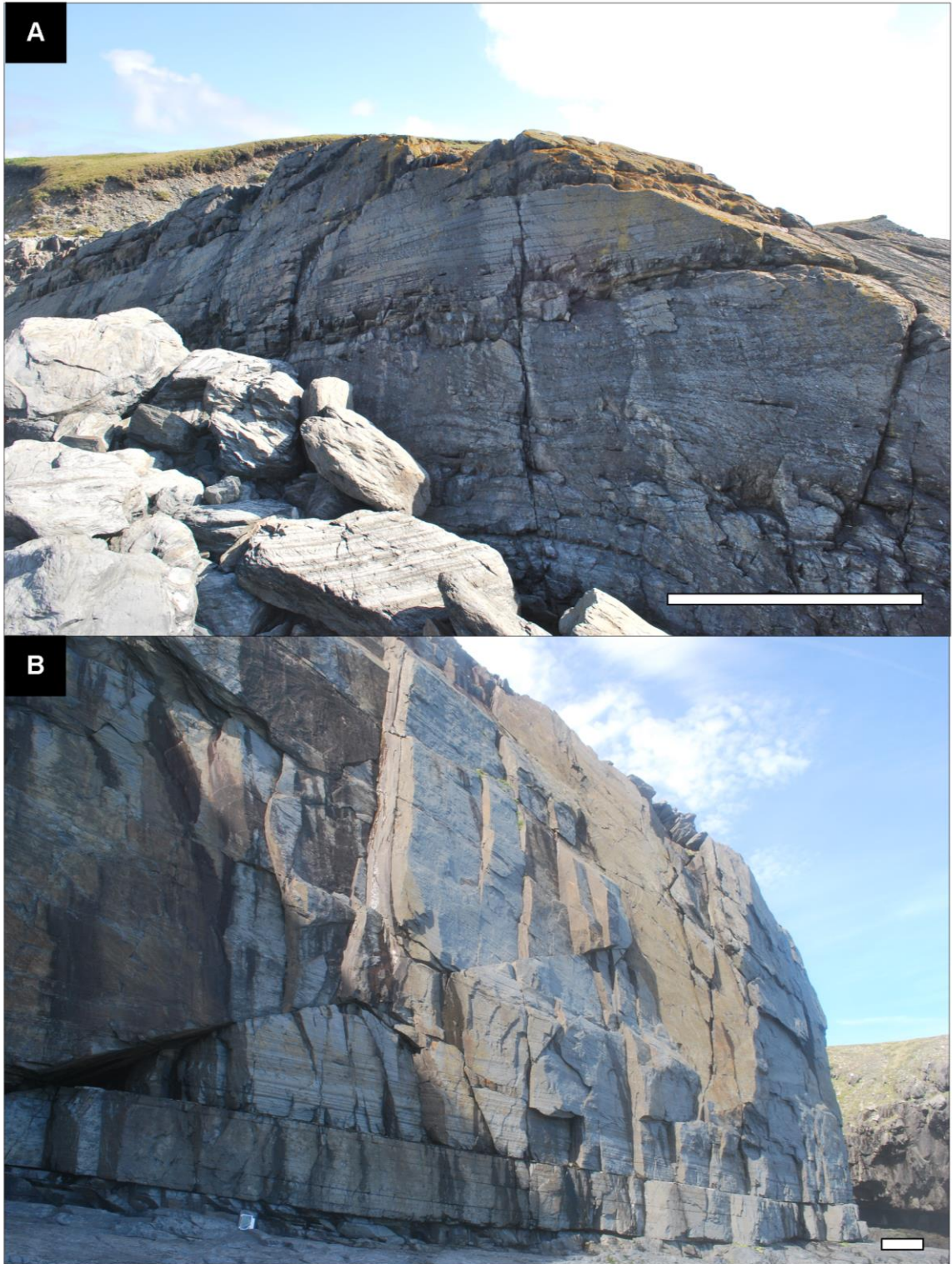


FIGURE 2.24. Supplementary photographs of the Fermeuse Formation. A) Slumped bed with the Fermeuse Formation at Shingle Head. Scale bar is 1 m. B) Cliff of Fermeuse Formation siltstones to the west of Cripple Cove. Scale bar is 1 m.

Slabbed sections of the Fermeuse Formation sampled from the outcrops at Cape Race show a number of interbeds between two different facies (Figure 2.25). The first are 0.5 – 1 cm thick dark grey normally graded siltstones, sometimes exhibiting faint parallel laminations, and often pyritiferous (framboidal) at the base (Figure 2.22). The second are 0.5 – 1.5 cm thick dark grey parallel to wispy laminated mudstones with rare isolated silt grains.

*Palaeontology:* The most common fossil in the Fermeuse Formation is *Aspidella*, with the abundance of this taxon, combined with the typical sedimentology being used historically to map the unit. The bottom ~300 metres of the formation does, however, contain other taxa, including *Charnia*, *Charniodiscus*, *Pectinifrons*, *Fractofusus*, *Primocandelabrum*, *Bradgatia*, and *Thectardis*.

## **LITHOSTRATIGRAPHY OF THE CATALINA DOME**

*Statement of Intent:* The following is an assessment of the validity of using the Drook, Briscal, Mistaken Point, Trepassey, and Fermeuse Formations of Williams and King (1979) within the Catalina Dome area. In place of the Avalon-based stratigraphic scheme, the Trinity Bay North Group, comprising the Shepherd Point, Murphy's Cove, Rowland Head, Port Union, and Little Catalina formations are created. As this is an unpublished DPhil thesis, the following does not constitute a formal revision, as defined by the International Stratigraphic Guide (Salvador, 1994), until published in a peer-reviewed journal.

### **Trinity Bay North Group**

*Name.* Designated after the township of Trinity Bay North, Bonavista Peninsula, Newfoundland, which was incorporated in 2005.

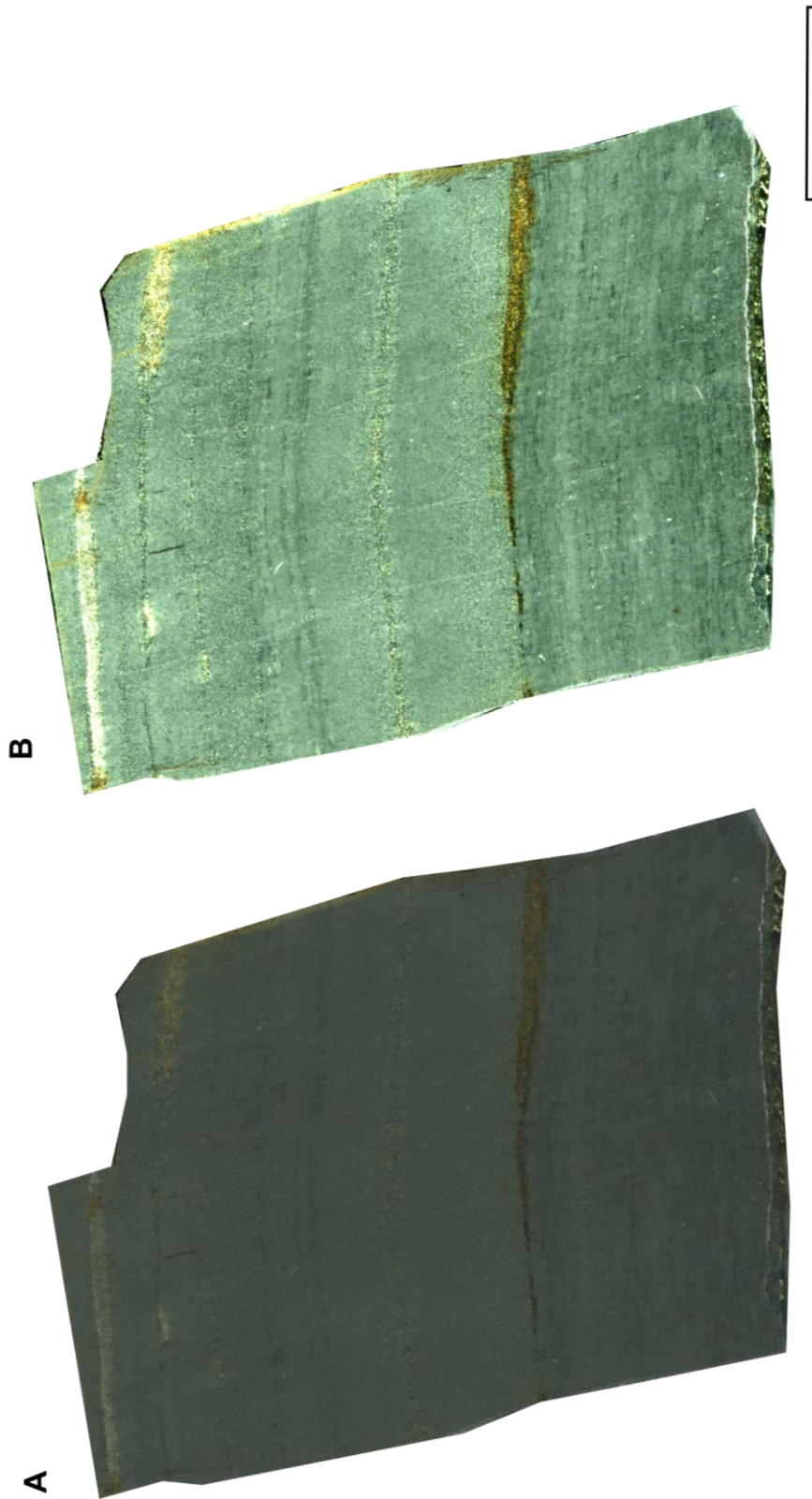


FIGURE 2.25. Slabbed section from the Fermeuse Formation. A) Very thinly bedded dark grey, normally graded siltstones, and occasional mudstones of the Fermeuse Formation. Note also pyritiferous horizons at the top (brassy) that have oxidised lower in the slab (brown-orange). B) False colour image to help emphasise internal structures. Scale bar is 1 cm.

*Type Locality and Stratotypes.* The type locality is Catalina Harbour, in which Trinity Bay North is situated. The stratotype is the southern coast of Catalina Harbour, running from Burnt Point (N: 48°30'33.5" W: 053°02'59.5") to the back of Catalina Harbour at Port Union (N: 48°29'57.7" W: 053°05'09.5"). These outcrops provide a near complete stratigraphic section from the top of the Shepherd Point Formation, through to the base of the Little Catalina Formation as defined here.

*Distribution, Thickness, and Boundaries.* The base of the Trinity Bay North Group is not exposed within the Catalina Dome, and the top of the unit lies outside of the area mapped in this thesis. The Trinity Bay North Group comprises at least 660 m of stratigraphy in and around the type locality. The true stratigraphic thickness is likely to be much greater, since stratigraphic revision of the strata of the Bonavista Peninsula will naturally precipitate revision of the overlying rocks that are currently assigned to the St. John's and Signal Hill groups as defined on the Avalon Peninsula.

*History.* The rocks now comprising the Trinity Bay North Group were originally compared to the rocks of the Avalon Peninsula during the first geological surveys of Newfoundland (Jukes, 1843; Murray, 1881), but were then assigned to the Musgravetown Group (Christie, 1950). Recently they have been described as belonging to the Conception and St. John's Groups (See Table 2.2: O'Brien and King, 2004; O'Brien and King, 2005; Hofmann et al., 2008).

*Sedimentary Description.* Grey and green siltstones and sandstones showing a net shallowing upwards trend dominate the Trinity Bay North Group, which is composed, in stratigraphic order, of the Shepherd Point, Murphy's Cove, Rowland Head, Port Union, and Little Catalina formations.

*Palaeontology.* The Trinity Bay North Group contains more than 100 fossiliferous horizons, showing discoidal, frondose, and other morphologies of Ediacaran organism.

O'Brien and King (2004)		O'Brien and King (2005)			Here	
St. John's Group	"Unseparated Renew's Head and Fermeuse formation equivalents"	St. John's Group	Fermeuse Formation	Back Cove Member	Trinity Bay North Group	Little Catalina Formation
	Trepassey Formation		Trepassey Formation	Port Union Member		Port Union Formation
Conception Group	Mistaken Point Formation	Conception Group		Mistaken Point Formation		Murphy's Cove Member
			Goodland Point Member			Murphy's Cove Formation
			Drook Formation	Shepherd Point Member		Shepherd Point Formation

TABLE 2.2. Comparison of stratigraphic classifications used for the rocks of the Catalina Dome during the 21<sup>st</sup> Century. Not drawn to scale.

### Shepherd Point Formation

*Name.* Designated after Shepherd Point (Figure 2.2), Trinity Bay, this formation is located at the core of a large-scale anticlinal structure known as the Catalina Dome. The Shepherd Point Formation is created herein by merging the Shepherd Point and Goodland Point members of O'Brien and King (2005), to produce one regionally mappable unit.

*Type Locality and Stratotype.* The type locality is Shepherd Point (N: 48°30'56.3" W: 053°03'14.6") and Shepherd Cove, Catalina, Bonavista Peninsula, Newfoundland. The stratotype is the rocks at the back of Shepherd Cove (N: 48°30'54.6" W: 053°03'45.3").

*Distribution, Thickness, and Boundaries.* The Shepherd Point Formation comprises the centre of the Catalina Dome, and its base is not exposed. Only 100 metres is exposed and the total thickness of the Formation is not known. The top of the unit is defined as the base of the overlying Murphy's Cove Formation.

*History.* The newly described Shepherd Point Formation comprises rocks formerly assigned to the Shepherd Point Member of the Drook Formation and the Goodland Point Member of the Mistaken Point Formation (O'Brien and King, 2005). In earlier work these two members have been included wholly within the Mistaken Point Formation (O'Brien and King, 2004).

*Sedimentary Description.* The Shepherd Point Formation comprises thinly to very thinly bedded, cherty, parallel and wispy laminated fine-grained sandstones, siltstones and mudstones, that are commonly variegated between white, green, pink, red, grey, brown and purple (Figure 2.26; Figure 2.27; Figure 2.28). The formation includes rare medium to thickly bedded normally graded sandstones, with loading and flame structures at the base of beds. Sandstones may show ripple cross-lamination. There are rare tuffaceous horizons, no more than a few centimetres thick, recognised by a buff-green colour and cleaved nature. A revised sedimentary log from Mason et al. (2013) for the Shepherd Point Formation is given in Figure 2.29.

A slabbed section sampled from Shepherd Cove shows the variegated nature of the unit, the fine laminations, and one of the uncommon cross-laminated beds (Figure 2.30). In places the laminations are wispy, and slightly wavy. Thin section analysis shows that the siltstones are dominated by quartz grains, with minor amounts of feldspar and lithic fragments.

*Palaeontology.* The Shepherd Point Formation records the oldest known fossils from the Bonavista Peninsula of Newfoundland, including examples of the Ediacaran forms *Aspidella*, *Hiemalora*, *Charnia*, *Vinlandia*, *Trepassia*, *Charniodiscus*, *Beothukis*, *Primocandelabrum*, *Bradgatia*, *Parviscopa*, and *Hadrynichorde*.

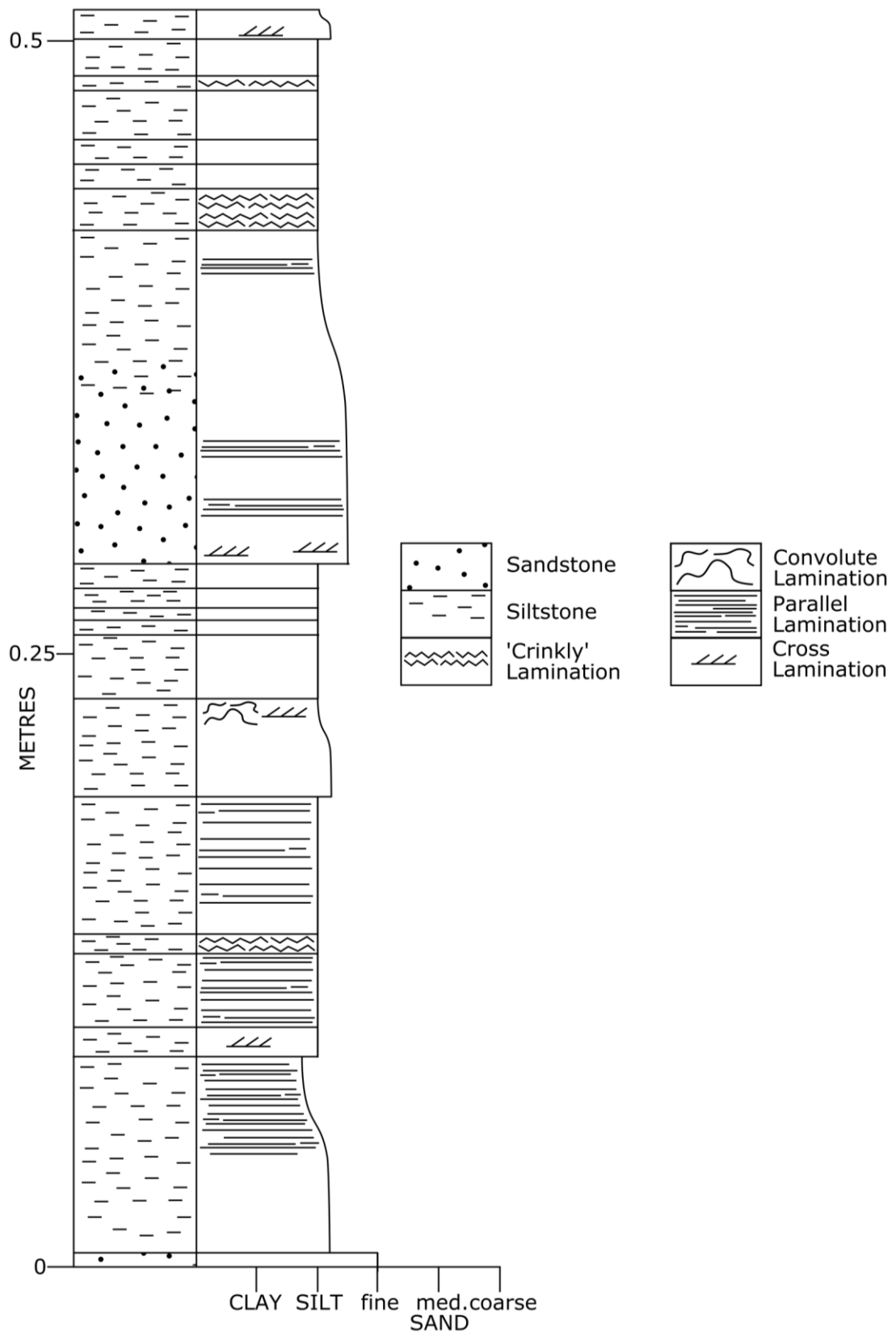


FIGURE 2.26. Sedimentary log through a section of the Shepherd Point Formation, from within the type locality at Shepherd Cove. The section is dominated by thinly and very thinly bedded, green, brown, grey, pink, and buff, parallel-laminated, cherty siltstones. There are occasional medium-bedded, normally graded sandstones. Enigmatic light-green and orange 'crinkly' laminations are found at this locality.

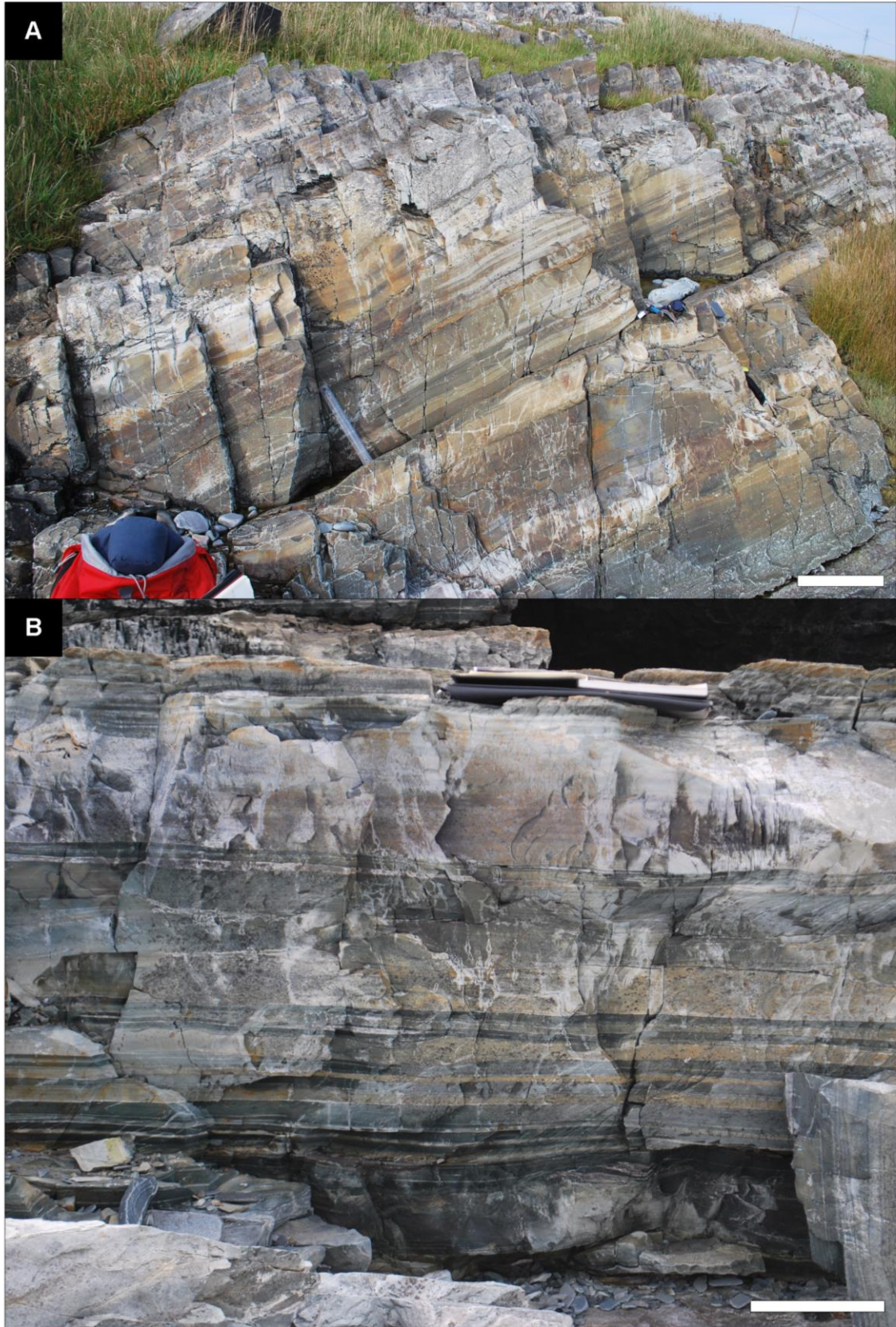


FIGURE 2.27. The Shepherd Point Formation. A) Example of the cherty lithologies of the Formation in Shepherd Cove. Scale bar is 25 cm. B) Example of the Shepherd Point Formation from west of Burnt Point—formerly mapped as the Goodland Point member. Scale bar is 25 cm.



FIGURE 2.28. Supplementary photographs of the Shepherd Point Formation. A) Typical variegated, cherty beds from Shepherd Point. Scale bar is 1 m. B) Variegated and cherty beds from Goodland Point. Scale bar is 1 m.

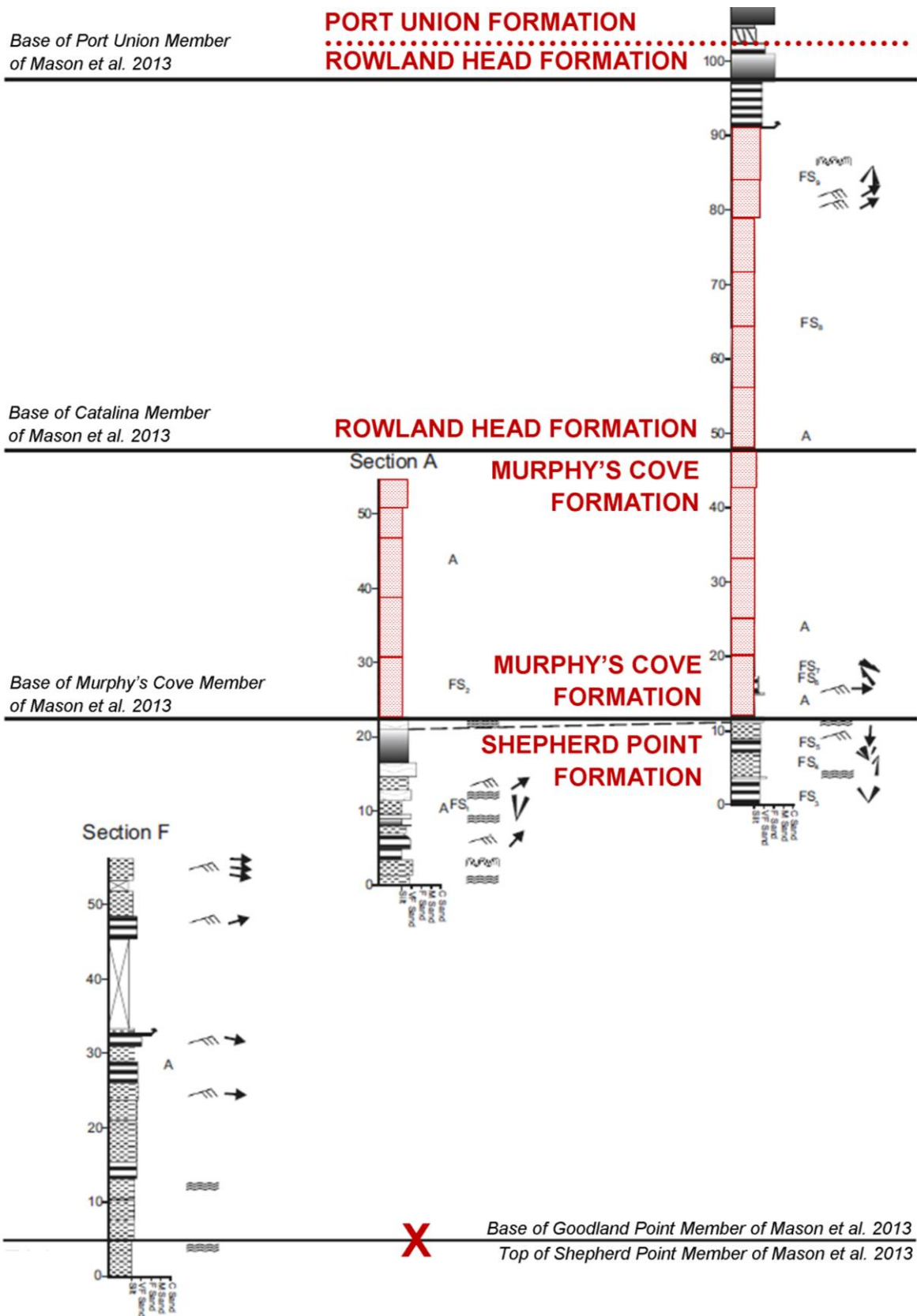


FIGURE 2.29. Logs through parts of the Shepherd Point, Murphy's Cove, and Rowland Head formations reproduced from Mason et al. (2013), whose field of study was restricted to the southern part of the Catalina Dome. Revisions to boundaries are shown in red. For legend see Figure 2.45. Scale in metres.



FIGURE 2.30. Slabbed section from the Shepherd Point Formation. The section is dominated by cherty buff, grey, and green siltstones, with pervasive parallel lamination, and minor zones of cross-lamination. Note light-green 'crinkly' lamination near the top of the samples. Scale bar is 1 cm.

## **Murphy's Cove Formation**

*Name.* Designated after Murphy's Cove, site of the former fishing settlement of the same name. This is a revision to the Murphy's Cove Member of O'Brien and King (2005), in that the unit is being promoted to formation status.

*Type Locality and Stratotypes.* The type locality is Murphy's Cove, also known as Southeast Cove, Trinity Bay North, specifically the back half of the Cove (N: 48°30'17.4" W: 053°03'30.1"). The stratotype is the stratigraphic section within the type locality. A basal boundary stratotype is defined as the tuff-rich strata ~275 m west of Burnt Point around Locality 5 of Hofmann et al. (2008) (N: 48°30'31.2" W: 053°03'12.8").

*Distribution, Thickness, and Boundaries.* The Murphy's Cove Formation is a 45 m thick formation within the Catalina Dome. Major outcrops are recognised in Murphy's Cove, the western side of Burnt Point, and the western side of Rowland's Head (Map 2). The base of the Formation is characterised by a zone containing numerous thinly bedded buff-green, often cleaved, tuffites – the first as thick as this within the succession. The top of the Murphy's Cove Formation is defined as the base of the overlying Rowland Head Formation.

*History.* The newly described Murphy's Cove Formation comprises those rocks formerly designated as the Murphy's Cove Member of the Mistaken Point Formation (O'Brien and King, 2005). Prior to the creation of the Murphy's Cove Member, the rocks were part of the Mistaken Point Formation, without member-level subdivision (O'Brien and King, 2004).

*Sedimentary Description.* The Murphy's Cove Formation is dominated by thinly bedded dark green and grey, sometimes purple, slightly mottled, laminated siltstones that are less

cherty than the underlying Shepherd Point Formation. The Murphy's Cove Formation contains abundant tuffaceous horizons (Figure 2.31; Figure 2.32). A revised log from Mason et al. (2013) for the Murphy's Cove Formation can be found in Figure 2.29.

Samples from the Murphy's Cove Formation, and the underlying Shepherd Cove Formation contain elongate, angular needles of optically-aligned carbonate. These needles can be up to 3 mm long and up to 0.5 mm wide. In most samples these are observed as isolated fragments, but in one case from the Murphy's Cove Formation, horizons rich in these needles can be found. The needles in these zones are often sub-perpendicular to bedding, cross-cutting any laminae present. One example is associated with a red-purple 1 cm thick horizon, which upon application of HCl effervesced, showing it to be rich in carbonate also (Figure 2.33).

Standard staining with Alizarin Red-S and Potassium Ferricyanide (Dickson, 1965) shows the needles to be either iron-free or iron-poor calcite.

This formation has previously been described as comprising medium and thickly bedded siltstones (Mason et al., 2013). Observations throughout this project show that while weathering along tuffaceous horizons may lead to outcrops that superficially appear to be medium to thick bedded, closer examination shows these outcrops to comprise multiple thin bedded units. This is reinforced by examination of nearly 4 m of the Murphy's Cove Formation near its base at Burnt Point. While attempting to correlate tuffite horizons of the Murphy's Cove Formation across the Catalina Dome, crude stratigraphic logs were created, noting tuffaceous and non-tuffaceous horizons, and their thickness. Forty seven beds were measured at the base of the Murphy's Cove Formation, with a mean thickness of 8 cm and a modal thickness of 1 cm. Several beds were medium thickness, none were

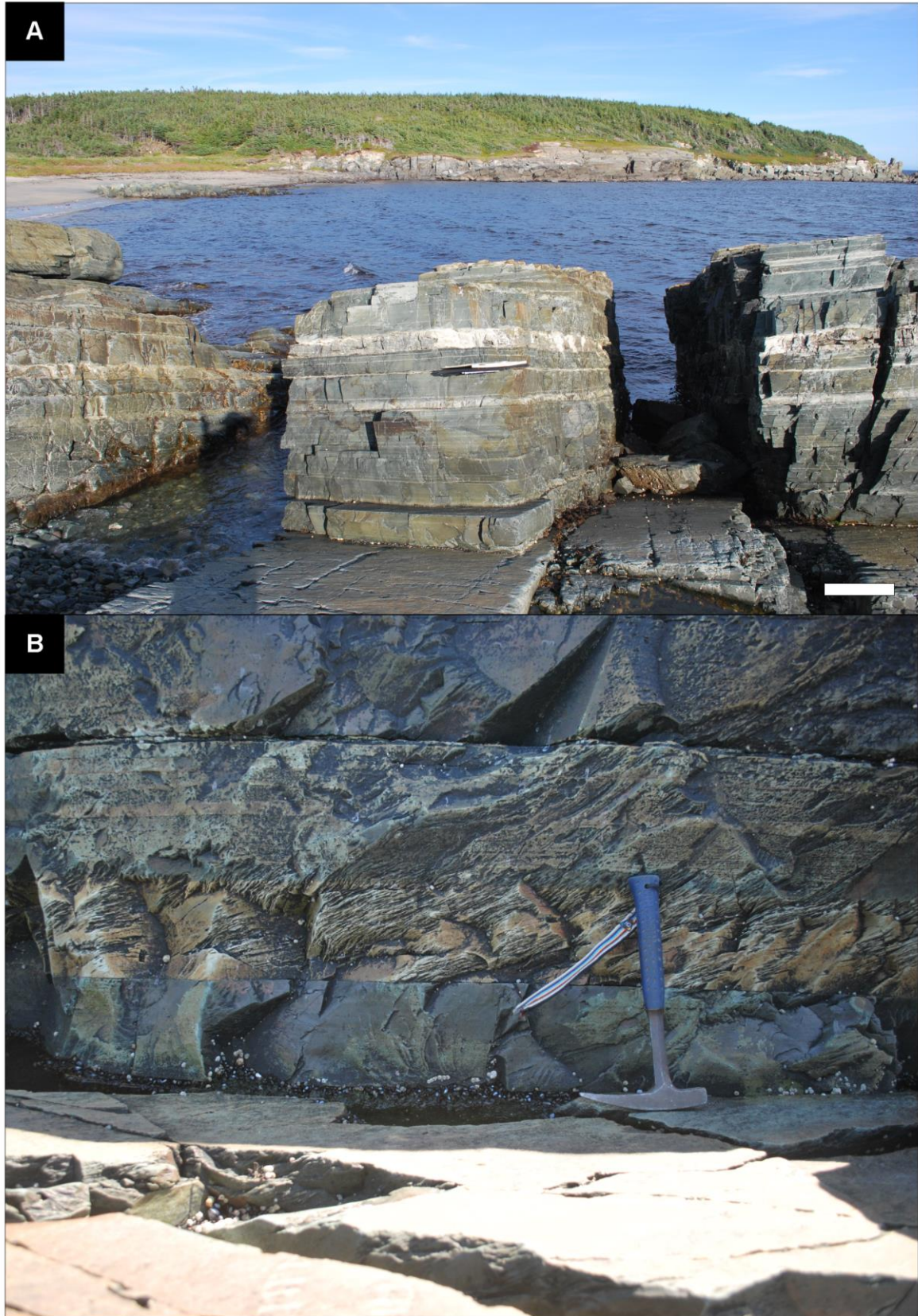


FIGURE 2.31. The Murphy's Cove Formation. A) Typical outcrop of green siltstones of the Murphy's Cove Formation, interbedded with buff-green tuffites. B) Example of typical bedding in the Murphy's Cove Formation. The cleaved, buff horizon was sampled for geochronological analysis (MRC-6). Note geological hammer for scale.



FIGURE 2.32. Supplementary photographs of the Murphy's Cove Formation. A) Typical beds of the Murphy's Cove Formation from the Rowland Head area. Note pen for scale. B) Typical beds of the Murphy's Cove Formation from Murphy's Cove. Note palaeontologist for scale.

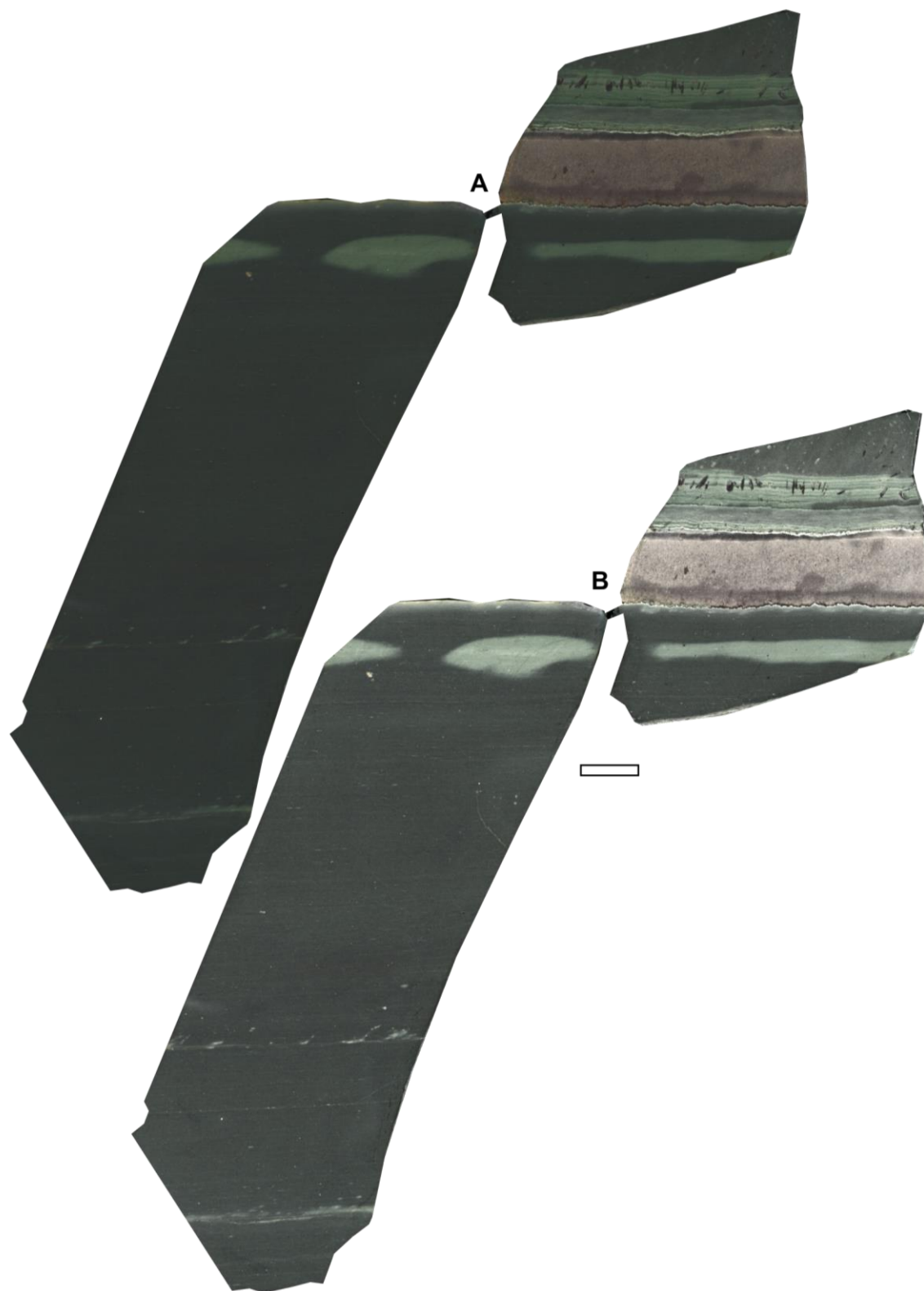


FIGURE 2.33. Composite slabbed section from the Murphy's Cove Formation. A) True colour scan of a medium bedded purple, parallel-laminated siltstone bed, capped by a thin, red-brown, carbonate cemented sandstone. Above this is a purple siltstone containing light-green laminations and relatively large, vertically-aligned calcite crystals. The top block has been stained for carbonate using Potassium Ferricyanide and Alizarin Red-S. When using a binocular microscope, smaller, vertically-aligned calcite crystals can also be observed at the bottom and top surfaces of the red-brown sandstone layer. B) False colour image to emphasise internal structures. Scale bar is 1 cm.

thick bedded. The formation is therefore amended to being predominantly comprised of thin bedded siltstones.

*Palaeontology.* The Murphy's Cove Formation contains specimens of *Aspidella*, *Hiemalora*, *Charnia*, *Vinlandia*, *Charniodiscus*, *Fractofusus*, *Primocandelabrum*, *Bradgatia*, *Parviscopa*, *Hadryniscalia*, and *Hadrynichorde*.

### **Rowland Head Formation**

*Name.* Designated after Rowland Head, a small headland between Catalina and Little Catalina. This unit is a revision of the former Catalina Member of O'Brien and King (2005) in that it is being promoted to formation status. The unit is also being renamed for the purpose of disambiguation, as the Catalina Formation (McAlpine, 1990), itself formerly the Catalina member of the Whiterose Formation (Sinclair, 1988), is already in use for a subsurface Cretaceous unit from the Hibernia oil field, of offshore Newfoundland.

*Type Locality and Stratotypes.* The type locality is Rowland Head, near Trinity Bay North, Bonavista Peninsula, Newfoundland (N: 48°31'35.8" W: 053°02'44.0"). The stratotype is those rocks from Rowland Head, along ~600 m of coastal section along the eastern coast of the headland, up to and including the large *Fractofusus* bearing horizon designated as Locality 14 by Hofmann et al. (2008), also known locally as the "Johnson Surface" (N: 48°31'52.8" W: 053°02'49.3").

*Distribution, Thickness, and Boundaries.* The Rowland Head Formation is a 65 m thick unit, within the Catalina Dome, cropping out around Catalina itself, as well as the western side of Murphy's Cove, Burnt Point, and Rowland's Head. The base of the Rowland Head Formation is defined as the lowest stratigraphic occurrence of siltstone beds containing

containing thin sandstone beds with starved ripple cross-lamination. The top of the formation is defined as the base of the overlying Port Union Formation.

*History.* The rocks now comprising the Rowland Head Formation were first described in the fourth book of *The English Pilot* (Fisher and Thornton, 1689) – an early navigational guide and atlas for the North Atlantic. The book states in describing the Catalina Harbour area;

*...And near a small Cove in the W.N.W. within the small island is a Fire-stone of a glittering Colour, a kind of Mineral, excellent good for Wheel-Locks, growing in the Rocks.*

More recently these rocks were described as being part of the Trepassey Formation (O'Brien and King, 2004), and then more specifically the Catalina Member of that Formation (O'Brien and King, 2005).

*Sedimentary Description.* The Rowland Head Formation comprises thinly and occasionally medium bedded, normally graded, grey and green siltstones, often with carbonate cemented starved ripples in sandstone at the base of beds (Figure 2.34; Figure 2.35; Figure 2.36). Beds within the Rowland Head Formation tend to increase in thickness and become coarser towards the top of the unit. Tuffaceous horizons are common, typically buff-green siltstones and mudstones that are highly cleaved. The lower part of the formation contains abundant cubic pyrite crystals. The top of the formation contains a number of strata containing fist sized phosphatic concretions. A revised sedimentary log from Mason et al. 2003 of the Rowland Head Formation is presented in Figure 2.29.

Slabbed sections show that the graded siltstones of the Rowland Head Formation are commonly capped by several centimetres of olive green wispy laminated mudstone with

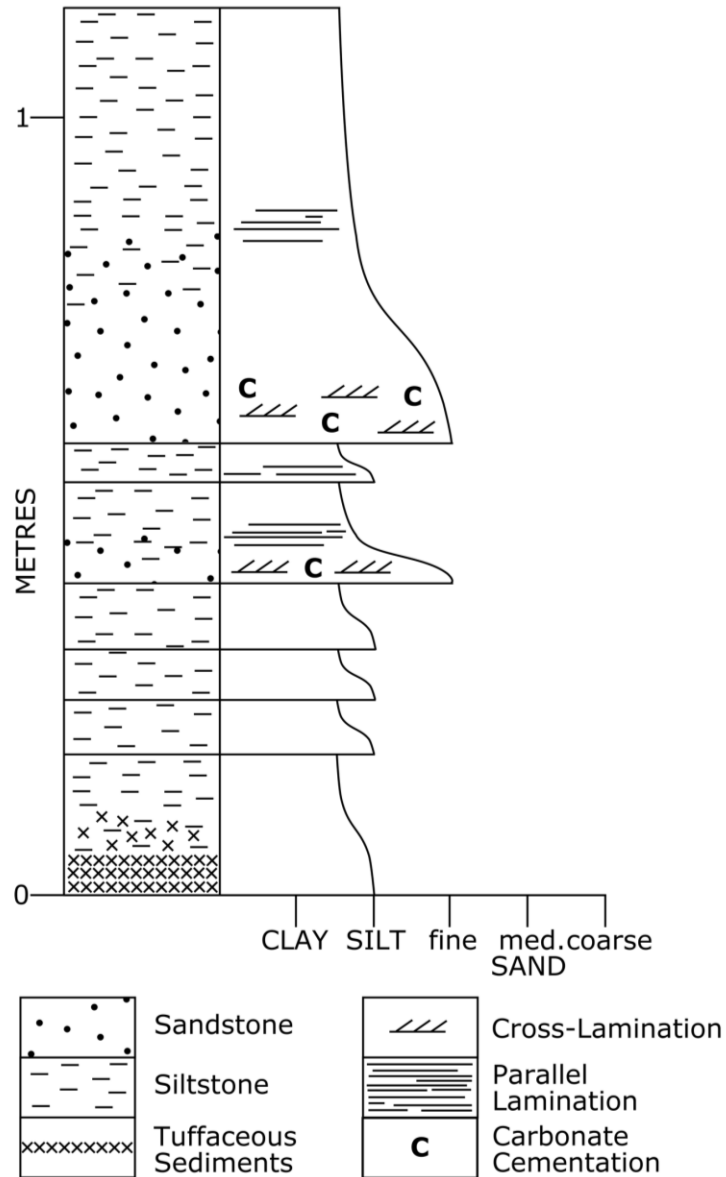


FIGURE 2.34. Sedimentary log through a section of the Rowland Head Formation. The ash at the base of the log directly overlies the 'Hofmann 14' fossil locality, also known as the 'Johnson Surface', and was sampled as "HF14-6" for geochronological analysis. The section is dominated by normally-graded, grey and grey-green siltstones, with occasional carbonate cemented ripple cross-laminated sandstones at the base of beds. The bed at the top of the unit shows one of the rare thickly bedded units.



FIGURE 2.35. The Rowland Head Formation. A) Typical cliff exposure of the Rowland Head Formation. Geochronology sample HF14-6 is taken from the base of this cliff. Scale bar is 50 cm. B) Grey siltstone beds of the Rowland Head Formation. Note that some of the beds have a carbonate cemented, ripple cross-laminated sandstone at the base. Rule with cm graduations for scale.

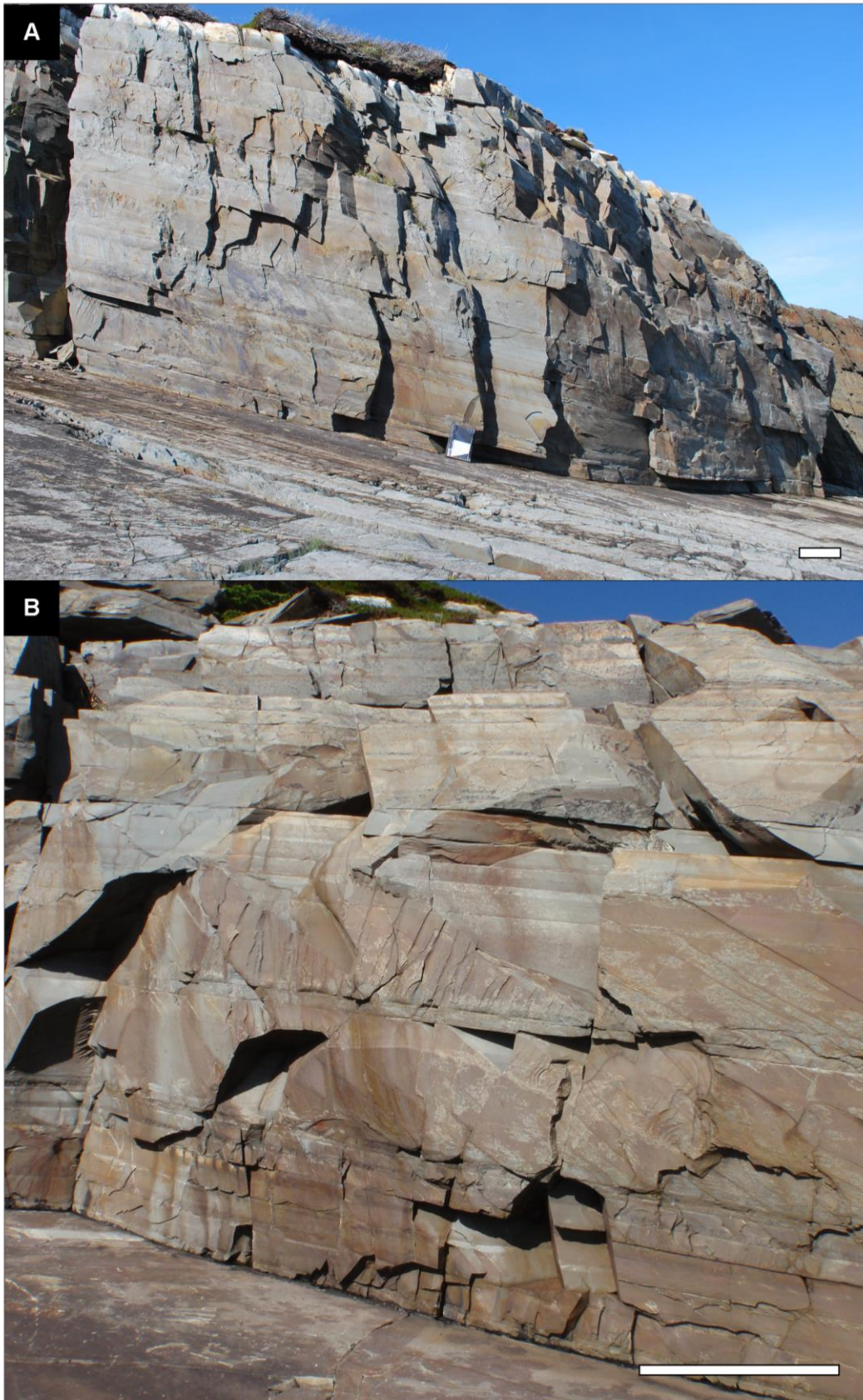


FIGURE 2.36. Supplementary photographs of the Rowland Head Formation. A) Typical cliff outcrops of the Rowland Head Formation from south of Little Catalina. Scale bar is 50 cm. B) Typical Rowland Head Formation from Rowland Head itself. Note that weathering may give make bedding superficially appear thicker than it is. Scale bar is 50 cm.

silt-grade particles that may be isolated or aggregated (Figure 2.37). These siltstone grains are commonly angular, quartz-rich and polycrystalline.

As with the Murphy's Cove Formation, this formation has been previously described as comprising medium and thick bedded siltstones (Mason et al., 2013). Again, it is believed that preferential weathering along tuffaceous and carbonate cemented sandstone horizons reveals outcrops that superficially appear to be thicker bedded than they actually are.

Closer examination during this research shows the unit to be predominantly thin bedded, with occasional medium beds, and rare thick beds. Regardless of bed thickness, it is the presence of sediment starved ripple cross-lamination at the base of beds that is most characteristic of this formation.

*Palaeontology.* The Rowland Head Formation has over 30 fossiliferous surfaces including examples of *Aspidella*, *Hiemalora*, *Charnia*, *Vinlandia*, *Charniodiscus*, *Beothukis*, *Pectinifrons*, *Fractofusus*, *Primocandelabrum*, *Bradgatia*, *Hadryniscala*, *Hadrynichorde*, and *Thectardis*.

### **Port Union Formation**

*Name.* Designated after the community of Port Union. A constituent part of the community of Trinity Bay North, the settlement's name recognises its origins in the Fisherman's Protective Union. This is a revision to the Port Union Member of O'Brien and King (2005) that is herein promoted to formation status.

*Type Locality and Stratotypes.* The Port Union Formation underlies much of the settlement of Port Union, although the formation is best observed on the eastern coast of Burnt Point, directly opposite Green Island, which is designated as the type locality. The stratotype is from the MUN Surface of Liu et al. (2016) (N: 48°30'26.1" W:053°02'59.8") then along

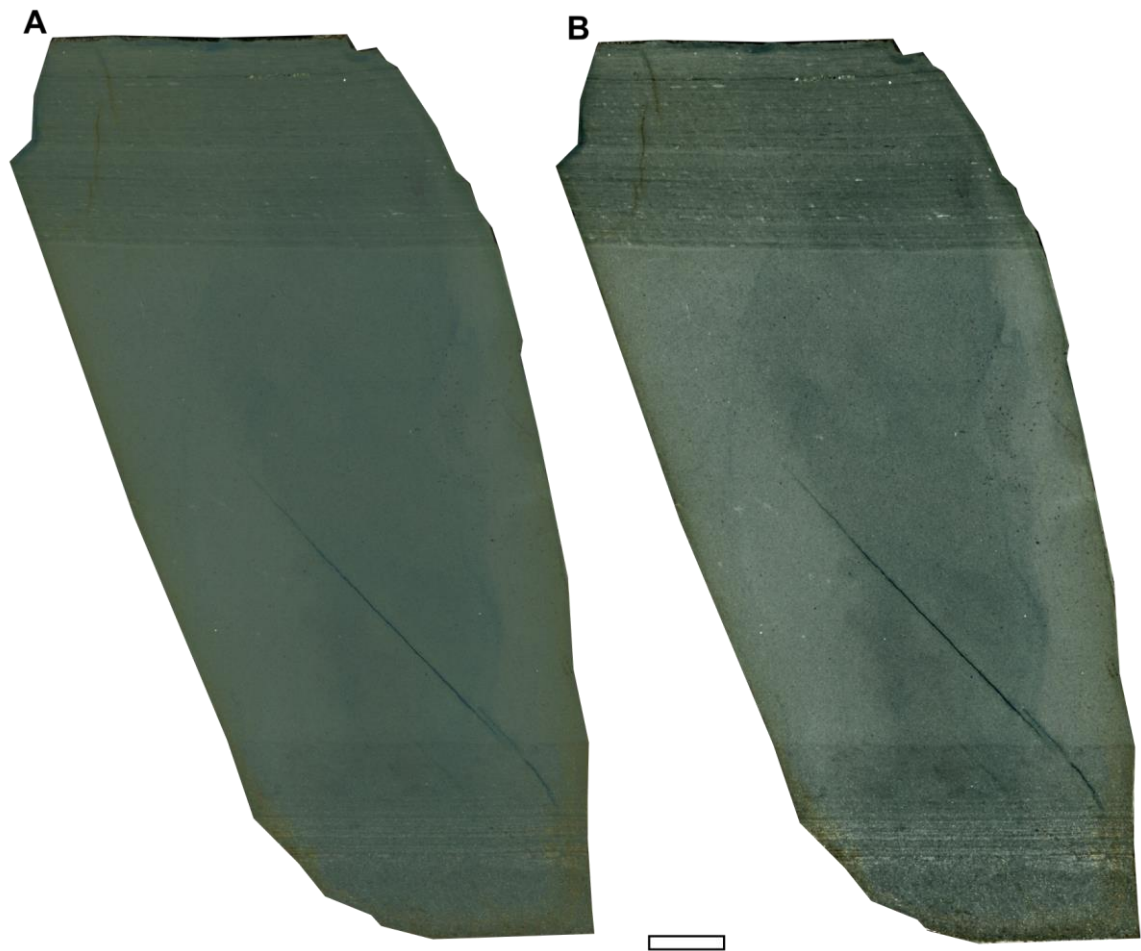


FIGURE 2.37. Slabbed section from the Rowland Head Formation. A) True colour scan of a normally-graded siltstone turbidite with parallel laminations at the base, and possible contourite deposit at the top, on which the Hofmann 14 fossil surface (also known as the Johnson Surface) is found. Blue staining is a by-product of testing for carbonate and is not indicative of mineralogy. B) False colour image to emphasise internal structures. Scale bar is 1 cm.

the coastal outcrop to the south west until reaching a fault (N: 48°30'09.8" W: 053°03'12.5") that runs across the headland from Murphy's Cove, separating Burnt Point from the mainland.

*Distribution, Thickness, and Boundaries.* The Port Union Formation is a ~120 m thick unit within the Catalina Dome that crops out on the eastern side of Port Union, as well as on the mainland coast alongside Green Island, and on the western side of Little Catalina Harbour. The lower boundary of the Port Union Formation is defined by a very thickly bedded sandy unit with convolute and deformed lamination (Figure 2.38B), containing phosphatic nodules. The top of the Port Union Formation is defined as the bottom of the Little Catalina Formation.

*History.* The rocks now comprising the Port Union Formation have most recently been described as part of the Trepassey Formation (O'Brien and King, 2004), and more specifically as the Port Union Member of that formation (O'Brien and King, 2005).

*Sedimentary Description.* The Port Union Formation is dominated by medium to thickly bedded grey, normally graded sandstones, commonly with convolute bedding and zones of carbonate cementation (Figure 2.38). Minor thinly to medium bedded grey siltstone beds are ubiquitous. There are some very thickly bedded light-grey medium-grained sandstone beds, commonly containing quartz filled fractures (Figure 2.39). The formation contains minor, thinly bedded, tuffites (Figure 2.40). A revised sedimentary log from Mason et al. (2003) is provided in Figure 2.41.

The subarkosic sandstones of the Port Union Formation contain sub-angular/angular grains, suggesting shorter transport histories than the sandstones of other formations in the Bonavista area, and commonly contain patchy carbonate cementation. Staining with Alizarin Red-S and Potassium Ferricyanide reveal that the carbonate cements are iron-rich

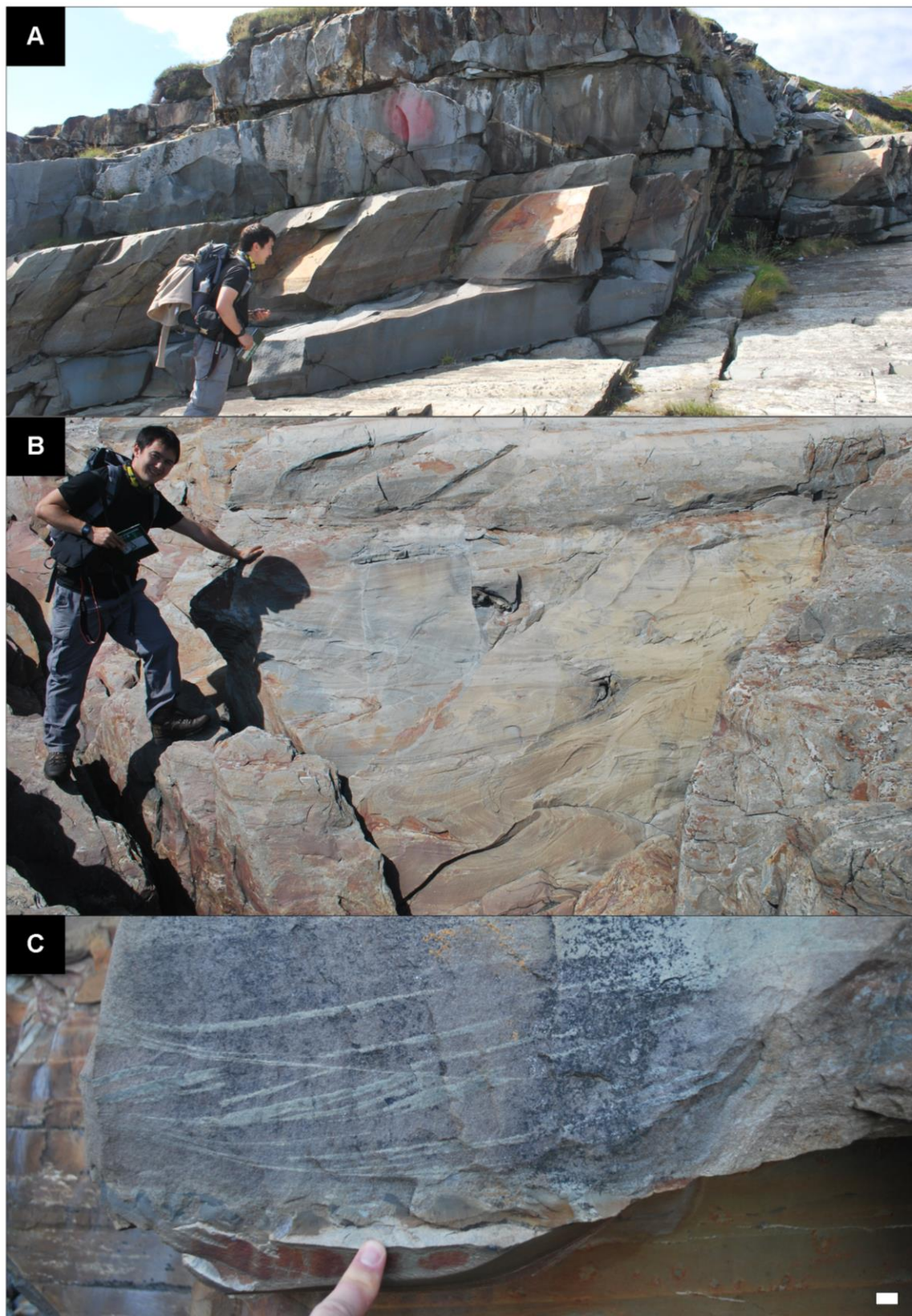


FIGURE 2.38. The Port Union Formation. A) Typical thickly bedded sandstones of the Port Union Formation within the type locality. Palaeontologist for scale. B) Convolute laminated layer, interpreted as a seismoturbidite at the base of the Formation. Palaeontologist for scale. C) Trough cross-lamination and load and flame structures at the base of a thickly bedded sandstone. Scale bar 1 cm.



FIGURE 2.39. Supplementary photographs of the Port Union Formation. A) Typical beds of the Port Union Formation from Little Catalina. Scale bar is 1 m. B) Port Union Formation from near Green Island. Note massive light grey ~2 m thick sandstone bed. Scale bar is 1 m.

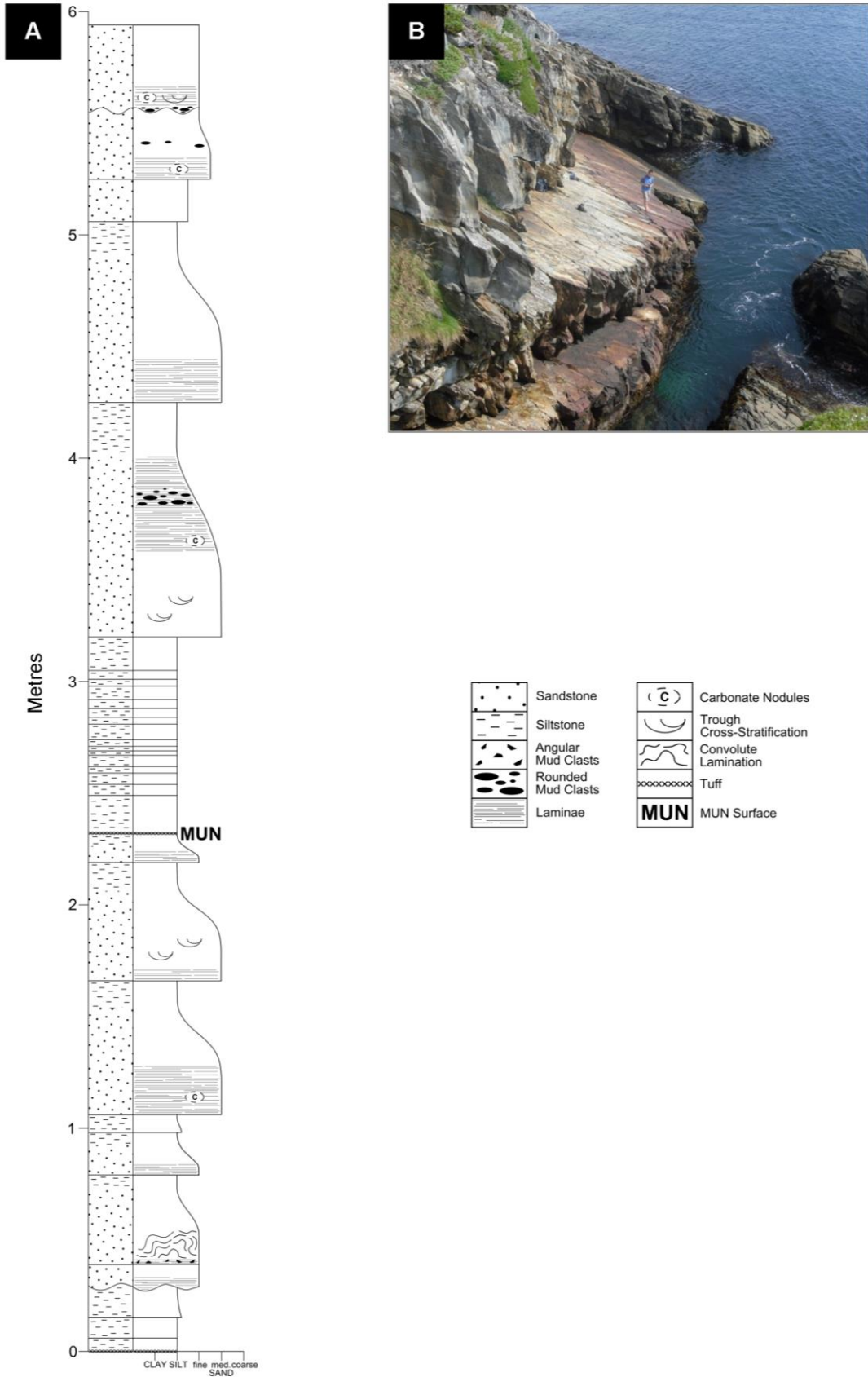


FIGURE 2.40. A) Log through the Port Union Formation, incorporating the MUN surface of Liu et al. (2016). B) Overview of the MUN Surface. Note red-rusty colour on the fossil surface. Diminutive palaeontologist for scale.

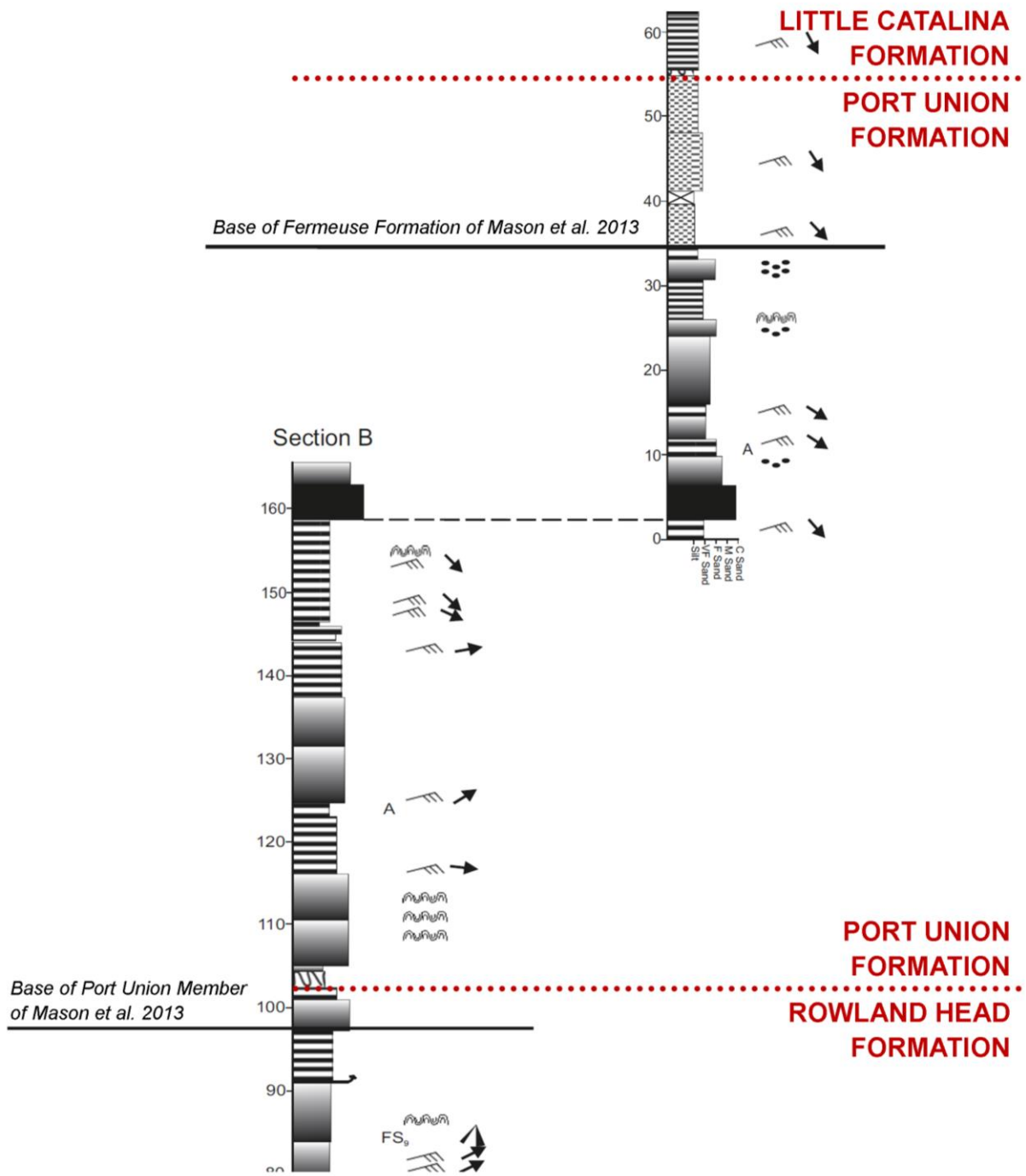


FIGURE 2.41. Log through the Port Union Formation, reproduced from Mason et al. (2013), whose field of study was restricted to the southern part of the Catalina Dome. Revisions to boundaries are shown in red. For legend see Figure 2.45. Scale in metres.

calcite (Figure 2.42). Rounded shale clasts are common and can be found isolated or clustered in the middle of a bed or in the troughs of erosive basal surfaces. Angular shale clasts are also found at the base of beds.

*Palaeontology.* The Port Union Formation has previously been regarded as the least fossiliferous of the units of the Catalina Dome (Mason et al., 2013). However, following extensive mapping of the area and cataloguing of fossil horizons undertaken as part of this thesis, the Port Union Formation is seen to exhibit the richest diversity of all the formations in the Trinity Bay North Group. The fossil assemblage includes: *Aspidella*, *Hiemalora*, *Charnia*, *Vinlandia*, *Charniodiscus*, *Beothukis*, *Fractofusus*, *Primocandelabrum*, *Bradgatia*, *Parviscopa*, *Hadryniscala*, *Thectardis*, and *Haootia*.

### **Little Catalina Formation**

*Name.* Designated after the community of Little Catalina in Trinity Bay North, where the type locality is situated. This is a revision to the former Back Cove Member of O'Brien and King (2005) and the unit is being promoted to formation status. The unit is also being renamed to avoid confusion, since the name Back Cove has previously been used for an Ordovician formation within the White Bay Group of the Baie Verte Peninsula, Newfoundland (Government of Canada, 2015).

*Type Locality and Stratotypes.* The type locality is Little Catalina, Trinity Bay North, Bonavista Peninsula, Newfoundland. The stratotype is those rocks cropping out in a small promontory at the back of Little Catalina Harbour, including Locality 22 of Hofmann et al. (2008) (N: 48°32'29.7" W: 053°0.'50.6").

*Distribution, Thickness, and Boundaries.* The Little Catalina Formation is the stratigraphically highest and therefore geographically outermost unit of the Catalina Dome



FIGURE 2.42. Patchy carbonate cementation in the Port Union Formation. A) Thin section in plane polarized light of siltstone with patchy carbonate cementation. The thin section is stained with Potassium Ferricyanide and Alizarin Red-S. Carbonate is faint purple in colour. B) As (A) but viewed under cross-polarized light. Scale bar is 1 cm.

mapped herein. The formation underlies the majority of the community of Little Catalina in the north, and outcrops on the coast in Back Cove. The top of the Little Catalina Formation was not mapped as the boundary was outside the study area. The thickness of the unit is therefore unknown. The base of the formation is defined at the onset of widespread slump structures within the succession.

*History.* The Little Catalina Formation comprises those rocks formerly described as the Back Cove Member of the Fermeuse Formation (O'Brien and King, 2005). Before this, they were mapped as “unseparated Renew’s Head and Fermeuse formation equivalents” (O'Brien and King, 2004).

*Sedimentary Description.* The Little Catalina Formation comprises thinly bedded grey to dark grey siltstones and shaley mudstones (Figure 2.38A; Figure 2.39). Some siltstone beds show a thin layer of starved ripple sandstones at the base. The Little Catalina Formation is best characterised by the presence of several units of very thickly bedded units of siltstones, mudstones, and carbonate-cemented fine-grained sandstones with contorted bedding that are inferred to be caused by large-scale slumping events (Figure 2.38B). Very thinly bedded tuffites are found throughout the formation. The Little Catalina Formation contains some zones of medium-bedded, normally-graded fine to medium-grained sandstones, especially near the base. A revised sedimentary log from Mason et al. (2013) from the Little Catalina Formation is provided in Figure 2.40.

The siltstones and minor sandstones of the Little Catalina Formation are dominantly quartzitic, with sub-angular grains. Sandstone lamina-sets at the base of beds, where present, are carbonate cemented.

*Palaeontology.* The Little Catalina Formation contains an abundance of fossils, especially near the base of the formation. Specimens include *Charnia*, *Vinlandia*, *Charniodiscus*,

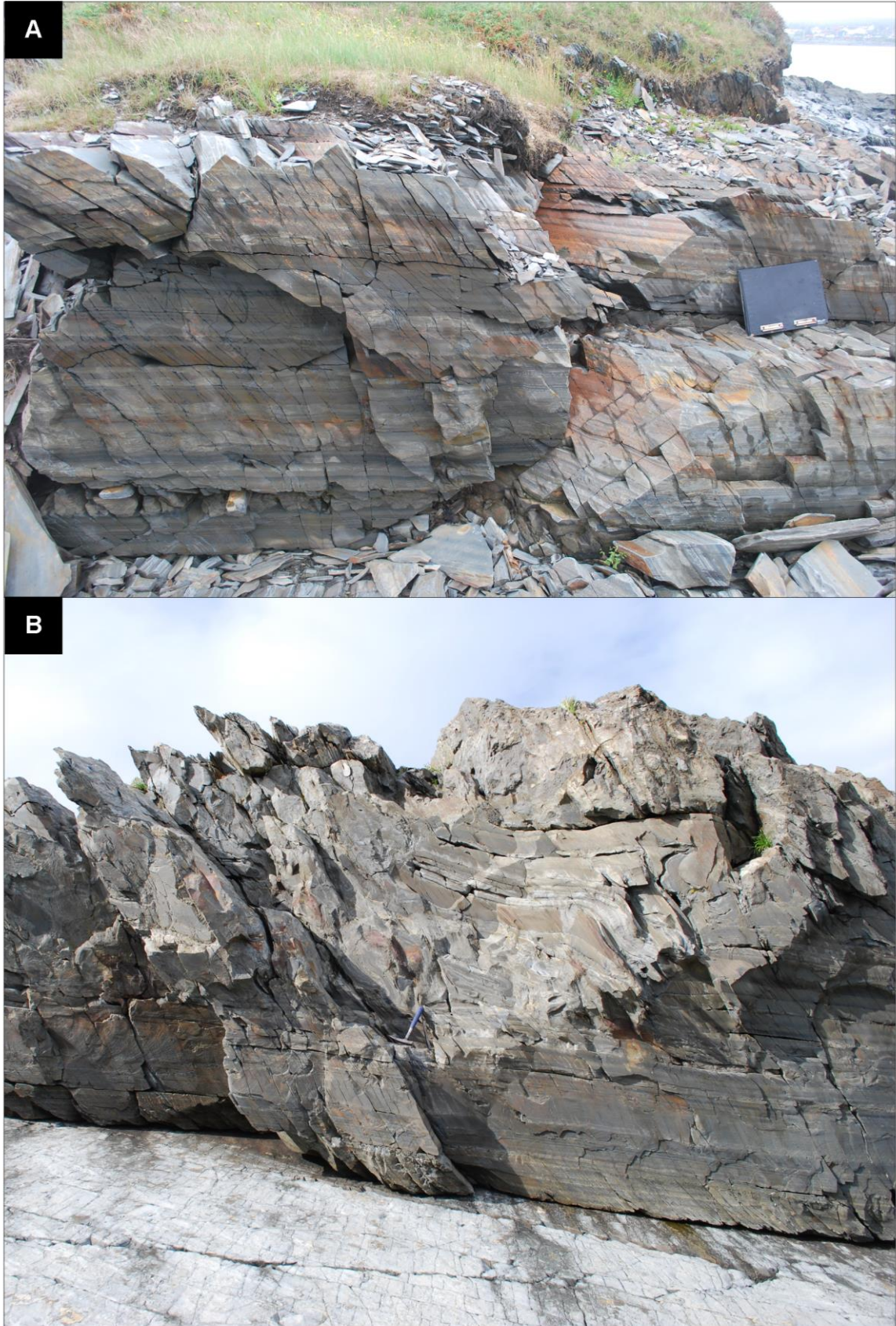


FIGURE 2.43. The Little Catalina Formation. A) Typical thin-bedded dark grey siltstones from the type locality in Little Catalina. Note A3 clipboard for scale. B) Slumped bedding within the Little Catalina Formation at Back Cove. Note geological hammer for scale.



FIGURE 2.44. Supplementary photographs of the Little Catalina Formation. A) Slumped and convolute bedded siltstones from the Little Catalina area. Note scale card with 1 cm gradations for scale. B) Thinly bedded grey siltstones from the Port Union area. Scale bar is 50 cm.

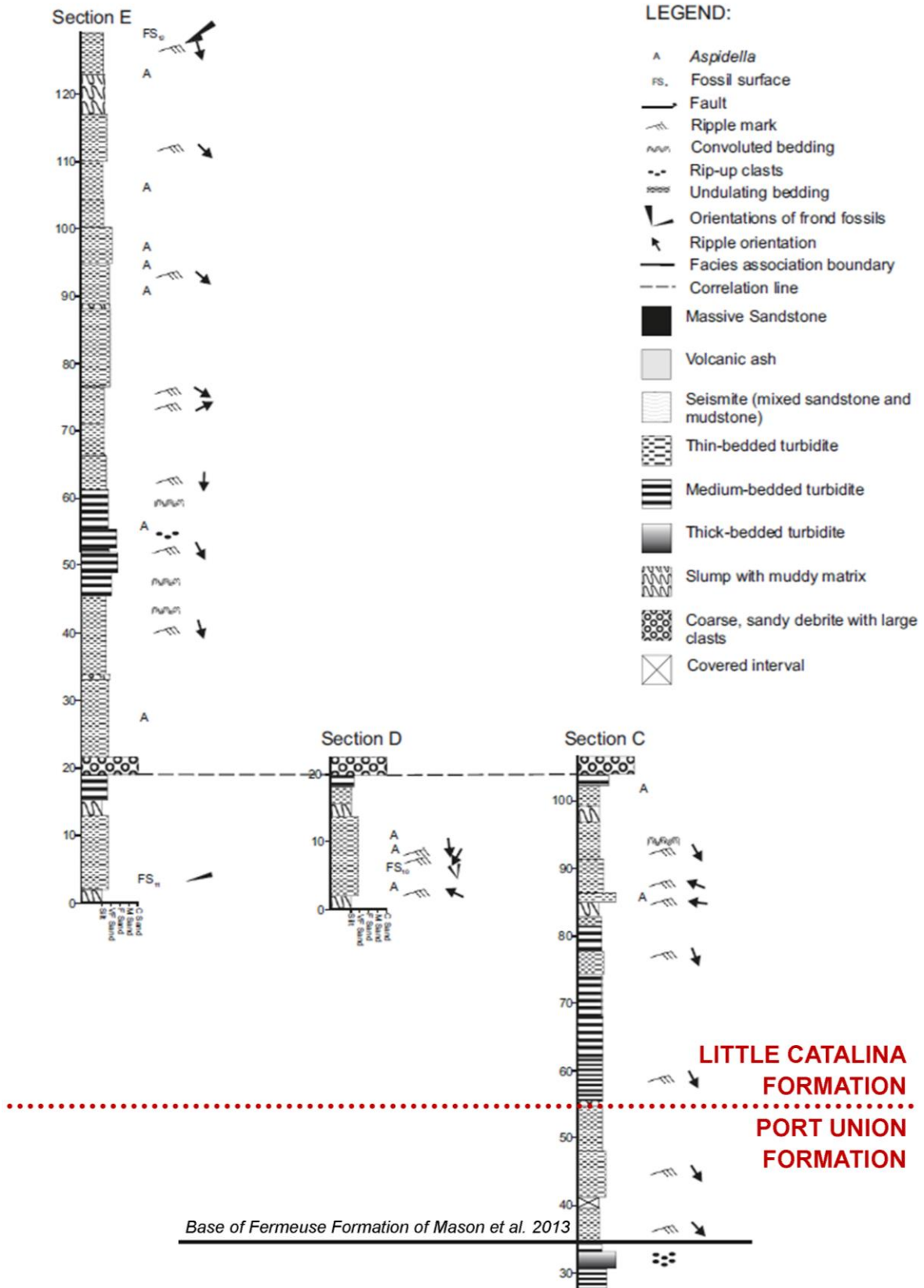


FIGURE 2.45. Log through the Little Catalina Formations, reproduced from Mason et al. (2013), whose field of study was restricted to the southern part of the Catalina Dome. Revisions to boundaries are shown in red. Scale in metres.

*Beothukis*, *Primocandelabrum*, *Bradgatia*, *Hadrynichorde* and the discoidal forms *Aspidella* and *Hiemalora*. The Little Catalina Formation is also host to the only known complete specimen of the stauromedusan-like *Haootia quadriformis*.

## **LITHOSTRATIGRAPHY OF EASTERN NEWFOUNDLAND REGION**

While the siliciclastic successions of Mistaken Point Ecological Reserves and the Catalina Dome are not worthy of direct lithostratigraphic correlation, as set out above, their general similarities, regional proximity, and shared palaeontology require recognition in stratigraphic classification.

*Statement of Intent:* The following is an attempt to erect the Chance Cove Supergroup, comprising the Conception Group, St. John's Group, Signal Hill Group, and Trinity Bay North Group. As this is an unpublished DPhil thesis, the following does not constitute a formal revision, as defined by the International Stratigraphic Guide (Salvador, 1994), until published in a peer-reviewed journal.

*Name.* Designated after Chance Cove, on the east coast of the Avalon Peninsula, Newfoundland, and site of the Chance Cove Provincial Park.

*Type Locality and Stratotypes.* The type locality is Chance Cove. The stratotype is the coastline in the region around Chance Cove, running from Cripple Cove (N: 46°38'40.7", W: 053°06'08.8") in the south to Cape Ballard (N: 46°47'07.3" W: 052°57'07.4") in the North. These outcrops provide a near complete section for the supergroup. The section is divided by the Frenchman's Cove Fault, with rocks to the south of Frenchman's Cove younging from the Drook Formation to the Fermeuse Formation, and rocks to the north east younging from the Fermeuse Formation to the Cape Ballard Formation. A para-stratotype on the Bonavista Peninsula runs from Burnt Point (N: 48°30'33.5", W:

053°02'59.5") to the back of Catalina Harbour at Port Union (N: 48°29'57.7" W: 053°05'09.5"), giving a near complete stratigraphic section from the top of the Trinity Bay North Group. The basal stratotype is found to the east of Mobile First Pond, Mobile where the Conception Group is seen to unconformably lie upon the Harbour Main Group (cf. O'Brien et al., 2001, Plate 7). The top of the supergroup is not seen in outcrop.

*Distribution, Thickness and Boundaries.* The base of the Chance Cove Supergroup is defined as the onset of widespread siliciclastic sedimentation upon the igneous derived units of the Harbour Main Group and the Holyrood Intrusive Suite. The top of the unit is not observed. The unit crops out across much of the eastern Avalon Peninsula, between St. Mary's Bay and the east coast of Newfoundland, as well as the eastern side of the Bay de Verde and Bonavista Peninsulas. The Chance Cove Supergroup comprises in excess of 7 km of sediments on the Avalon Peninsula, but is considerably thinner on the Bonavista Peninsula.

*History.* The rocks now comprising the Chance Cove Supergroup have never before been classified at supergroup level. A complete review of the units comprising the Chance Cove Supergroup is given in Figure 2.46.

*Other Relationships.* Further work is required to reveal whether the Connecting Point Group, Musgravetown Group, and Marystown Group should also be classified within the Chance Cove Supergroup.

*Sedimentary Description.* The Chance Cove Supergroup comprises a broadscale shallowing upwards sequence from siliceous, cherty siltstones, through turbiditic sandstones and siltstones, to dark grey siltstones with slumped bedding. In places these are overlain by a shallow marine succession of grey siltstones and sandstones, which in turn are overlain by fluviially deposited red conglomerates and sandstones.

## LITHOSTRATIGRAPHY OF THE CHANCE COVE SUPERGROUP

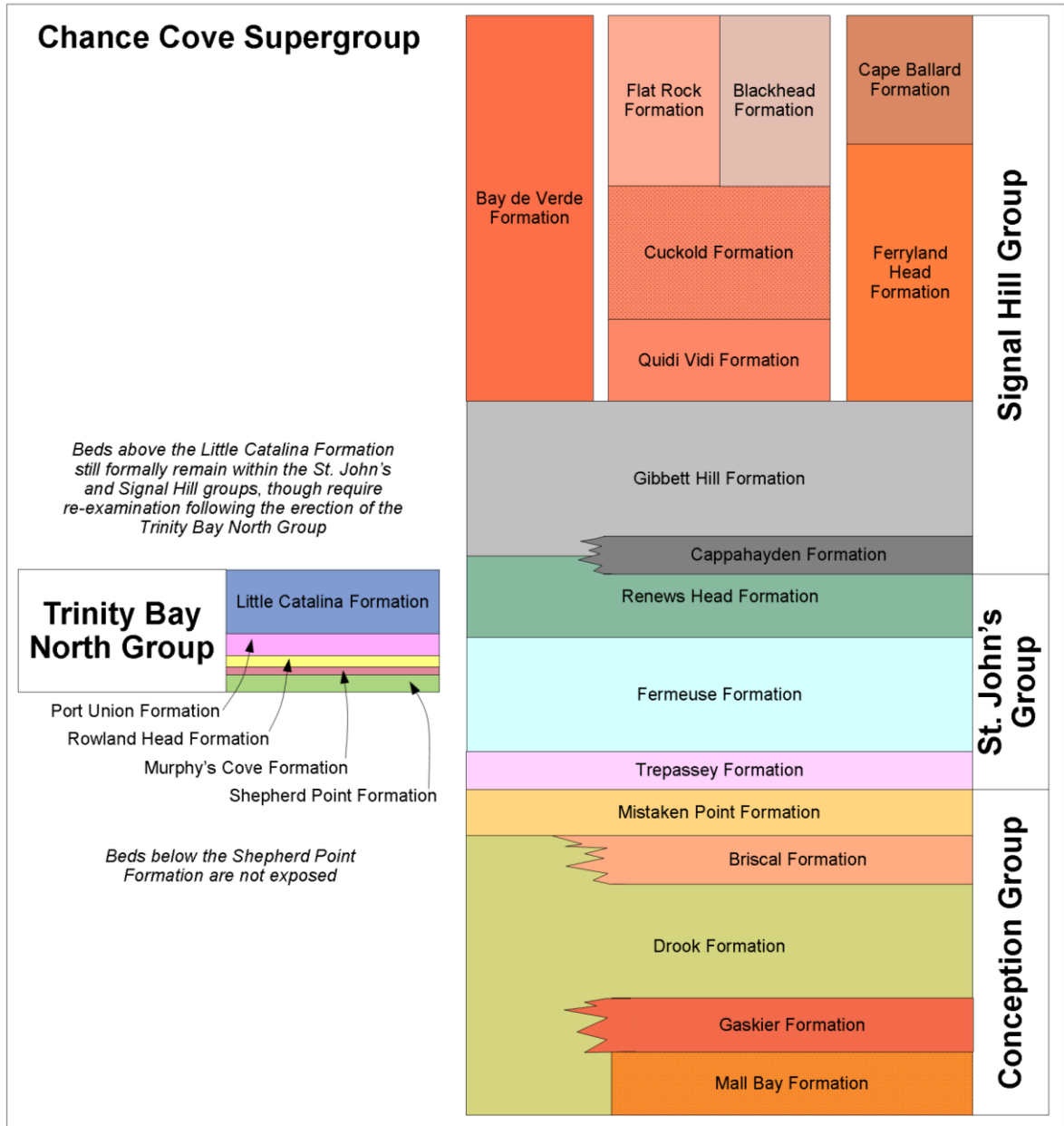


FIGURE 2.46. Overview of the newly created Chance Cove Supergroup, containing the Conception, St. John's, Signal Hill, and Trinity Bay North groups.

*Palaeontology*. The lower parts of the Chance Cove Supergroup are known to contain a diverse assemblage of late Ediacaran fossils, dominated by rangeomorph taxa such as *Charnia*, *Charniodiscus*, *Fractofusus*, and *Bradgatia*. The dominance of the discoidal form *Aspidella* had been used to assist in mapping some of the constituent units of the supergroup (Murray and Howley, 1918). The upper, shallow marine parts of the supergroup contain enigmatic structures such as *Palaeopascichnus*, *Beltinelliformis*, and *Intrites* (Matthews, 2011).

## **REVISIONS TO THE GEOLOGICAL MAP AND LITHOSTRATIGRAPHY**

### **Mistaken Point Ecological Reserve**

A more precise definition for the boundary between the Drook and Briscal Formations has led to revision of the stratigraphic affinity of the rocks to the north-west of Pigeon Cove. The rocks between Pigeon Cove and Daley's Point had previously been mapped as within the Drook Formation, but the presence of many thickly-bedded sands is better attributed to the Briscal Formation. The implication of this is to move several fossiliferous horizons, including the highest fidelity examples of *Trepassia wardae*, along with geochronological sample DRK-1, into the basal strata of the Briscal Formation.

In keeping with the geological map of Williams and King (1979), the Mistaken Point peninsula is here mapped as a dipping anticline of Mistaken Point Formation, with a fault differentiating the peninsula from the mainland, and outcrops of the overlying Trepassey Formation on the north eastern and south eastern sides of the peninsula. This is contrary to the geological maps of Clapham et al. (2003; 2004), and the logs of Wood et al. (2003), thereby affecting the stratigraphic position of a number of significant fossil-bearing surfaces. Bamforth et al. (2008) place the holotype and type locality for *Pectinifrons* at their 'Mistaken Point North' locality, said to be ~20 m up section from the D-Surface, and

within the Mistaken Point Formation. Detailed mapping of the area reveals that this surface crops out again, ~65 m directly above the D-Surface on the southern side of the Mistaken Point peninsula, in what is mapped here as the Trepassey Formation.

The stratigraphic position of the Trepassey Formation deposits situated directly to the south-west of Long Beach has remained a complex matter. The conspicuous lack of exposure around Long Beach, the relatively complex structure, and the herein described faulted contact with the Mistaken Point Formation has made correlation difficult.

Following the discovery of a unique horizon of notable character in the area around Long Beach, this section can now be confidently lithostratigraphically correlated into the rest main outcrops surrounding Mistaken Point.

Within a section dominated by grey, thinly bedded fine sandstones, normally graded, and often containing shale clasts, a horizon of elongate nodules is found. These nodules preferentially weather compared to the surrounding lithologies, with a characteristic 'crinkly' texture. The bedding above is convolute, with carbonate cement highlighting the laminations, and includes a conspicuous amount of blocky pyrite crystals. Sampling of the marker horizon itself has not been possible as of yet due to conservation regulations within MPER, however thin-section analysis on an isolated nodule of similar texture within the Fermeuse Formation revealed it to mainly consist of carbonate minerals.

This 'crinkly' carbonate layer, with accompanying beds of soft sediment deformation and cubic pyrites has also been found on south-east side of the Mistaken Point Formation (Figure 13B, C). This not only allows for the accurate positioning of the Long Beach area sediments within the wider stratigraphy, but also reinforces the case that the sediments on the eastern coast of the Mistaken Point Peninsula are from the Trepassey Formation.

Both the upper Trepassey Formation and the Fermeuse Formation have been previously described to contain slump structures (Wood et al., 2003). The onset of slumping within the succession is a clear indicator of a change in palaeoenvironmental setting, and one that is easily mappable across large distances. The base of the Fermeuse Formation was therefore revised to be the first occurrence of slumping within the succession, and as such the Trepassey-Fermeuse boundary has moved down section in the area of Shingle Head. This has the effect of moving a number of minor fossiliferous surfaces, mostly dominated by *Aspidella* into the Fermeuse Formation.

Detailed mapping along the entire coastline, assisted by the provision of photographs taken from offshore by MPER staff, has led to a more complete understanding of the structural complexity of the area. This has not only led to the discovery of new outcrops of previously known fossil surfaces, but also revisions of the thicknesses of the units present (Table 2.3). With the exception of the Trepassey Formation, the thicknesses of the formations within MPER has been substantially amended from that given by Williams and King (1979), mainly due to previously unrecognised folds and faults within the section.

<b>Formation</b>	<b>Thickness in MPER (Williams and King, 1979)</b>	<b>Thickness in MPER (herein)</b>
Fermeuse	~ 400 m	720 m
Trepassey	250 m	240 m
Mistaken Point	400 m	290 m
Briscal	1200 m	310 m
Drook	~500 m	770 m

TABLE 2.3. Comparison of thicknesses of the various formations within the Mistaken Point Ecological Reserve. Note that complete sections of the Drook and Fermeuse Formations are not present within MPER.

### **Catalina Dome**

The rocks of the Catalina Dome were first compared to those of the Avalon Peninsula, Newfoundland, during the first geological survey of the then Colony of Newfoundland,

where the rocks were identified as part of the '*Lower Slate Formation*' (Jukes, 1843). They have since been mapped as part of the Musgravetown Group (Christie, 1950), and most recently as the same lithostratigraphic units used around Mistaken Point (O'Brien and King, 2004; O'Brien and King, 2005; Hofmann et al., 2008).

This most recent lithostratigraphic correlation is based on a '*proposed biostratigraphic correlation of the fossiliferous turbidites around Catalina and Port Union with the Mistaken Point Formation*' (O'Brien and King, 2004), namely that they both contain Ediacaran fossils. Extensive mapping of the Trinity Bay North area, while confirming the presence of abundance fossiliferous horizons similar to Mistaken Point, shows that these two sections cannot be confidently correlated lithostratigraphically, based on international norms;

*'Units should be extended only so far as the definite lithological features on which the unit is based at the type section are known certainly to exist or through indirect evidence are presumed with assurance to continue'*

The International Stratigraphic Guide (Salvador, 1994)

The null hypothesis in stratigraphy should therefore be that lithostratigraphic units are different, until such time as they can reasonably be proved to be the same. This prevents observations in one locality being unduly applied to another section of rock, and tempers the habit of lithostratigraphic correlation being used to incorrectly infer chronostratigraphic correlation.

Table 2.4 shows the comparison of the descriptions for the formations mapped herein from the Mistaken Point Ecological Reserve and the Catalina Dome, but based on the lithostratigraphic correlation of O'Brien and King (2005). While there are some similarities, such as cherty rocks at the base, and slumped thinly bedded rocks at the top, there are also many differences between the sections.

Mistaken Point Ecological Reserve	Catalina Dome
<p><b>Fermeuse Formation</b> - Thinly bedded dark grey and black siltstones with local phosphatic nodules. Metre-scale slump structures. Discreet tuffite units are rare.</p>	<p><b>Little Catalina Formation</b> - Thinly bedded grey to dark grey siltstones and shales, some with thin starved ripple sandstones at base. Metre-scale slump structures. Minor thinly bedded tuffites. Minor medium bedded sandstones.</p>
<p><b>Trepassey Formation</b> - Thinly bedded grey siltstones with local cross-laminated, carbonated cemented, often pyritiferous starved ripple sandstones at the base of units. Rare thickly bedded debris flows near base of unit. Minor tuffite beds.</p>	<p><b>Port Union Formation</b> - Medium to thickly bedded grey, normally graded sandstones, often with areas of convolute bedding, rounded shale clasts, and zones are carbonate cementation. Minor thinly to medium bedded grey siltstones are ubiquitous. Minor thinly bedded tuffites.</p>
	<p><b>Rowland Head Formation</b> - Thinly bedded, normally graded, grey and green siltstones, often with carbonate cemented starved ripples of sand at the base of beds. Tuffaceous horizons. Lower part of the Formation contains abundant cubic pyrite crystals. Local phosphatic nodules near top of unit.</p>
<p><b>Mistaken Point Formation</b> - Thickly bedded graded purple, green and grey sandstones and thin to medium bedded grey, green and occasionally purple graded siltstones. Tuffaceous beds common.</p>	<p><b>Murphy's Cove Formation</b> - Thinly bedded dark green and grey, slightly mottled, laminated siltstones, which are noticeably less cherty than the underlying Shepherd Point Formation. Abundant tuffaceous horizons.</p>
<p><b>Drook Formation</b> - Thinly to medium bedded green, grey, and pink siliceous siltstones and sandstones, normally graded, with local thickly bedded sandstones. Rare debrites and rafts of shale clasts within beds.</p>	<p><b>Shepherd Point Formation</b> - Thinly to very thinly bedded cherty laminated fine sandstones, siltstones and mudstones, often variegated between white, green, pink, red, grey, brown and purple, with rare medium and thickly bedded strata. Rare tuffaceous horizons.</p>

TABLE 4. Comparison of lithologic descriptions (presented herein) of formations at Mistaken Point Ecological Reserve, and the Catalina Dome, based on lithostratigraphic correlation of O'Brien and King (2005). Briscal Formation not included as this formation has never been correlated to the Catalina Dome.

The Shepherd Point and Murphy's Cove Formations lack debris flow deposits – that are present in the Drook and Mistaken Point Formations with which they were formerly correlated. The Shepherd Point and Murphy's Cove Formation are also less-characteristically turbiditic in nature than their former correlatives. The Shepherd Point and Murphy's Cove Formations are dominated by laminated siltstones and with many beds lacking the graded bedding expected of proximal sand-rich turbidity current deposits. The

depositional setting is likely to be distal turbidite fan or a setting rich in mud-rich turbidite flows.

The Murphy's Cove Formation is noticeably thinner bedded and finer grained than the Mistaken Point Formation, and the dominance of thickly bedded sandstones in the Port Union Formation argues against correlation with the Trepassey Formation, based on the description of the Formation at its type locality.

The presence of minor medium bedded sandstones within the otherwise siltstone-dominated Little Catalina Formation makes it lithologically most similar to the Trepassey Formation of the Avalon Peninsula, rather than the Fermeuse Formation with which it has been previously correlated – save for the fact that both the Little Catalina and Fermeuse Formations contain slumped bedding.

There is insufficient evidence to correlate the two successions on lithostratigraphic grounds, and therefore there is a need for a distinct stratigraphic scheme, as is presented herein.

The Goodland Point Member of O'Brien and King (2005) was described as being characterised by medium to thick bedded siliceous turbidites with tuffaceous interbeds. Recent fieldwork shows the rocks of Goodland Point to be mostly lacking in tuffaceous horizons, and the outcrops are dominated by thinly bedded cherty rocks. These rocks are indistinguishable from those of the Shepherd Point Formation. Therefore, areas previously mapped as Goodland Point Member should be considered as part of the new Shepherd Point Formation.

The names of all the described formations are based on previous members that stood in their place, save for that of the former Catalina Member and Back Cove Member whose geographic terms had already been used to name geological units within Newfoundland.

A more accurate geological map has been produced by careful bed-level correlation across the Catalina Dome. The highly fossiliferous MUN Surface of the Port Union Formation at Burnt Point (Liu et al., 2016), was found to crop out again south of Little Catalina, though a paucity of bedding plane exposure prevented observation of the fossil assemblage. The *Fractofusus*-rich outcrop known as the “Johnson Surface” (Locality 14, Hofmann et al., 2008) was also found to outcrop again at Rowland Head.

## **STRATIGRAPHIC RELATIONSHIPS**

Separation of the stratigraphies at the Mistaken Point Ecological Reserve and the Catalina Dome necessitates a re-evaluation of the stratigraphic relationships between these two sections.

The mapped section at MPER comprises nearly 2500 m of deposits, ascribed to the Conception and St. John’s groups. These are overlain by the red beds of the Signal Hill Group, though these are not seen within the study area. The field of study at the Catalina Dome comprises over 500 m of deposits, herein catalogued as the Trinity Bay North Group. These are overlain by deposits still defined as the St. John’s and Signal Hill groups; though this needs to be reconsidered following the work presented here. The thicknesses of the mapped units for both sections is shown in Figure 2.47.

Four hypotheses are considered to explain the relationship between the two localities (Figure 2.47). For simplicity, those deposits above the Trinity Bay North Group previously described as the St. John’s and Signal Hill groups, but now requiring revision,

## STRATIGRAPHIC THICKNESS AND RELATIONSHIPS

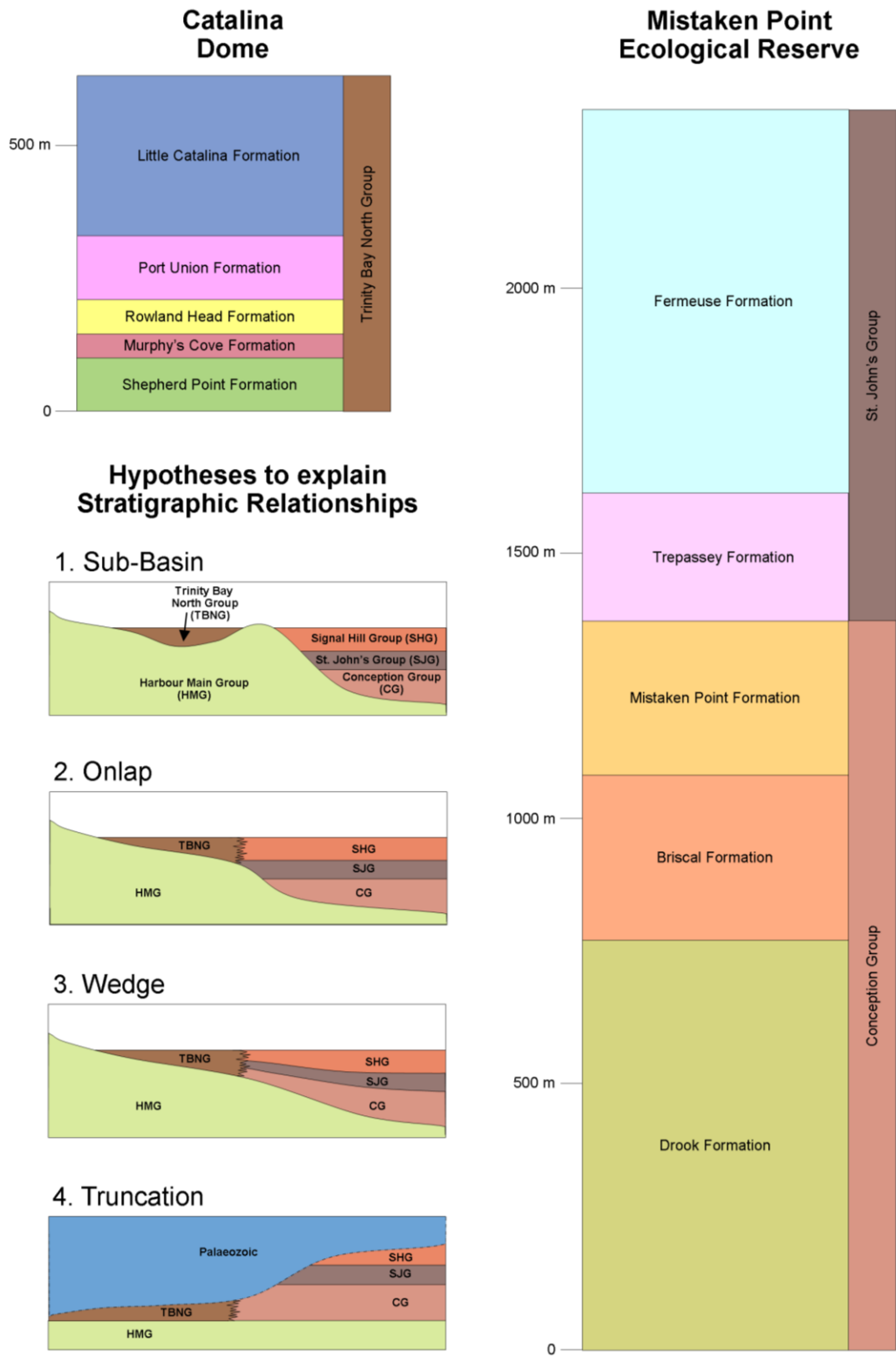


FIGURE 2.47. Stratigraphic thickness comparison and relationship hypotheses between the Catalina Dome and Mistaken Point Ecological Reserve sections.

have been included within the Trinity Bay North Group. The sub-basin hypothesis assumes the Trinity Bay North Group is deposited in a sub-basin, off the basin in which the Conception, St. John's, and Signal Hill groups are deposited. It is assumed that the Harbour Main Group underlies the basin. The onlap hypothesis explains the great difference in thickness between MPER and Catalina Dome sections by having the MPER sediments onlap onto a slope, with the Trinity Bay North Group deposited upslope from this and as a lateral equivalent to the deposits above the Conception Group. The wedge hypothesis assumes that the Trinity Bay North Group is a lateral equivalent of the Conception, St. John's, and Signal Hill groups, with a necessary thinning of these groups towards the Bonavista Peninsula to facilitate this. The truncation hypothesis assumes the difference in thickness between MPER and Catalina Dome is due to post-depositional erosion, most likely in the event now observed as the sub-Palaeozoic unconformity. The Trinity Bay North Group would therefore be the lateral equivalent of the Drook Formation of MPER.

Geochronological data presented herein (Chapter 4) can be used to reject some of these hypotheses. While the Catalina Dome section is much thinner than that seen in MPER, the age data shows it was deposited at the same time, and across a similar duration of time to the MPER section. The onlap and truncation hypotheses can therefore be ruled out, as they assume the Trinity Bay North Group was syndepositional with comparative thicknesses of lithology at the top and bottom of the Avalon Peninsula section, respectively. The differences in sedimentation rate implied by the geochronological data can only be accommodated by the sub-basin and wedge models.

Distinguishing between these two remaining hypotheses is not possible with the currently available information. The sub-basin model would require a palaeo-high in the Harbour Main Group (Figure 2.48). Assuming the deposits of the Bay de Verde Peninsula remain

**DIAGRAM OF MAJOR STRATIGRAPHIC RELATIONSHIPS**  
(not drawn to scale)

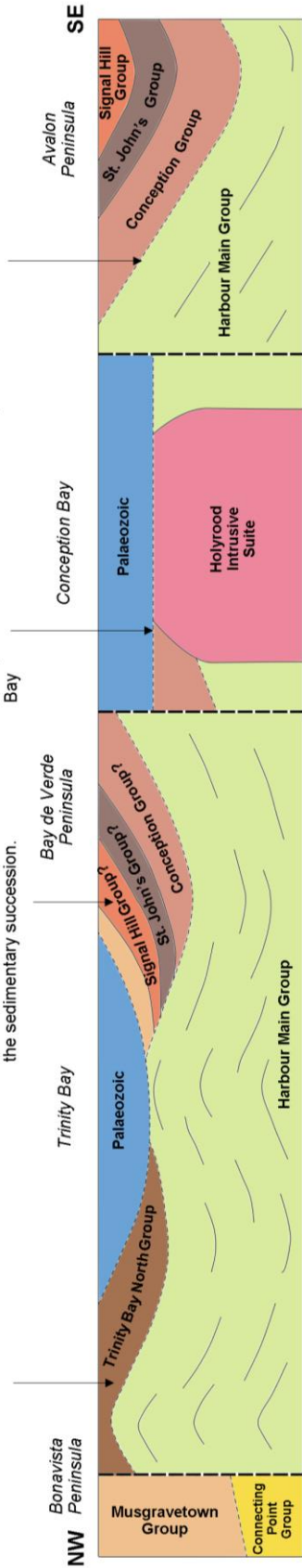
**SUB-BASIN MODEL**

The Trinity Bay North Group is deposited in a subbasin of the wider eastern Avalon back arc basin, and may not have a direct stratigraphic contact with the sediments of the Avalon Peninsula.

Conception, St. John's, and Signal Hill groups are overlain by the Musgravetown Group in the Bay de Verde Peninsula. Harbour Main Group assumed to underlie the sedimentary succession.

Palaeozoic deposits lie unconformably upon the Conception Group, Holyrood Intrusive Suite, and the Harbour Main Group, as observed around Conception Bay.

Unconformable contact between the Conception Group and the Harbour Main Group, as observed on the Avalon Peninsula.

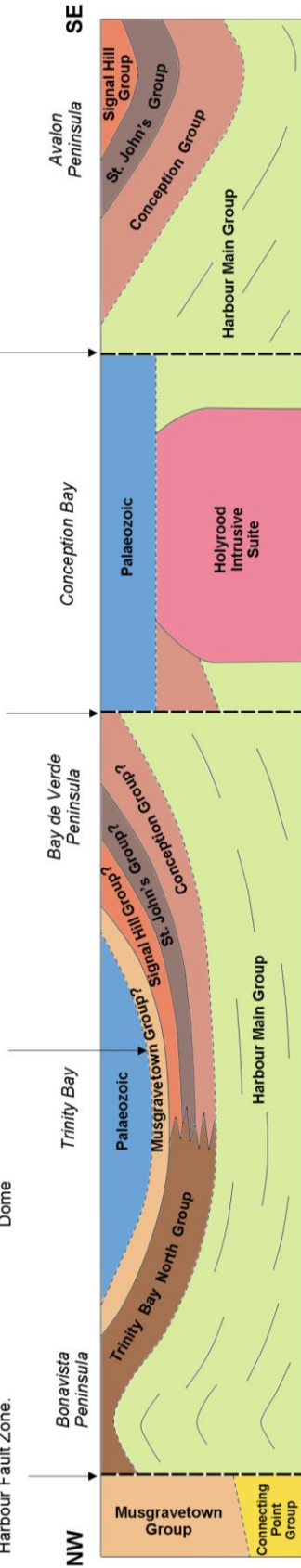


Trinity Bay North Group faulted against the Musgravetown Group to the west of the Catalina Dome by the Spillers Cove-English Harbour Fault Zone.

The Trinity Bay North Group is a thinner, lateral equivalent of the Ediacaran sediments of the Bay de Verde Peninsula—the stratigraphic affinity of which requires confirmation following work on the Catalina Dome.

Conception Group faulted against Palaeozoic and Harbour Main Group deposits along the Brigus Fault.

Harbour Main Group faulted against Palaeozoic deposits along the Topsail Fault.



**WEDGE (LATERAL EQUIVALENT) MODEL**

FIGURE 2.48. Diagram of major stratigraphic relationships for the Sub-Basin and Wedge models that attempt to explain the association between the Catalina Dome and Mistaken Point Ecological Reserve sections.

assigned to the Conception, St. John's, and Signal Hill groups, then the palaeo-high is expected somewhere in or around Trinity Bay, with formations from both sides of the high expected to onlap onto it. This has not yet been observed, but may not currently be expressed as outcrop. The wedge model requires a lateral transition between the Catalina Dome and MPER sections (Figure 2.48). Again, assuming the intermediate rocks of the Bay de Verde Peninsula remain associated with the Conception, St. John's, and Signal Hill Groups, this transition would be expected to be in or around Trinity Bay. Currently known outcrops preclude the testing of this hypothesis, as with the sub-basin model, however future studies of palaeocurrent direction from a more geographically diverse area than those areas known for exceptionally preserved Ediacaran macrofossils may assist in understanding this question.

## **CONCLUSIONS**

Extensive field mapping of coastal outcrops has generated a more accurate geological map of the Mistaken Point Ecological Reserve (MPER) area, and improved understanding of the lithostratigraphic relationships within the succession. Increased understanding of the structure with the MPER has led to the revision for formation thicknesses, most notably in the Briscal Formation where the discovery of repeated sections has radically decreased the thickness of the unit. Stratigraphic revisions provide a more robust framework for future litho-correlation studies across the Avalonian outcrops of Newfoundland, and allows for more accurate correlation of outcrops within MPER. The succession cropping out around MPER comprises ~2500 m of siliciclastic rocks, containing a diverse community of late Ediacaran fossils.

Re-evaluation of the stratigraphy of the Catalina Dome, Bonavista Peninsula, via comprehensive field studies reveals the previous lithological correlation with the rocks of

MPER to be erroneous. The rocks of the Catalina Dome are therefore reclassified as part of the newly created Trinity Bay North Group. This group comprises a ~500 m thick siliciclastic succession containing a number of key Ediacaran fossil horizons, including that which yielded *Haootia quadriformis*, which has been tentatively assigned to the Cnidaria.

The decoupling of the Trinity Bay North Group of the Catalina Dome, from the Conception and St. John's groups of MPER promotes independent study, and allows a lithostratigraphic framework in which palaeontological and other stratigraphic data can be compared and contrasted between the two sections, without the biases erroneously implied by lithostratigraphic correlation.

It is suggested that the relationship between the MPER and Catalina Dome sections can be explained by the Trinity Bay North Group being deposited in a sub-basin to that in which the Conception and St. John's Groups were deposited, or alternatively as part of a sediment wedge where the Trinity Bay North Group is the thinner stratigraphic equivalent of the MPER formations. Further evidence is needed to decide between these hypotheses.

The reclassification of the rocks of the Catalina Dome precipitates not only a similar reanalysis of the formations lying above the Catalina Dome, but also other Ediacaran outcrops between the Bonavista Peninsula and MPER that are currently assigned to the Conception and St. John's groups. Future work in areas such as Spaniard's Bay and Torbey is necessary to further explore the lateral variations in the Chance Cove Supergroup.

## **ACKNOWLEDGEMENTS**

This research was supported by the Natural Environment Research Council (grant number NE/J5000045/1) and a NIGFSC award. Alex Liu and Tom Hearing are thanked for their help and assistance in gathering the data. Peter J. Matthews is thanked for assistance in slabbing of large samples. The people of Portugal Cove South, and Trepassey are thanked for their hospitality. The Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, provided permits to conduct research within the Mistaken Point Ecological Reserve. Access for research to fossil localities within the Mistaken Point Ecological Reserve is by permit only. Grid references for localities are not published, in accordance with MPER research permit conditions, but can be obtained from the author directly. Readers are advised that the fossils around Cape Race are protected by the Paleontological Resource Regulations 67/11, under the Historic Resources Act, 1990.

## **REFERENCES**

- Bamforth, E.L., and Narbonne, G.M., 2009, New Ediacaran Rangeomorphs from Mistaken Point, Newfoundland, Canada: *Journal of Paleontology*, v. 83, no. 6, p. 897–913.
- 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*, v. 82, no. 4, p. 763–777.
- Benus, A.P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland): *Trace Fossils, Small Shelly Fossils and the Precambrian Cambrian Boundary: Proceedings, 1987, Memorial University (New York State Museum and Geological Survey Bulletin)*, p. 8–9.
- Bokman, J.W., 1957, Suggested use of bed-thickness measurements in stratigraphic descriptions: *Journal of Sedimentary Research*, v. 27, no. 3, p. 333–335, doi: 10.1306/74D706E1-2B21-11D7-8648000102C1865D.
- Brasier, M.D., Antcliffe, J.B., and Liu, A.G., 2012, The architecture of Ediacaran Fronds: *Palaeontology*, v. 55, no. 5, p. 1105–1124, doi: 10.1111/j.1475-4983.2012.01164.x.
- Brett, C.E., and Baird, G.C., 2002, Revised stratigraphy of the Trenton Group in its type area, central New York State: *sedimentology and tectonics of a Middle Ordovician*

shelf-to-basin succession: *Physics and Chemistry of the Earth, Parts A/B/C*, v. 27, no. 1–3, p. 231–263, doi: 10.1016/S1474-7065(01)00007-9.

- Christie, A.M., 1950, *Geology of Bonavista map-area, Newfoundland*: Department of Mines and Technical Surveys.
- Clapham, M.E., Narbonne, G.M., and Gehling, J.G., 2003, Paleoeecology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland: *Paleobiology*, v. 29, no. 4, p. 527–544, doi: 10.1666/0094-8373(2003)029<0527:POTOKA>2.0.CO;2.
- Clapham, M.E., Narbonne, G.M., Gehling, J.G., Greentree, C., and Anderson, M.M., 2004, *Thectardis avalonensis*: A new Ediacaran fossil from the Mistaken Point biota, Newfoundland: *Journal of Paleontology*, v. 78, no. 6, p. 1031–1036.
- Dickson, J. a. D., 1965, A Modified Staining Technique for Carbonates in Thin Section: *Nature*, v. 205, no. 4971, p. 587–587, doi: 10.1038/205587a0.
- Eyles, N., and Eyles, C.H., 1989, Glacially-influenced deep-marine sedimentation of the Late Precambrian Gaskiers Formation, Newfoundland, Canada: *Sedimentology*, v. 36, no. 4, p. 601–620, doi: 10.1111/j.1365-3091.1989.tb02088.x.
- Fisher, W., and Thornton, J., 1689, *The English Pilot. The Fourth Book, describing The Sea-Coasts ... from the River Amazons to Newfoundland, with all the West India Navigation, etc.* pp. 50.: London.
- Flude, L.I., and Narbonne, G.M., 2008, Taphonomy and ontogeny of a multibranch ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland: *Canadian Journal of Earth Sciences*, v. 45, no. 10, p. 1095–1109.
- Gardiner, S., and Hiscott, R.N., 1988, Deep-water facies and depositional setting of the lower Conception Group (Hadrynian), southern Avalon Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 25, no. 10, p. 1579–1594, doi: 10.1139/e88-151.
- 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*, v. 44, no. 3, p. 367–387, doi: 10.1139/E07-003.
- Government of Canada, N.R.C., 2015, *Lexicon of Canadian Geological Names on-line*:
- Hathway, B., and Lomas, S.A., 1998, The Jurassic–Lower Cretaceous Byers Group, South Shetland Islands, Antarctica: revised stratigraphy and regional correlations: *Cretaceous Research*, v. 19, no. 1, p. 43–67, doi: 10.1006/cres.1997.0095.
- Hofmann, H.J., O'Brien, S.J., and King, A.E., 2008, Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada: *Journal of Paleontology*, v. 82, no. 1, p. 1–36, doi: 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*, v. 44, no. 1, p. 25–41.
- Ingram, R.L., 1954, Terminology for the Thickness of Stratification and Parting Units in Sedimentary Rocks: *Geological Society of America Bulletin*, v. 65, no. 9, p. 937–938, doi: 10.1130/0016-7606(1954)65[937:TFTTOS]2.0.CO;2.
- Israel, S., 1998, Geochronological, structural and stratigraphic investigation of a Precambrian unconformity between the Harbour Main Group and Conception Group, east coast Holyrood Bay, Avalon Peninsula, Newfoundland.: Unpublished B.Sc. Thesis, Memorial University, p. 78.
- Jukes, J.B., 1843, General Report of the Geological Survey of Newfoundland: Executed Under the Direction of the Government and Legislature of the Colony During the Years 1839 and 1840: J. Murray.
- King, A.F., 1990, Geology of the St. John's area: Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador.
- Krogh, T.E., Strong, D.F., and Papezik, V.S., 1983, Precise U-Pb ages of zircons from volcanic and plutonic units in the avalon peninsula: Abstracts with Programs, 18th Annual Meeting, Northeastern Section, Geological Society of America, v. 15, p. 135.
- Liu, A.G., 2011, Understanding the Ediacaran assemblages of Avalonia: a palaeoenvironmental, taphonomic and ontogenetic study [Unpublished DPhil Thesis]: University of Oxford.
- 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*, v. 59, no. 1, p. 45–58, doi: 10.1111/pala.12206.
- 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*, v. 54, no. 3, p. 607–630, doi: 10.1111/j.1475-4983.2010.01024.x.
- 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*, v. 38, no. 2, p. 123–126.
- 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*, v. 169, no. 4, p. 395–403, doi: 10.1144/0016-76492011-094.
- Mackie, A., and Smallwood, S., 1987, A revised stratigraphy and sedimentology of the Abergwesyn–Pumpsaint area, Mid-Wales: *Geological Journal*, v. 22, no. S1, p. 45–60, doi: 10.1002/gj.3350220506.
- Mason, S.J., Narbonne, G.M., Dalrymple, R.W., and O'Brien, S.J., 2013, Palaeoenvironmental analysis of Ediacaran strata in the Catalina Dome, Bonavista

- Peninsula, Newfoundland: Canadian Journal of Earth Sciences, v. 50, no. 2, p. 197–212, doi: 10.1139/cjes-2012-0099.
- Matthews, J.J., 2011, The Palaeontology and Palaeoenvironments of the Ferryland Siliciclastic Sequence: Unpublished Masters Thesis, University of Oxford,.
- McAlpine, K.D., 1990, Mesozoic Stratigraphy, Sedimentary Evolution, and Petroleum Potential of the Jeanne D'Arc Basin, Grand Banks of New Foundland: Geological Survey of Canada.
- McLoughlin, S., and Drinnan, A.N., 1997, Revised stratigraphy of the Permian Bainmedart coal measures, northern Prince Charles Mountains, east Antarctica: Geological Magazine, v. 134, no. 3, p. 335–353, doi: 10.1017/S0016756897006870.
- Misra, S.B., 1971, Stratigraphy and Depositional History of Late Precambrian Coelenterate-Bearing Rocks, Southeastern Newfoundland: Geological Society of America Bulletin, v. 82, no. 4, p. 979–988, doi: 10.1130/0016-7606(1971)82[979:SADHOL]2.0.CO;2.
- Moreno, F., Hendy, A.J.W., Quiroz, L., Hoyos, N., Jones, D.S., Zapata, V., Zapata, S., Ballen, G.A., Cadena, E., Cárdenas, A.L., Carrillo-Briceño, J.D., Carrillo, J.D., Delgado-Sierra, D., Escobar, J., et al., 2015, Revised stratigraphy of Neogene strata in the Cocinetas Basin, La Guajira, Colombia: Swiss Journal of Palaeontology, v. 134, no. 1, p. 5–43, doi: 10.1007/s13358-015-0071-4.
- Murray, A., 1881, Reports of Progress on the Geological Survey of Newfoundland 1864-1881:
- Murray, A., and Howley, J.P., 1918, Reports of Geological Survey of Newfoundland: From 1881-1909: Robinson & Company.
- Narbonne, G.M., Dalrymple, R.W., Gehling, J.G., Wood, D.A., Clapham, M.E., and Sala, R.A., 2001, Neoproterozoic fossils and environments of the Avalon Peninsula, Newfoundland, *in* Field Trip B,.
- Narbonne, G.M., Dalrymple, R.W., Laflamme, M., Gehling, J.G., and Boyce, W.D., 2005, Life After Snowball: Mistaken Point Biota and the Cambrian of the Avalon, *in* NAPC 2005 Field Guide,.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: Geology, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- O'Brien, S.J., Dunning, G.R., Dube, B., Sparkes, B., Israel, S., and Ketchum, J., 2001, New insights into the Neoproterozoic geology of the central Avalon Peninsula (parts of NTS map areas 1N/6, 1N/7 and 1N/3), eastern Newfoundland: Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, p. 169–189.
- 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 Report, p. 4–1.
- O'Brien, S.J., and King, A.F., 2005, Late Neoproterozoic (Ediacaran) stratigraphy of Avalon Zone sedimentary rocks, Bonavista Peninsula, Newfoundland: Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, p. 6–1.
- Papezik, V.S., 1970, Petrochemistry of volcanic rocks of the Harbour Main Group, Avalon Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 7, no. 6, p. 1485–1498, doi: 10.1139/e70-141.
- Rose, E.R., 1952, Torbay map-area, Newfoundland.:
- Salvador, A., 1994, *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*: Geological Society of America.
- Shen, B., Dong, L., Xiao, S., and Kowalewski, M., 2008, The Avalon Explosion: Evolution of Ediacara Morphospace: *Science*, v. 319, no. 5859, p. 81–84, doi: 10.1126/science.1150279.
- Sinclair, I.K., 1988, Evolution of Mesozoic-Cenozoic sedimentary basins in the Grand Banks area of Newfoundland and comparison with Falvey's (1974) rift model: *Bulletin of Canadian Petroleum Geology*, v. 36, no. 3, p. 255–273.
- Skipton, D.R., Dunning, G.R., and Sparkes, G.W., 2013, Late Neoproterozoic arc-related magmatism in the Horse Cove Complex, eastern Avalon Zone, Newfoundland: *Canadian Journal of Earth Sciences*, v. 50, no. 4, p. 462–482, doi: 10.1139/cjes-2012-0090.
- Sparkes, G.W., O'Brien, S.J., Dunning, G.R., and Dubé, B., 2005, U–Pb geochronological constraints on the timing of magmatism, epithermal alteration and low-sulphidation gold mineralization, eastern Avalon Zone, Newfoundland: *Current research*, p. 5–1.
- Walcott, C.D., 1899, *Pre-cambrian Fossiliferous Formations*:
- Weston, T.C., 1892, *Notes on concretionary structure in various rock formations in Canada*:
- Williams, H., and King, A.F., 1979, *Trepassey map area, Newfoundland*: Geological Survey of Canada, Energy, Mines, and Resources Canada.
- 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*, v. 40, no. 10, p. 1375–1391.

# Chapter 3: Sedimentology of the Mistaken Point Ecological Reserve and Catalina Dome

---

## **ABSTRACT**

The Ediacaran fossils of the Mistaken Point Ecological Reserve, and the Catalina Dome have been reconstructed by some as having lived and died in terrestrial and shallow marine environments. Critical analysis of both these siliciclastic successions reveals no evidence for shallow marine or sub-aerial deposition, and geochemical proxies are found to have been used outside the parameters of their methodology in proposing non-marine depositional environments. Reanalysis shows these successions were most likely deposited in deep marine environments, excluding photoautotrophic affinities for the Ediacara Biota present. Close examination of the sedimentology of tuffaceous horizons, thought to have smothered and cast the Ediacaran palaeocommunities, reveals they were deposited by ashy turbidity currents. This not only has significant potential to improve the taphonomic understanding of the Ediacaran assemblage, but also required any geochronological data yielded therefrom to be scrutinised in detail due to the implied resedimentation. The stratigraphic succession exposed in the Mistaken Point Ecological Reserve evidences the initial rifting, spreading, and mature phases of an Ediacaran backarc basin. The Catalina Dome succession shows deposition within similar environments to the Mistaken Point Ecological Reserve, revealing similar depositional processes. More research is required to better understand the precise depositional environments of specific formations within Catalina Dome succession.

## **INTRODUCTION**

The Chance Cove Supergroup of Newfoundland comprises two Ediacaran siliciclastic successions. On the Avalon Peninsula, the Conception, St. John's, and Signal Hill Groups, crop out most notably within the Mistaken Point Ecological Reserve (MPER). On the Bonavista Peninsula, the Chance Cove Supergroup is best studied at the Catalina Dome, centred around the town of Trinity Bay North. Both successions show spectacularly preserved soft-bodied macrofossils, representing the oldest known complex multicellular organisms in the fossil record. Their biological affinities are still greatly debated, with suggestions including algae (Ford, 1958), an extinct phyla (Seilacher, 1992), lichens (Retallack, 1994), fungi (Peterson et al., 2003), and protists (Seilacher et al., 2003). Of greatest interest is the proposal that these fossil may include representatives of stem- or crown-group animals (Jenkins, 1985; Narbonne, 2005; Sperling et al., 2011).

Understanding the wider environmental contexts of this key evolutionary transition in Earth history is vital to an improved understanding of the enigmatic biota that is found in these rocks. I here examine the sedimentology of the Mistaken Point Ecological Reserve (MPER) and the Catalina Dome, and assess the implications for our understanding of the taphonomy and palaeobiology of the Ediacara biota.

## **TUFFITE SEDIMENTOLOGY**

Tuffite samples, selected for geochronological analysis were collected under permit, issued by the Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador. Targeted tuffaceous horizons were identified in the field based on their light buff to grey-green colour, and tendency to be more cleaved than the surrounding lithologies. Other indicators include dark speckling caused by authigenic chlorite growth, and their association with fossil remains, which are often found

preserved beneath volcaniclastic horizons. The geochronological analysis is detailed in full in Chapter 4. Where cleavage and collection regulations allowed a sample for slabbing and sedimentological analysis was also obtained, as will be described below;

### **Mistaken Point Ecological Reserve Samples**

*DRK-10*: Sample DRK-10 was collected from the so-called 'Pizza Disk Bed' of Pigeon Cove. This locality from the upper Drook Formation, ~25 m from the top of the formation, is well known for its preservation of large lobate 'pizza disks' or ivesheadiomorphs (Liu et al., 2011), as well as a community of juvenile rangeomorphs (Liu et al., 2012). The fossil horizon is directly overlain by, a ~35 cm thick bed of volcanic ash, most noticeable for its green-buff colour and its highly cleaved nature.

A slabbed and polished section from the lower ~25 cm of the ash show it to have internal structures (Figure 3.1). The lowest 7.5 cm consists of normally graded fine-grained sandstone to siltstone with ubiquitous chloritic cement. There is possible convolute bedding at the very base of the ash, and diffuse patches of carbonate, probably of secondary origin. This horizon is also much darker in colour than the surrounding light green-buff sediments. Above this lies a siltstone with local sand-grade clasts, with several laminae that have a ~ 25° apparent dip when compared to the interpreted palaeo-horizontal of the plane of section. The sample continues to grade normally into a mudstone at the top. At the top of the unit (above the zone of the sample) there is evidence that the tuffite has been reworked post-depositionally, forming mm-scale interbeds with the overlying grey siltstone.

*DRK-1*: This sample from the lower Briscal Formation was collected from Daley's Cove. The bed lies ~50 m from the base of the formation, and comprises a discrete ~5 cm thick

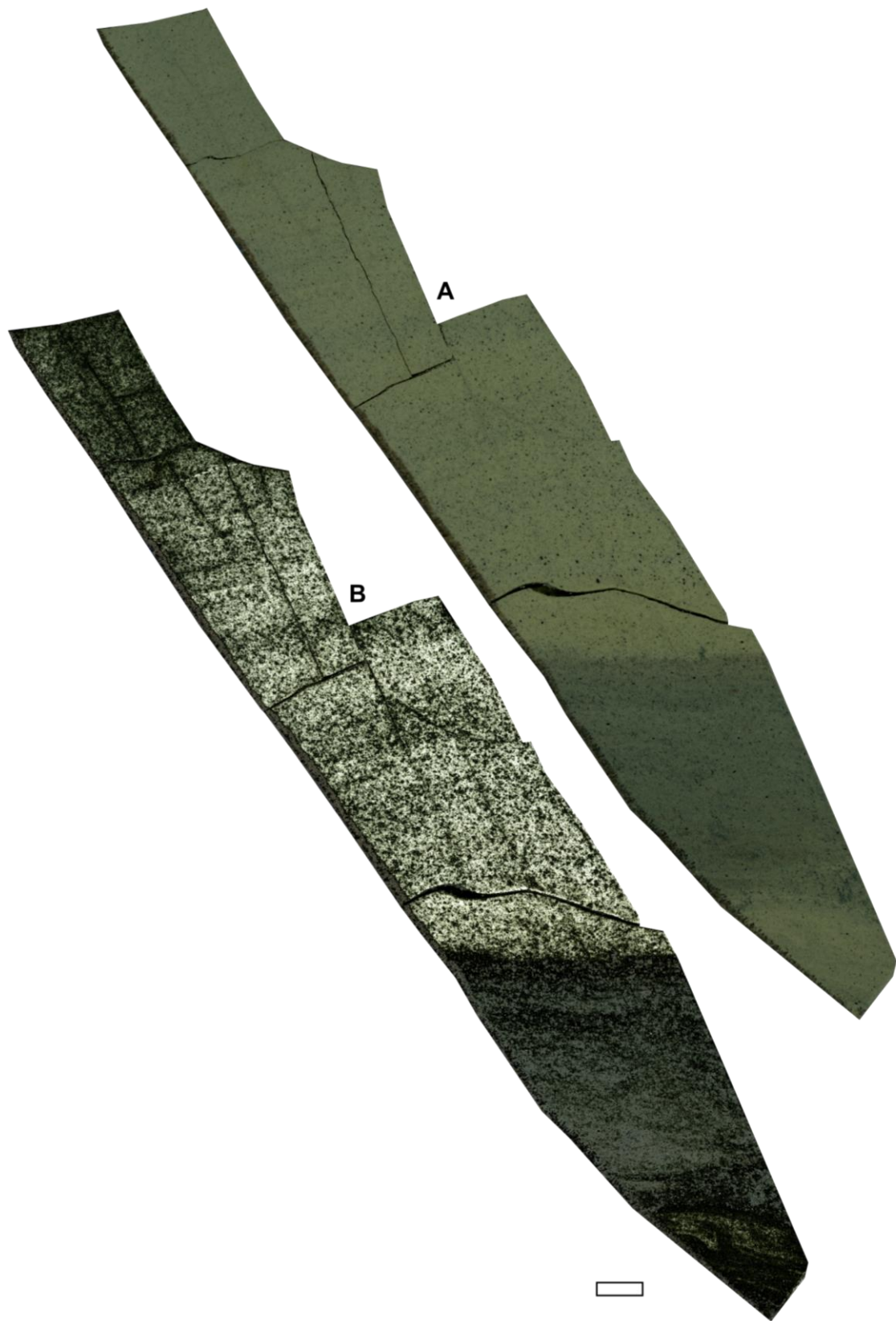


FIGURE 3.1. Slabbed and polished section of the DRK-10 buff-green volcaniclastic deposit that lies above the 'Pizza Disk Bed' of Pigeon Cove. A) True colour scan. B) False colour image to emphasise internal structures within the unit. Note deformed laminations at base and inclined lamination near the top. Scale bar is 1cm.

buff-green siltstone within a succession of thin to medium bedded grey sandstones that fine upwards to siltstones.

The basal ~1 cm of the sampled horizon is dark grey in colour, and contains shale clasts ~3 mm in diameter and a number of light-grey parallel laminae. This lowest layer grades into a ~8 mm thick zone of light-buff siltstone dominated by irregularly shaped ~1 mm diameter speckles. Fining upwards in the unit, these specks are interpreted to be authigenic chlorites, replacing unstable volcanic minerals in the original ash. The remainder of the horizon comprises normally graded, light-buff to green siltstone, with prominent parallel laminae throughout and some evidence of cross-lamination in the centre of the unit (Figure 3.2).

*BRS-1*: Sample BRS-1 is from a tuffaceous bed directly overlying a newly discovered fossil horizon within the lower Briscal Formation. The bed, ~110 m from the base of the formation, comprises a ~30 cm thick medium sandstone, normally graded and is noticeable greener at the base. This buff-green colour commonly indicates the presence of tuffaceous material, and so the sample was preferentially collected from the base of the bed. This bed is the lowest of several metres of thickly bedded buff-green tuffaceous beds that create a noticeable marker horizon in contrast to the dark grey deposits of the rest of the succession (Figure 2.8D).

*MP-14*: This sample is from the E-surface of Mistaken Point within the upper Mistaken Point Formation, ~60 m from the boundary with the Trepassey Formation. The sample was collected from the E-Surface Yale outcrop (Clapham et al., 2003), the most heavily studied fossil outcrop within the Reserve. Directly overlying the fossil surface is a ~5 mm thick crystal tuff horizon (Figure 2.15) comprising mainly feldspar and polycrystalline lithic fragments in a chlorite matrix. This is overlain by a 10 cm thick buff, highly cleaved

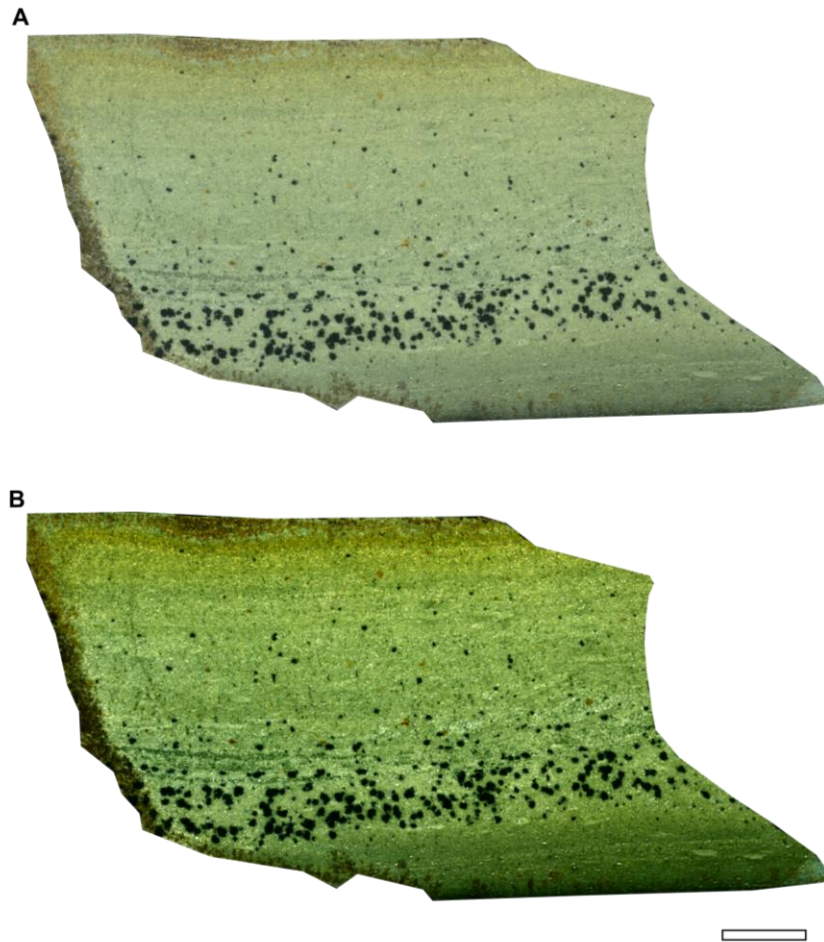


FIGURE 3.2. Slabbed section of the DRK-1 tuffite. A) True colour scan. Graded tuffaceous fine sandstone and siltstone with parallel laminations, and possible cross-laminations in places. Dark specks indicate chlorite, though to be authigenic in origin. B) False colour image to emphasise internal structures within the unit. Scale bar is 1 cm.

tuffite, grading from medium sand-grade material at the base to mud-grade sediments at the top. There is a marked transition from sand to silt grade material 2 cm from the base of the slab shown (Figure 3.3). The tuffite is capped by a ~15 mm thick horizon of black and pink material, revealed in thin section to be chlorite and carbonate respectively. This chlorite-carbonate horizon, thought to have been formed secondarily, is only visible above the Mistaken Point Yale and Queens Outcrops, and not the other outcrops of the E-Surface described later in the volume. Overlying this enigmatic unit is a 24 cm thick normally graded unit; green at the base and grey at the top.

The crystal tuff horizon could not be sampled in volumes necessary for geochronological analysis due to restrictions on collection; the analysed material comes from the overlying tuffite, below the chlorite-carbonate horizon.

*LC-1*: This is a ~4 cm thick buff ash that lies on top of a fossil surface within the Trepassy Formation referred to as the 'Pizzeria', on the account of the number of ivesheadiomorphs present. Specimens of *Charnia*, *Charniodiscus*, and *Pectinifrons*, amongst others, are also present.

The ash itself comprises green to light-grey siltstone, with possible parallel laminations in places (Figure 3.4). Further analysis of the internal structure within the unit is hampered by pervasive modern weathering and associated iron oxyhydroxide and dendritic manganese mineralisation.

*SH-2*: This sample is a ~30 cm tuffaceous deposit from within the Fermeuse Formation. The base of the unit is of uneven character, and likely loaded into the underlying typical black shales of the Fermeuse Formation. This undulating horizon is further highlighted by the presence of very coarse sand grains in the base of the ashy unit – denoted by its characteristic green colour and cleaved nature.

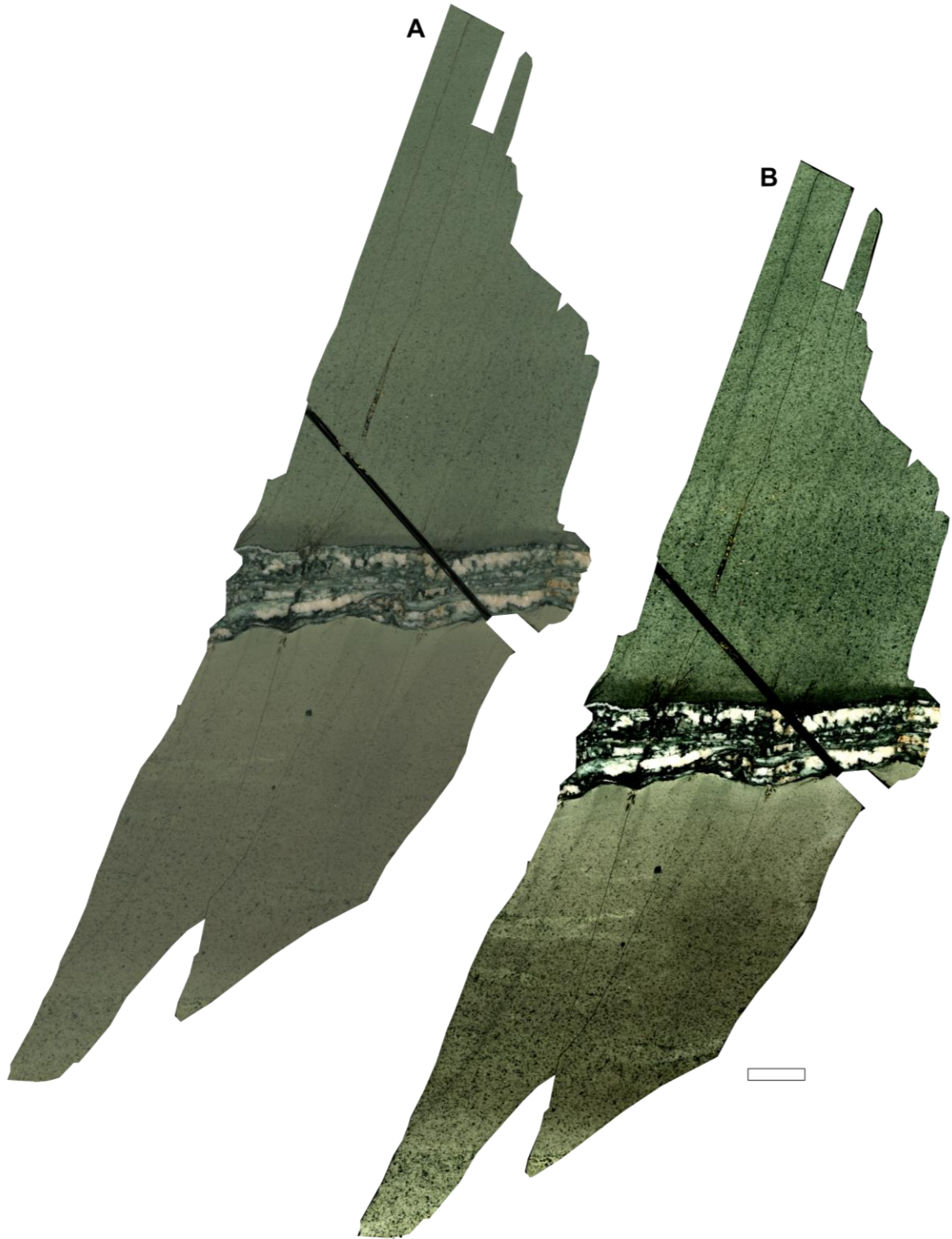


FIGURE 3.3. Slabbed and polished section of the buff-green volcaniclastic deposit that lies about the 'E' Surface. A) True colour scan of the overlying ashy deposits. Note that the black, 5 mm thick crystal tuff layer that directly overlies the fossil surface is not shown here as it preferentially adheres to the underlying surface as opposed to the overlying beds. These sediments directly rest upon the crystal tuff layer. Note mineral vein in the centre. B) False colour image to help emphasise internal structures within the horizons. Scale bar is 1 cm. This slab is the same horizon as geochronology sample MP-14.



FIGURE 3.4. Slabbed section of the LC-1 geochronological sample. A) True colour scan. Pervasive mineral growth prevents the observation of primary sedimentary structures. B) False colour image to attempt to emphasise internal structures within the unit. Scale bar is 1cm.

The bottom 8 cm of the tuffite itself is defined a fining upwards sandstone capped by mildly convolute mm-scale laminations of green ashy, and black mudstone material (Figure 3.5). This merges into a ~20 cm thick region of intense convolute lamination, with recumbent fold of sediment. These laminations are highlighted by the inclusion of medium and coarse grained sand. The top 8 cm of the sample is highly cemented with carbonate; staining with Alizarin Red-S and Potassium Ferricyanide, using the technique of (Dickson, 1965), revealed this to be dominated by iron-rich calcite.

### **Catalina Dome Samples**

*MRC-6*: This sample is taken from a 14 cm thick tuffaceous horizon, 17 cm above the fossiliferous horizon known as the “Discovery Surface” (Locality 5, Hofmann et al., 2008). The bed, near the base of the Murphy’s Cove Formation, is identified by its buff-green colour, and highly cleaved nature compared to the surrounding lithologies. Sampling for slabbing proved impossible due to the cleavage. The bed has clearly defined basal and upper contacts. There is no evidence for laminae or grainsize trends within the bed, though if present these could be masked by weathering, algal growth, and cleavage.

*HF14-6*: This sample, from the lower part of the Rowland Head Formation, lies directly upon the *Fractofusus*-rich horizon known locally as the “Johnson Surface” (Locality 14, Hofmann et al., 2008). The bed is 19 cm thick and is buff-green in colour rather than the typical grey colour of the adjacent lithologies, and is more highly cleaved. The cleavage prevents sampling for the purpose of slabbing. In many places the lowest part of the bed is adherent to the underlying fossil surface. The bed grades upwards into the grey lithology typical of the Rowland Head Formation and therefore the unit was preferentially sampled from the bottom. The ash is mostly clay and fine silt-grade material, with minor amounts of angular sand-sized grains, the majority of which were polycrystalline quartzites.



FIGURE 3.5. Slabbed section of the SH-2 geochronological sample, from the Fermeuse Formation. The slab shows disturbed bedding within a light green tuffite, thought to have been at the base of a slump. The top section of the slab had been stained for carbonate (red, blues, and purples) using Alizarin Red-S and Potassium Ferricyanide. Scale bare is 1 cm.

## TUFFITE DEPOSITION AND TAPHONOMY

Several of the tuffites sampled for geochronological analysis exhibit signs of sub-marine reworking of the volcanoclastic sediments, including bouma-like graded beds, cross-lamination, shale clasts, and units with an upper boundary that transitions into tuffite-free material. Samples DRK-10 and DRK-1, show signs of being deposited as volcanoclastic dominated turbidites. It was not possible to collect a sample of BRS-1 for slabbing, but from the field observations, this unit is interpreted as an ashy turbidite.

The volcanoclastics directly above the E-Surface at Mistaken Point is directly overlain by a 5 mm thick lithic and crystal tuff, with very little fine-grained material, save for the chlorite matrix (Figure 2.15). This stratum is overlain by a normally graded 10 cm thick tuffite with signs of laminae in places (Figure 3.3). This sequence of a fines-poor lithic/crystal tuff capped by a normally graded tuffaceous unit has been described from the Mediterranean ash turbidite deposits associated with the Minoan eruption of Santorini (Sparks and Wilson, 1983). In this Greek example, it was observed that beneath the T<sub>A</sub> division of turbidites resulting from the remobilisation of ash-fall deposits, a separate and distinct layer had formed. This layer was coarser than the overlying T<sub>A</sub> division, enriched in crystals and lithic fragments, and depleted in silt-sized material when compared to the base of the T<sub>A</sub> division. If this comparison is justified, the 5 mm lithic/crystal tuff directly overlying the fossils on the E-Surface is interpreted as a flow-head deposit, deposited rapidly by the front of the turbidity current, prior to the development of the typical Bouma succession.

Due to pervasive modern weathering the internal fabric of sample LC-1 cannot be easily observed. The SH-2 sample shows convolute and disturbed internal laminations, and is situated within a slump scar, where it is overlain by a slumped unit. The tuffaceous SH-2

unit likely acted as the décollement for the overlying slump unit, and was therefore previously deposited upslope and semi-lithified.

Detailed examination of the Catalina Dome tuffites was precluded by the pervasive cleavage in the region, however, it was noted that the HF14-6 sample did transition gradually into non-ashy material, rather than having a clear and defined top to the unit, suggesting some degree of re-sedimentation.

Since this model for deposition of these Ediacaran tuffites infers a hiatus between eruption of the tuffs and the final deposition of re-sedimented material, there is potential uncertainty on geochronological analyses therefrom. However, the hiatuses are thought to be relatively short – since there is no evidence for lithification of the tuff, and mudstone clasts in the resultant deposit have a non-tuffaceous composition.

The inference that turbidity currents deposited tuffites not only affects interpretation of geochronological data, but is also significant for geochemical and taphonomic studies:

#### *Bulk-rock geochemistry of the tuffites*

The geochemistry of ash-rich deposits within the succession has previously been studied for the purpose of elucidating tectonic setting (Retallack, 2014). The study concluded that the ash deposits yielded geochemical values indicative of an active continental margin setting. However, the process of reworking and transporting these tuffaceous deposits down slope will have led to the inevitable incorporation of non-volcaniclastic material, perturbing any whole-rock geochemical values away from those of the original volcanic ash. Such whole-rock analysis is therefore flawed.

### *Taphonomic implications of tuffites vs water-settled fallout ash*

The majority of taphonomic models for the preservation of Ediacaran organisms of the deep water facies of Newfoundland have assumed:

1) a prevalent contour current on the palaeo-seabed, based upon the alignment in felling direction of frondose taxa such as *Charniodiscus* (Wood et al., 2003; Flude and Narbonne, 2008), and;

2) that the tuffites were ‘water-lain’ (Bamforth et al., 2008; Bamforth and Narbonne, 2009; Brasier et al., 2011), deposited by an ‘ash-fall’ (Jenkins, 1992; Wood et al., 2003), or by ‘ash percolating down through the water column’ (Laflamme and Darroch, 2015).

The term ‘water-lain’ creates some confusion, as it can describe material deposited in *or* by water. From the contexts in which they are used, it is considered that all the authors were referring to the same process whereby an ash is deposited at the ocean surface, and then settles through the water column to be deposited at the sediment-water interface. The term ‘water-settled fallout ash’ is therefore used herein to describe this process, rather than the ambiguous term ‘water-lain’.

The vast majority of fossil surfaces within MPER are directly underlain by a dark or olive green, very thinly laminated mudstone with a sharp base, scattered isolated silt grains, and agglomerations of silt-grade material (Figure 3.6). These units have previously been interpreted as contourites, based on the observation that on many fossiliferous horizons, the fossils are orientated at a near orthogonal angle to the flow directions indicated by ripple-cross lamination in nearby turbidites (Wood et al., 2003; Ichaso et al., 2007). These

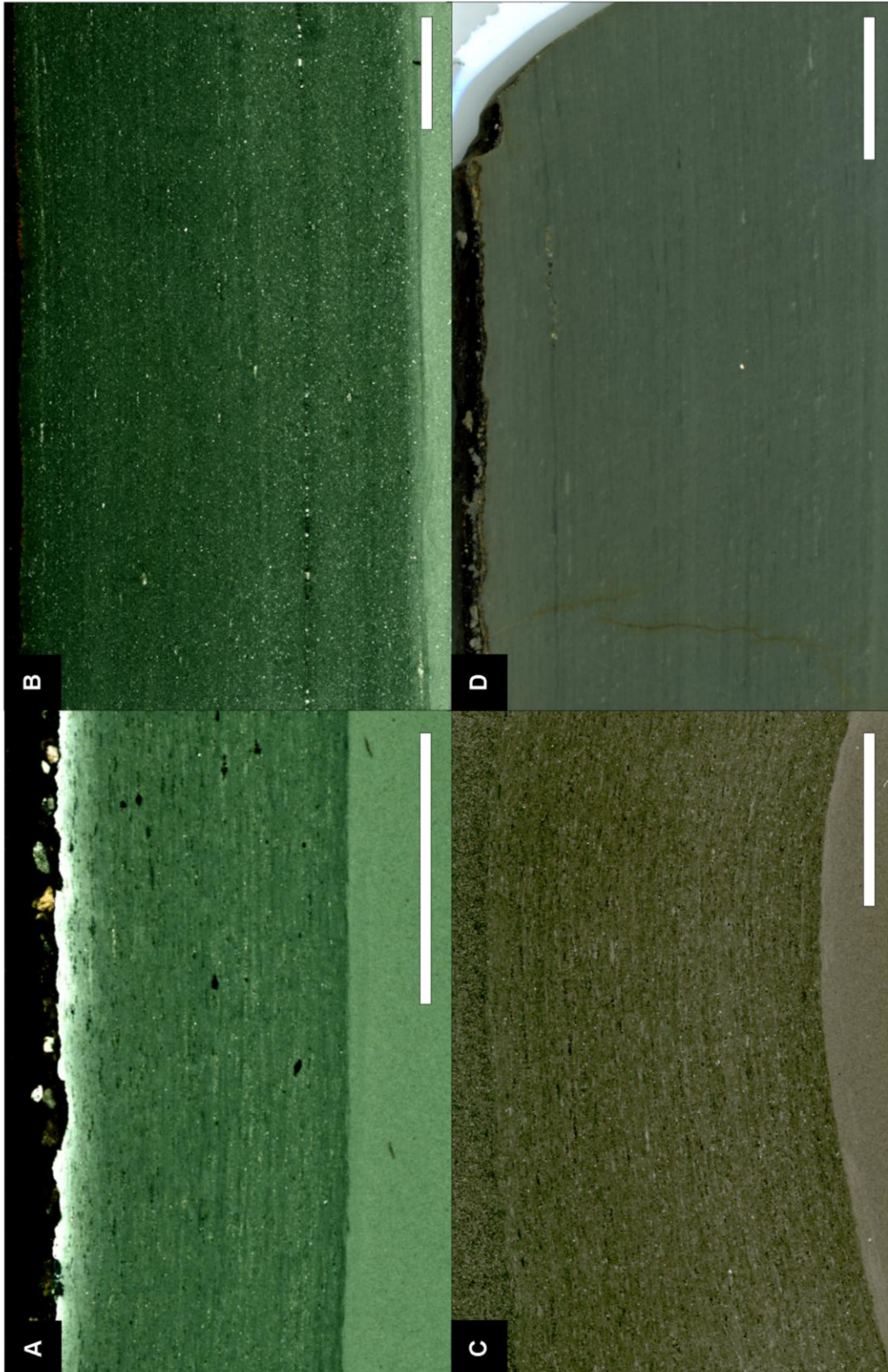


FIGURE 3.6. Green, laminated layer, underlying many fossiliferous horizons. Note clustered silt grains. A) Sample from the 'E' Surface outcrop at Cape Race, Mistaken Point Formation. (False Colour) B) Sample from the BR-5 fossil surface in the Briscal Formation. (False Colour) C) Sample from between the 'D' and 'E' Surfaces at Mistaken Point, Mistaken Point Formation. (False Colour) D) Sample from the HF-14 fossil surface near Rowland Head, Rowland Head Formation. Scale bars are 1 cm.

authors infer that the ripple-cross lamination provides the down slope direction of the depositing turbidity current, and the frond alignment reflects the contour current.

The features observed in these units are consistent with the Stow and Faugères (2008) facies model for muddy contourites, save that they are not expected to be laminated. It is important to note in this respect that most facies models are based upon observations of Phanerozoic environments that, in the case of most marine facies models, include the presence of animals. In this case, the contourite facies presumes bioturbation will have erased all primary laminae, something not possible at this stage in the Ediacaran.

Similar fine-grained facies have been categorised as hemipelagites in mud-rich deposits formed close to the continental margin (e.g. Stow and Tabrez, 1998). Again, recognition of Precambrian hemipelagites is hampered by the fact that existing facies models are based on the premise that biomineralisation and bioturbation had evolved. Hemipelagites are classified as deposits with >10% biogenic and >10% terrigenous material, with over 40% of the terrigenous clasts being silt sized (Stow and Piper, 1984). Similar definitions, using a median terrigenous grain size of >5 $\mu$ m have also been proposed (Berger, 1974). More general systems have simply noted that hemipelagites are fine grained sediments with a biogenic and terrigenous component, deposited by vertical settling through a water column with some contribution of material introduced by lateral advection (Stow et al., 1996).

A true pelagite, deposited in the open ocean away from terrigenous sediment-laden nephloid suspension, is expected to be devoid of silt grade material, save for a biogenic component (Stow and Piper, 1984) – though this would be restricted to the acritarchs in the Ediacaran. Coarse silt-grade material could be deposited in a pelagite if brought in as wind-blown loess, or as ice-rafted debris. In these scenarios the laminae would represent episodic input of silt-grade sediment.

The loess and ice-rafted deposition of silt grains in these units, whether in a pelagite or hemipelgite is countered by the observation of clustered, generally well-sorted grains into small lenses. This observation also rules out deposition directly from a nephloid suspension. Ice-rafted deposition is further questioned by the lack of other evidence for ice-rafted debris such as dropstones with deflected laminae.

Clustered silt grains have been associated with agglutinating foraminifera (e.g. McIlroy et al., 2001). This biogenic hypothesis is premature, when an abiogenic hypothesis is plausible, and there is no supplementary evidence for what would need to be the oldest evidence of foraminifera.

However the silt-grade material was originally transported to the deposition environment, it seems like that the deposit has been post-depositionally processed by a bottom current of some kind, allowing for the sorting and clustering of certain grain sizes. This is a known characteristic of contourites, where the silt fraction is often concentrated in irregular pockets and lenses (Faugères et al., 1984; Rebesco et al., 2014). Other bottom currents in the deep sea may create similar deposits to contourites, such as currents within canyons (Shepard et al., 1979). With no evidence for nearby canyons, these units are tentatively described as contourites.

Whatever their origin, currents appear to have flowed through the palaeocommunity, but if the ashy turbidite depositional method is correct, it seems unlikely that the felling direction of the frondose organisms would indicate the direction of contour current flow, rather than the much stronger turbidity current.

The water-settled fallout ash hypothesis also required the fronds to be in a prone position, sub parallel to the seabed prior to ash emplacement (Narbonne and Gehling, 2003). This alignment is necessary for the frond to be successfully felled and smothered without

substantial incorporation of tuffite below the specimen, for which there is no evidence. The taphonomic necessity in the ash-fall model for the fronds to be prone contradicts the epifaunal tiering model of Clapham and Narbonne (2002), which requires taxa to be occupying different tiers in the water column to increase feeding efficiency by partitioning nutrient supplies. Canopy flow modelling of these communities is predicated on the vertical orientation of fronds in the water column (Ghisalberti et al., 2014). The ashy turbidite mechanism of deposition resolves this inconsistency, allowing for the fronds to be vertical in life-position, and then toppled by the head of the smothering ashy turbidity current that transports remobilised tuffaceous material from up-slope.

In the Mistaken Point Formation, the down-slope direction given by turbidites is broadly to the south east, whereas the felling direction of fronds is generally to the north east, although the 'E' Surface frond vectors are broadly south easterly (Wood et al., 2003; Figure 2:14). If the orientation of fronds does record the current direction of the ashy turbidite that buried them, then the discrepancy in flow direction between ashy and non-ashy turbidites may simply be a product of differing source areas for epiclastic and primary-volcanic material, rather than indicating toppling of fronds by contour currents.

## **COMPARATIVE SEDIMENTOLOGY**

The macrofossil bearing rocks of MPER and the Catalina Dome have been widely interpreted as deep marine deposits (Williams and King, 1979; Wood et al., 2003; O'Brien and King, 2005; Mason et al., 2013), with the exception being the suggestion that some horizons within both successions represent shallow marine deposits and palaeosols (Retallack, 2013; Retallack, 2014; Retallack, 2016).

Various parameters which can, or have been used to infer the environment of deposition are critically reviewed below. A summary of the characters discussed is found in Table 3.1.

## **Sedimentary Structures**

### *Hummocky Cross Stratification*

Hummocky bedding has been used as evidence for a shallow-water depositional setting for various units considered herein. True hummocky cross stratification is only found at depths shallower than hydrodynamic wave base, which is known at depths up to 250 m (James et al., 1999). Retallack (2016) cites Dalrymple et al. (1999) as evidence of hummocky bedding within the Mistaken Point Formation. It is worthy of note that all three authors of this, non-peer reviewed, conference abstract have since published peer-reviewed journal articles in which they describe the Conception Group, including the Mistaken Point Formation, to have been deposited within deep marine environments (e.g. Wood et al., 2003).

Hummocky cross stratification has also been described from the Shepherd Point Formation of the Catalina Dome (Figure 3.7; Fig 4F, Retallack, 2014). The photograph provided by Retallack does not conclusively show the hummocks, swales, and truncated lamination expected of Hummocky Cross Stratification. Others have suggested this deposit is a seismonslope, and that the undulations are the product of seismic disturbance of unconsolidated sediments (Fig 5E, Mason et al., 2013). Hummocky cross-stratification-like structures associated with turbidites have also been described from deep marine sub-hydrodynamic wave base environments in the Cretaceous (Mulder et al., 2009).

Formation	Colour	Grain Size	Bed Thickness	Slumps	Debris	Turbidites	Mud Clasts	Phosphate Nodules	Carbonate Concretions	Tool/Flute Marks	Load/Flame Structures	Dewatering Structures	Convolute Lamination	Ripple Mark Palaeocurrent Direction	Mean $\delta^{34}\text{S}$	Mean wt% C	Mean $\text{Fe}_{\text{org}}/\text{Fe}$
Little Catalina	Grey, Dark Grey	Mudstone, Siltstone, Sandstone	Thin	✓		✓		✓	✓				✓	↗	?	?	?
Port Union	Grey	Sandstone, minor Siltstone	Medium to Thick, minor Thin to Medium	✓		✓	✓		✓		✓		✓	↗	?	?	?
Rowland Head	Grey, Green	Siltstone, minor Sandstone	Thin to Medium			✓		✓	✓					↗	?	?	?
Murphy's Cove	Dark Green, Grey, some purple	Siltstone	Thin			✓								→	?	?	?
Shepherd Point	White, Green, Pink, Red, Grey, Brown, Purple	Siltstone, Sandstone	Thin to Very Thick, Rarely Thick			✓					✓			?	?	?	?
Fermeuse	Dark Grey, Black	Siltstone, minor Sandstone	Thin	✓		✓		✓	✓		✓		✓	↗	21.82	0.060	0.206
Trepassey	Grey	Siltstone, Sandstone	Thin, Rarely Thick		✓	✓			✓	✓				↗	7.18	0.002	0.250
Mistaken Point	Purple, Green, Grey	Siltstone, Sandstone	Thin to Medium, Minor Thick		✓	✓	✓		✓			✓	✓	↗	3.27	0.024	0.205
Briscol	Grey, Green, Pink	Sandstone, Grit, Siltstone	Thick to Very Thick, Some Medium			✓	✓		✓	✓	✓	✓	✓	↗	16.97	0.004	0.243
Drook	Green, Grey, Pink	Siltstone, Sandstone	Thin to Medium, Locally Thick		✓	✓	✓		✓	✓				↗	-2.12	0.004	0.245

TABLE 3.1. Review of various sedimentary and geochemical parameters characterising the formations at MPER and the Catalina Dome. Palaeocurrent data from Wood et al. (2003) and Mason et al. (2013). Geochemical data from Canfield et al. (2007).

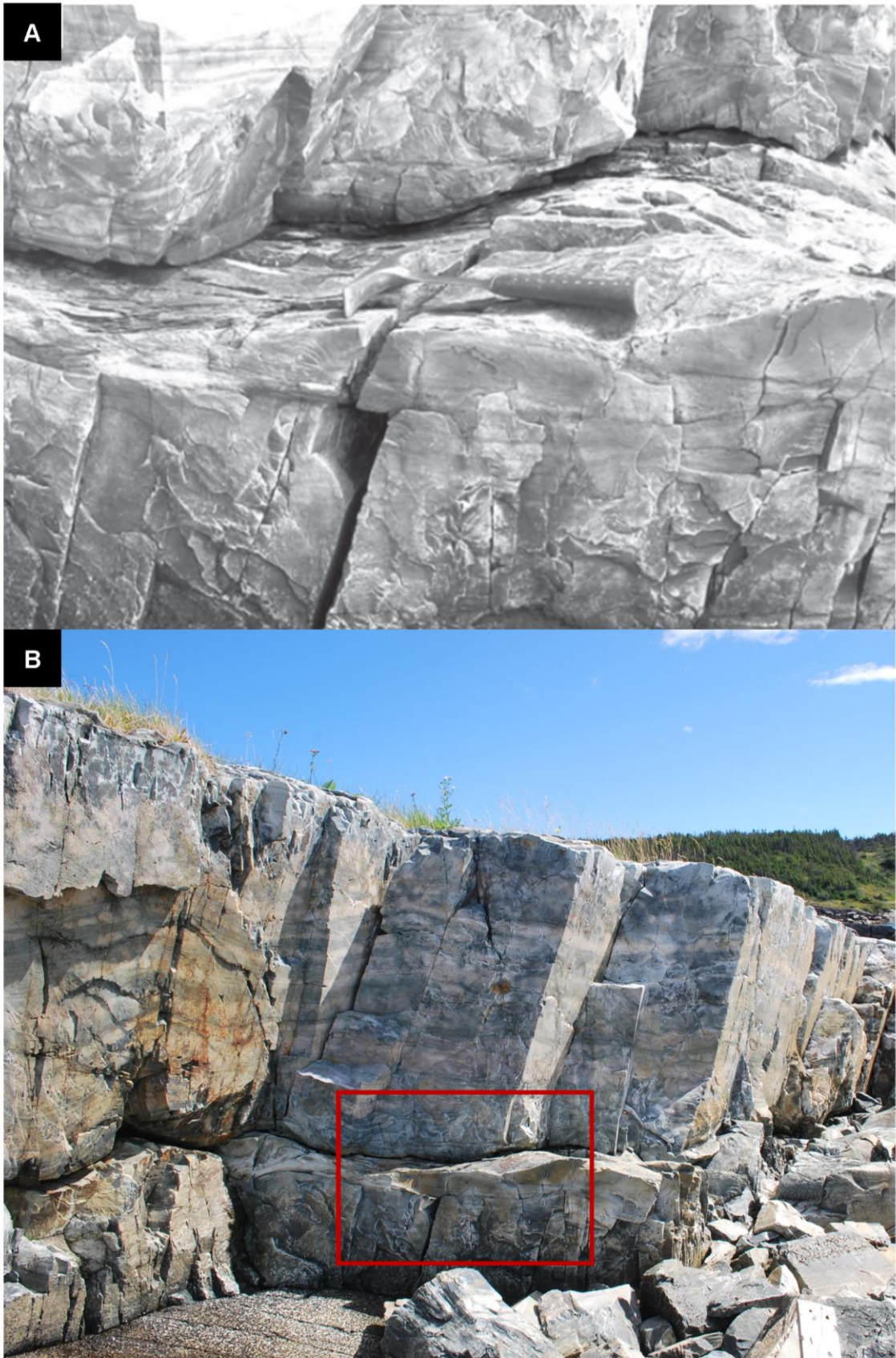


FIGURE 3.7. A) Proposed hummocky cross stratification from Retallack (2014). B) The same outcrop from the Murphy's Cove Formation, with wider context. Photographed area from Retallack shown by red box.

### *Ripple Marks*

Ripple marks are common throughout both the MPER and Catalina Dome sections (Williams and King, 1979; Benus, 1988; Wood et al., 2003; O'Brien and King, 2005; Wignall et al., 2005; Mason et al., 2013; Retallack, 2014; Retallack, 2016). The majority of the published records of ripples, as well as those observed during this research have straight, parallel crests, with rounded tops, and are often asymmetric in shape (Figure 3.8). These are therefore interpreted as having been deposited by a unidirectional current, which can occur at virtually any water depth, as well as subaerially. The only Ediacaran wave-generated ripple marks – which would indicate a depositional environment landward of storm wave base but could also be non-marine – that have been documented in the course of this study are from the Gibbett Hill Formation at the base of the Signal Hill Group. These ripples show sharp crest tops and bifurcating waveforms (Figure 3.8D).

### *Subaerial Exposure Surfaces*

The best evidence for non-marine deposits of this age are structures such as desiccation cracks and soil fabrics such as calcretes. Such features are not known from either MPER or the Catalina Dome. During this study, desiccation cracks were observed at the boundary between the Renew Head and Cappahayden formations at Renew Head, over 1 km stratigraphically above the highest bed of Fermeuse Formation within MPER. Care must be taken to distinguish between desiccation cracks and subaqueous shrinkage cracks that characterise many matground surfaces (Harazim et al., 2013).

### *Pipe Structures*

A sinuous, vertical 'tubule' has been figured and described from a tuffite in the Drook Formation of MPER (Retallack, 2014). It was argued that these were comparable to gas

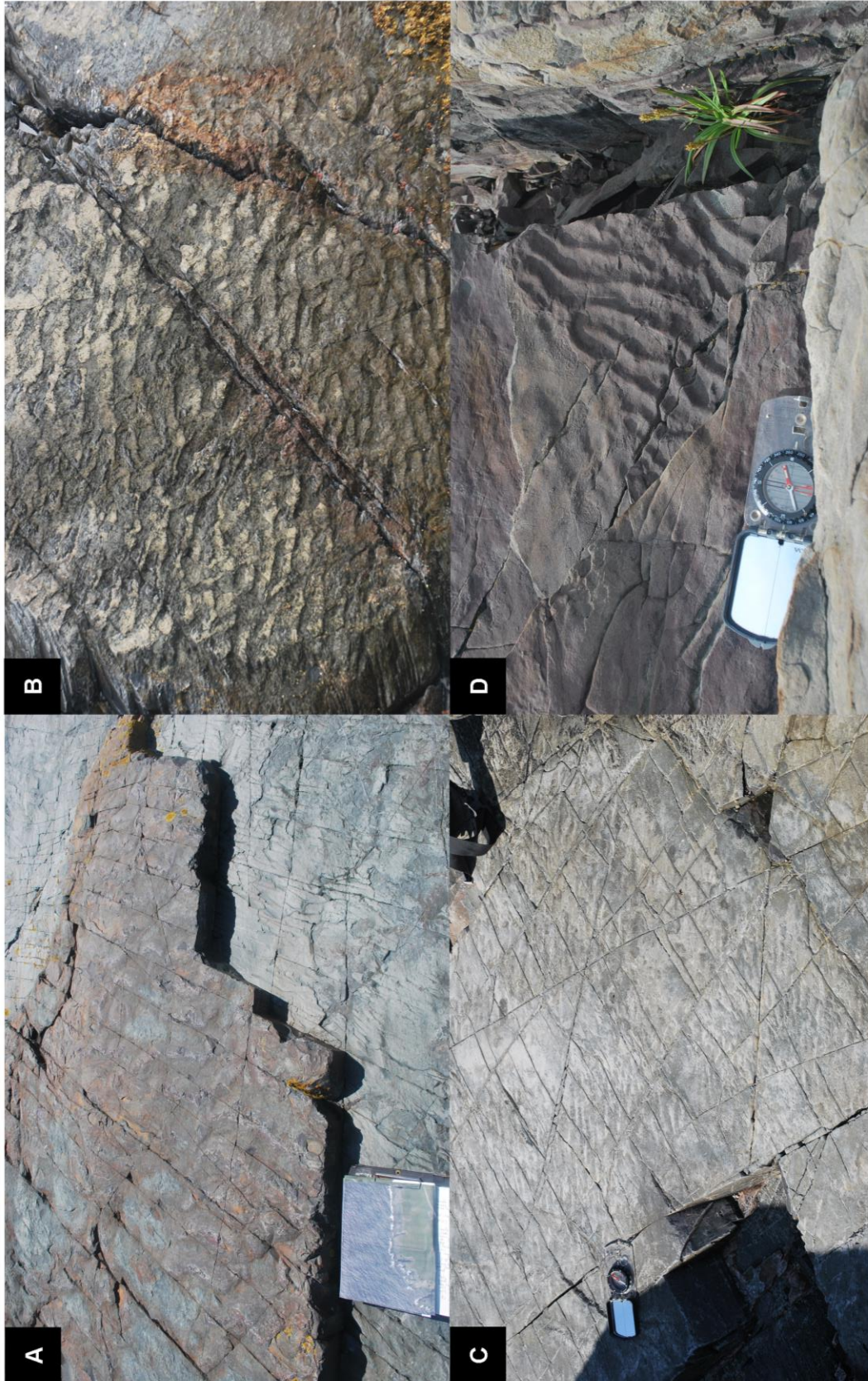


FIGURE 3.8. Ripples from the Chance Cove Supergroup. A) Rippled horizon from the Drook Formation. Note A3 clipboard (long axis 49.5 cm). Interpreted as current ripples. B) Rippled horizon from the Fermeuse Formation. Interpreted as current ripples. C) Rippled horizon from the Murphy's Cove Formation. Interpreted as current ripples. D) Ripples from the Gibbett Hill Formation. Interpreted as wave ripples.

escape structures in pyroclastic flows on land. Inversed grading, which is often associated with pyroclastic flows, was not observed, and extensive study of the same horizon (DRK-10) in the course of this thesis failed to reproduce the findings. It is noted that sedimentary units associated with microbial matgrounds commonly produce small fluid escape columns (Menon et al., 2016). No morphological characteristic of the tubule of Retallack (2014) is uniquely associated with a pyroclastic flow.

#### *Intra-formational Clasts*

Intra-formational clasts are known from beds in the Drook, Briscal, Mistaken Point, Trepassey, and Port Union formations. These take a variety of forms, including tabular clasts over cobble grade in size, to smaller, well-rounded imbricated clasts at the bottom of beds, as has been observed in the Mistaken Point Formation at St. Schott's. The presence of intra-formational clasts has been used to argue that the Mistaken Point Formation cannot have a deep water depositional environment (Retallack, 2014). This assertion is incompatible with the established literature that documents many examples of deep marine sediments containing intra-formational clasts (e.g. Stow and Shanmugam, 1980; Stow and Piper, 1984; Johansson and Stow, 1995; Hiscott et al., 1997; Cronin et al., 1998; Stow and Johansson, 2000; Fugelli and Olsen, 2007; Haughton et al., 2009). Any erosive current has the potential to create intra-formational clasts and as such their presence in a sedimentary rock cannot be used to infer anything about palaeoenvironment.

#### *Bed Grading*

Normally graded beds have been described from all formations covered in MPER and the Catalina Dome (Williams and King, 1979; Benus, 1988; Wood et al., 2003; O'Brien and King, 2005; Mason et al., 2013), as is reinforced herein. The claim that no graded beds are present in the Mistaken Point Formation (Retallack, 2014), is erroneous. It is also noted

that turbidity currents can deposit structureless and ungraded beds (Kneller and Branney, 1995), but it is clear from this study that the majority of the Mistaken Point Formation comprises normally graded beds showing classic Bouma divisions (e.g. Figure 2.16, Figure 2.17).

### *Carbonate Concretions*

Carbonate concretions been previously described from around the Mistaken Point Formation at Mistaken Point (Benus, 1988). During the course of this study, carbonate concretions were discovered in all formations studied at MPER and the Catalina Dome, except for the Shepherd Point and Murphy's Cove formations. Mineralogy was confirmed via thin section analysis, and a pilot stable isotope study.

Four samples from eastern Newfoundland were tested. Oxygen and carbon isotope results were obtained using a VG Isogas Prism II mass spectrometer with an on-line VG Isocarb common H<sub>3</sub>PO<sub>4</sub> acid bath preparation system at 90°C. Results are presented relative to the VPDB international standard (Table 3.2).

<b>Sample</b>	<b>Formation</b>	<b>Location</b>	<b>δ<sup>13</sup>C</b>	<b>δ<sup>18</sup>O</b>
GIB-2	Gibbet Hill	Ferryland Head	-24.35	-19.37
SC-1	Fermeuse	Silos Cove, Ferryland	-10.85	-16.43
CPTBB-1	Port Union	Port Union, Catalina Dome	-14.69	-15.52
MP-9	Mistaken Point	Mistaken Point, MPER	-21.30	-8.47

Table 3.2: Oxygen and carbon isotope data from a pilot study on carbonate concretions from eastern Newfoundland.

The isotope values of these samples are consistent with the carbonate concretion being associated with carbon sourced from methanotrophic bacteria (cf. Konhauser, 2006), though further investigation is required. It is noted that these concretions often form in sandy horizons with the pore space to allow for CH<sub>4</sub> accumulation.

The presence of carbonate concretions has been used as an indicator of shallow-marine deposition (Retallack, 2014; Retallack, 2016), however carbonate concretions are also common in deep-marine environments where they represent a significant carbon sink (Marlow et al., 2014).

#### *Volcanic Clasts*

Volcanic clasts, including scoria bombs and basaltic andesite clasts have recently been described from throughout the MPER and Catalina Dome sections (Retallack, 2014; Retallack, 2016). Without exception, the structures imaged are either the product of fractures in the outcrop, or carbonate concretions. The presence of deflected laminae is used by the same author to infer a subaerial environment, but cannot be verified on the basis of the figured material.

#### **Geochemical Indices**

Several geochemical proxies have been used to infer depositional environments for the rocks of Mistaken Point and the Catalina Dome.

#### *Fe<sub>HR</sub>/Fe<sub>T</sub> Ratio*

The ratio of highly reactive iron to total iron (Fe<sub>HR</sub>/Fe<sub>T</sub>) has been used to determine the oxygenation of the depositional environment. Canfield (2007) argued that the change in Fe<sub>HR</sub>/Fe<sub>T</sub> values from relatively high (~0.38) in the Mall Bay and Gaskiers formations to lower (~0.20) for the Drook and subsequent formations reflects a switch from an iron containing anoxic ocean, to oxic marine conditions. However Retallack (2016) plotted the same data (Canfield et al., 2007) from the Mistaken Point Formation on a chart labelled with three fields representing Soils, Normal Marine, and Anoxic. The majority of points plot within the Soil field. While initially compelling it is found herein that the reasoning

for these field boundaries is not given, beyond a statement that they are based on a modern day study on a tropical carbonate setting (Ku et al., 2008).

It should be noted that the majority of the datapoints are within one standard deviation of the average modern marine  $Fe_{HR}/Fe_T$  value of 0.26 (Poulton and Raiswell, 2002). The very lowest points  $Fe_{HR}/Fe_T$  values ( $\sim 0.1$ ), and therefore those interpreted to be most soil-like are within one standard deviation of the average  $Fe_{HR}/Fe_T$  value (0.14) given from 60 Cambrian Marine samples (Poulton and Raiswell, 2002). The use of low  $Fe_{HR}/Fe_T$  values to infer a pedologic origin for sediments is therefore shown to be flawed in the context of the data available for the Mistaken Point Ecological Reserve.

### $\delta^{34}S$

Analysis of sulfur isotopes on the southern Avalon Peninsula has been used to propose a deep-ocean oxygenation hypothesis for the Ediacaran (Canfield et al., 2007). Increased sulfur isotope fractionation around the Gaskiers and Drook formation is inferred to demonstrate a change in the sulfur cycle. The authors suggest that melting associated with the Gaskiers Glaciation increased nutrient load into the ocean, which stimulated primary production in the oceans, with concomitant carbon burial, and therefore increased atmospheric oxygen levels. Increased atmospheric oxygen in turn enhances continental weathering of sulfide to sulfate, and increases the flux of sulfate to the oceans. It has been proposed that the return to lower sulfur fractionations in post-Mistaken Point Formation deposits may reflect a return to lower oceanic sulfate levels (Canfield et al., 2007), but may also reflect the reduction in fractionation expected with the higher sedimentation rates and increased sulfate reduction in delta front environments of the Fermeuse Formation (Habicht et al., 2002).

### *C<sub>org</sub> Concentration*

The concentration of organic carbon in the rocks from the Mall Bay to the Trepassey formations is very low (Canfield et al., 2007), consistent with deposition in an oligotrophic deep water basinal or outer slope marine setting (Premuzic et al., 1982). Higher levels in the Fermeuse Formation are inferred to reflect the delta front depositional environment for this formation, and the increased sedimentation rate expected (Canfield et al., 2007).

### *C/S Ratio*

Analysis of the ratio of wt% carbon:sulfur (C/S) has been used repeatedly to infer palaeoenvironment (Retallack, 2013; Retallack, 2014; Retallack, 2016). These calculations use data presented by Canfield et al. (2007) and the author, which are then plotted and fall within three fields (Intertidal-Euxinic, Marine, Freshwater) based on modern C/S ratios (Berner and Raiswell, 1984). High C/S ratios (>2.8) are considered to evidence low-sulfate, freshwater palaeoenvironments for the Mistaken Point and Gaskiers formations (Retallack, 2013; Retallack, 2014; Retallack, 2016). This >2.8 C/S ratio boundary is an arbitrary construct created by the author, and is not supported by other peer-reviewed research, which shows that 2.8 is the average value for Quaternary marine shales (Raiswell and Berner, 1986). Moreover, the original methodology of Berner and Raiswell (1984) states that the method is not applicable to rocks with less than ~1% organic carbon. No wt% C value from the Canfield et al. (2007) dataset is above 1%. All analyses from the lower Mistaken Point Formation have a value of 0, and the middle Mistaken Point Formation has a mean average wt% C value of 0.036, with a high of 0.089. In the Mall Bay and Gaskiers formation data presented by Retallack (2013), only one value was above 1%, and the mean average was 0.17%. The data is therefore well outside the acceptable

range of interpretable data as set out in the original study (Berner and Raiswell, 1984), and any inference based thereon is flawed.

### *Chemical Index of Weathering*

The Chemical Index of Weathering (CIW) allows for the calculation and classification of the extent of weathering in soils, and is calculated as follows, using molar proportions:

$$CIW = \frac{Al_2O_3}{Al_2O_3 + CaO + Na_2O}$$

Retallack (2016) uses this technique to calculate the mean annual palaeotemperature (MAT) under which the Mistaken Point Formation (and the new Shepherd Point and Murphy's Cove formations of the Catalina Dome) was deposited, yielding results around 11 °C. The palaeotemperature is calculated using the technique of Óskarsson et al. (2012) using the formula:

$$MAT = 0.21 \times CIW - 8.93$$

The methodology for calculating MAT was developed based on analyses of Icelandic soils with ages up to 5,500 b2k (Óskarsson et al., 2012). That study concludes that the technique may be used as a climate proxy for volcanic soils and palaeosols in Iceland, or regions with basaltic soils and a similar climate to that in the original study. There are a number of flaws in the application of this method to the Ediacaran of Newfoundland: 1) There is a lack of independent corroborating evidence for a basaltic origin for the sediments; 2) the Ediacaran is five orders of magnitude older than the sediments studied in Iceland; and 3) diagenesis, metamorphism, and modern weathering are likely to have altered the geochemistry of the Ediacaran samples. This technique is therefore considered unsuitable for use on the Mistaken Point and Catalina Dome localities.

Retallack (2016) also uses CIW to calculate the mean annual precipitation (MAP) experienced by the Mistaken Point Formation (and the now erected Shepherd Point and Murphy's Cove formations of Catalina Dome) during deposition, obtaining results between 633 and 1065 mm. MAP is calculated using the following formula (Sheldon et al., 2002);

$$MAP = 221e^{0.0197 \times CIW}$$

The relationship between MAP and CIW is based on comparison of modern American soils with climatic data from nearby weather stations (Sheldon et al., 2002). The extreme uniformitarian approach of Retallack (2016) in applying these complex modern day geochemical relationships to Ediacaran strata fails to account for differences in physical and chemical weathering in the Precambrian world, and neglects the possible effects of half a billion years of post-depositional chemical change due to diagenesis, metamorphism, and weathering. Use of the Sheldon et al. (2002) technique, or indeed any methodology using CIW on the Ediacaran requires more explanation of how post-depositional chemical changes can be ruled out as controls on any results acquired, and would only be valid if the strata themselves could be proven to be palaeosols – an assertion that finds no support in the evidence provided to date.

## **A CRITICAL REVIEW OF DEPOSITIONAL ENVIRONMENT**

Within the formations described as part of this study from MPER and the Catalina Dome, there have been no confirmed descriptions of wave ripples, hummocky cross stratification, tempestites, or evidence of other shallow marine tidal processes. Critically, there is no evidence for subaerial exposure, such as desiccation cracks.

Both the Avalon and Bonavista Peninsula successions are dominated by normally graded siltstones and sandstones, showing typical Bouma sequences, and inferred as turbidites by most authors (Gardiner and Hiscott, 1988; Wood et al., 2003; O'Brien and King, 2005; Mason et al., 2013). While turbidites are most well-known from deep marine environments, prodelta turbidites and lacustrine turbidites are common in the rock record. The basis for distinguishing waning flows driven by storm events and crevasse splays are generally contextual. A sediment laden waning flow in a body of standing water will tend to include Bouma-like successions.

Turbidites have been described from shallow (~50 m deep) lakes in the United States (Ludlam, 1974), and examples exist within shallow marine settings. Shallow marine, medium to fine grained sandstone turbidites are known to randomly occur among other deeper than storm wave base facies on the shelf in a backarc basin in Japan (Tokuhashi, 1996). Mutti et al. (2003) describe turbidite-like sandstone to mudstone beds deposited by hyperpycnal flows in shallow marine settings of foreland basins. They differ from classic turbidites in being associated with hummocky cross stratification and interfingering with river-fed delta facies. Turbiditic sandstones accompanied by hummocky cross stratification, forming isolated sand bodies within mudstones, are known from the Campanian of Utah where they are inferred to be prodelta turbidite deposits between fair and storm wave base (Pattison, 2005). Shallow marine turbidites inferred to have been deposited below wave base but in water less than 200 m deep have been documented from the Pliocene of Taiwan (Castelltort et al., 2011).

Fining upwards crevasse splay deposits of the type that might be expected in association with immature floodplain palaeosols should be traceable laterally into fluvial meander belts. There are no channelised facies in either the ~1200 m thick fossiliferous section at MPER, or the ~600 m thick fossiliferous section at the Catalina Dome.

While a few examples of shallow marine turbidites do exist, the vast majority are attributed to deep marine environments. In addition, with  $C_{org}$  levels that are consistent with deposition in a deep marine open ocean setting, and since there is no independent evidence for a shallow marine environment, it is most parsimonious to ascribe a deep marine deposition environment to the sediments of the Mistaken Point Ecological Reserve, and the Catalina Dome as all previous authors have done excepting Retallack (2013; 2014; 2016). If this deep marine association is true, then the Ediacara biota within these deposits would most likely have been below the photic zone, and could not therefore have been photoautotrophic. This would rule out suggestions such as that the Ediacara biota were lichens (Retallack, 1994).

### **Mistaken Point Ecological Reserve**

The majority of beds within the Drook Formation are medium bedded sandstones and siltstones, however it is the other facies that are most indicative of depositional environment. Many of the beds in the type locality show signs of amalgamation. One example is the partial amalgamation of beds where only some of the underlying units capping shale horizon has been eroded. Another is the presence of shale clasts that are concentrated in a zone near the centre of what appears to be a bed. This latter example is likely formed by the erosional break-up of a thin mudstone layer between two successive sandy beds (Stow and Johansson, 2000). These thickly bedded sandstones often show little textural change throughout, but are banded in colour, though alteration haloes around shale clasts may affect this (Figure 2.4D).

Debrisites are also found within the formation (Figure 2.4B). The size and rafted nature of the shale clasts, alongside the massive wackaceous nature of the matrix excludes a turbiditic origin. Clasts of this size are also a likely explanation for the large erosional

grooves seen within the Drook Formation (Figure 2.4C). Debris flows producing beds <2 m thick are known from continental slope settings (Tripsanas et al., 2008), but are commonly observed in distal lobe and fan fringe environments (Wood and Smith, 1958; Talling et al., 2004; Haughton et al., 2009).

The presence of both turbidites and debrites, along with the mineralogy of the deposit, is indicative of deposition within a basin fill complex associated with a tectonically active area (Johansson and Stow, 1995). With no other evidence of a slope setting, such as slump deposits, the debrite facies is interpreted as indicating a distal depositional environment. This is consistent with previous interpretation of the Drook Formation as basin plain and distal submarine fan-lobe deposits (Gardiner and Hiscott, 1988).

The sedimentary facies of the Briscal Formation are compatible with a similar, though possibly more proximal setting. Thickly bedded sandstones with reverse grading at the base, and dewatering structures are consistent with deposition by high-density turbidity currents (Lowe, 1982). Within the slabbed example (Figure 2.11), the coarsening upwards zone at the base of the turbidite represents an S<sub>2</sub> traction carpet, deposited by a mixture of frictional freezing and suspension. This is overlain by an S<sub>3</sub> normally graded sandstone, equivalent to the Bouma sequence T<sub>A</sub> zone. The interval of interbedded sands and silts with dish structures probably lies directly upon an amalgamation surface, representing the transition to deposition by a low-density, silt dominated turbidity current in the wake of the high density flow. Dewatering dish and pillar structures are observed well into the T<sub>D</sub> zone, which is overlain by a T<sub>E</sub> division.

The north westerly flow direction obtained from a horizon of flute marks within the Briscal Formation differs from the north easterly flow direction given by Wood et al. (2003). Further investigation is required as the measurement is isolated, but this alternative

flow direction is contrary to the easterly, south-easterly, and southerly flow directions measured from the other formations in the Conception Group, and may either indicate a unique epiclastic source region or complex basin floor topography. The former explanation would go some way to explaining the localised nature of the Briscal Formation which differs from the other formations that are regional in aerial extent.

The Mistaken Point Formation contains the richest diversity of Ediacaran organisms, and includes some of the highest fidelity impressions such as those of the E-Surface within MPER.

The turbidites of the Mistaken Point Formation include  $T_{(A)(B)(C)DE}$  turbidite divisions. The direction of flow estimated from ripple cross-lamination could not be accurately measured due to lack of bedding plane exposure, but perpendicular cliff sections suggest a flow direction towards the south, broadly consistent with Wood et al. (2003). Metre-thick beds near the top of the formation, often with massive sands at the base and cobble-sized tuffaceous clasts at the top likely represent linked-debrite deposits. These hybrid beds, between turbidite and debrite, are common in systems where the up-dip slope is out-of-grade (Haughton et al., 2009).

The red-purple colour of some Mistaken Point Formation beds, especially those around Mistaken Point itself, has been used as evidence to suggest that the beds were deposited terrestrially (Retallack, 2014). Others have more parsimoniously used the red-purple colour as evidence for oxygenated bottom waters (Wood et al., 2003), which is consistent with the abundance of red marine beds including Cambrian fossiliferous limestones with hyolithids throughout Avalonia and elsewhere at this stratigraphic interval.

Careful mapping throughout MPER, and the wider area, has revealed several new outcrops of the E-Surface that are recognised by the characteristic fossil assemblage and the

distinctive stratigraphic succession. The newly discovered outcrop of the 'E' Surface at Cape Race is generally green in colour, with the succession becoming redder several metres below the E-Surface outcrop. This is opposed to the colour trend is seen at the Yale Outcrop of the E-Surface at Mistaken Point, where the transition from reddish-purple to green colours takes place several tens of metres above this particular marker horizon. The transition from rocks with a red element to their colour, to green lithologies therefore crosses the event horizon that is the E-Surface and its associated overlying tuffite.

A possible explanation for this observation could be that there is a degree of diachroneity between the successions at Mistaken Point and Cape Race. The two outcrops, over 8 km apart, are not exactly alike. The beds at Cape Race are generally thinner, with the distance between the 'D' and 'E' Surfaces here being 1.85 m, compared to 2.59 m. This leads the Cape Race E-Surface outcrop to have an appearance, which were it at Mistaken Point, would likely be described as being much closer to the Mistaken Point – Trepassey Formation boundary.

This evidence is suggestive of the Mistaken Point – Trepassey boundary (a line of litho-correlation) being diachronous, and closer to the E-Surface (a line of chrono-correlation) at Cape Race than at Mistaken Point. This is inkeeping with previous suggestions of the direction of basin-scale sediment progradation (King, 1990).

The difference in position of colour transition within the upper Mistaken Point Formation between the two outcrops mentioned may therefore be related to the two sections being diachronous. A more parsimonious suggestion, however, is that the colour change is a secondary, post-depositional factor, and unrelated to palaeoenvironment.

The Trepassey Formation is dominated by  $T_{(C)DE}$  silty turbidites, though the Bouma C zone is often just a thin horizon of sediment-starved ripple cross-laminated sandstone at the base

of the bed, and, also contains a number of turbidite-linked debrites, similar to those of the upper Mistaken Point Formation. The relative paucity of fossiliferous outcrops is likely to be a product of lack of accessible outcrop of the formation, especially around Long Beach where the unit remains buried by Quaternary deposits. The Trepassey Formation is significantly less tuffaceous than the underlying deposits.

The presence of starved ripples indicates that rates of suspension fallout from the turbidity current were much lower than the rate of down-flow tractional reworking. Combined with the lack of evidence for bypass channels in the upper part of the MPER succession, and therefore the suggestion of a sediment apron across the slope, these starved ripples may imply sandy flows overshot this part of the slope, with the Trepassey Formation comprising the silty tail-of-turbidite deposits associated with the same flows that produce sand-dominated lithologies down-slope. Alternatively the starved ripples may indicate a mud-rich sediment source with low sand content.

The Fermeuse Formation is also dominated by T<sub>DE</sub> turbidites, and can contain cross-laminated starved ripple sands at the base of beds; however beds are generally thinner than in the underlying Trepassey Formation, and are darker in colour. The Fermeuse Formation is characterised by the first common occurrence of large-scale slump deposits, which may be a product of either increased sediment supply or increased slope gradient (cf. MacNaughton et al., 2000).

Previous workers have agreed on the Conception Group succession being deposited within an arc-based tectonic system. Proposals include a continental magmatic arc (Nance et al., 2002), a coastal forearc basin (Retallack, 2014), or a forearc basin transitioning to a basin dominated by strike-slip tectonics (Wood et al., 2003). Myrow (1995) suggested a backarc setting, which is supported by geochemical analysis of the Harbour Main Group from the

Horse Cove Complex (Skipton et al., 2013). Using cross-cutting relationships and U-Pb (zircon) geochronology it has been shown that the older igneous rocks of the Harbour Main Group have E-MORB-like signatures, which transition through to volcanic arc signatures in the later deposits (Skipton et al., 2013).

Backarc basins are less likely to be preserved in the geological record than forearc settings (Draut and Clift, 2013), but the sedimentological succession describe below, along with the lack of large-scale faulting expected in a forearc basin, suggests a backarc setting for these deposits.

The Drook and Briscal Formations record a sequence of volcanoclastic sedimentation with notable debrites and high-density turbidites. It is likely the Whalesback Gabbro was emplaced at this time as it is only seen within the Drook Formation, though not within MPER. This interval corresponds to initial rifting and development of an inter-arc basin, where steep and unstable margins would be conducive to the generation of slumps, debris flows and high-density turbidity currents (Carey and Sigurdsson, 1984).

The Briscal and Mistaken Point Formations represent the transition to back arc spreading and island arc volcanism. During this interval volcanism was at its peak, as evidences by the abundant tuffites in both formations. At this stage of the evolution of marginal basins, deposition is typified by turbidity currents and the creation of volcanoclastic fans, with relatively high rates of sedimentation (Carey and Sigurdsson, 1984). This is consistent with the high rates of sedimentation in the Briscal and Mistaken Point formations in the MPER (Chapter 4).

The Trepassey and Fermeuse Formation mark the transition to basin maturity. Tuffites, while still present in the Fermeuse and higher formations (Matthews, 2011), are much rarer than lower in the succession, and mark the waning of volcanism. This stage in the

evolution of back arc basin is associated with a decrease in the rate of spreading (Carey and Sigurdsson, 1984), which allows increased rates of progradation of the basin slope towards the basin centre. The cessation of the creation of accommodation space may be associated with the progradation, slumping, and associated debrites seen in this part of the section.

### **Catalina Dome**

The Shepherd Point Formation, at the base of the Trinity Bay North Group is dominated by cherty, laminated siltstones, with only some beds showing the characteristic features of sandy turbidites. The remainder of the deposit is defined by fine, wispy laminae and dispersed coarse silt grains (Figure 4), which is similar to the tentative contourite facies seen in the Mistaken Point Formation.

The Murphy's Cove Formation marks the onset of increased volcanism. The unit is less cherty than the underlying deposits, and most likely represents turbidite beds with T<sub>DE</sub> divisions. Enigmatic red-purple carbonate rich horizons are associated with calcite needles (Figure 2.33). Carbonate rich horizons with calcite needles are known from elsewhere in the Neoproterozoic and are there interpreted as deep-marine correlatives of shallow-marine cap-carbonates (Sumner, 2009).

The transition to the Rowland Head Formation is marked by a slight increase in siltstone bed thickness, and thinning of the tuffaceous deposits, relative to the underlying Murphy's Cove Formation. The beds were deposited as T<sub>CDE</sub> beds, with the Bouma C division no more than a few centimetres thick, represented by cross-laminated, starved rippled sandstones. This stratigraphic interval records a more energetic environmental setting than that responsible for the deposition of earlier formations. Fossil horizons in the Rowland Head Formation are underlain by distinctive olive-green, laminated deposits (Figure 3.6D)

possibly representing contourite sedimentation with a noticeable lithic and feldspathic component.

The Port Union Formation reflects the continuing trend towards increasing thickness of turbidite beds deposited in association with more intense hydrodynamic regimes, with thick  $T_{BCDE}$  turbidite sandstones. The presence of mudstone clasts as scour lags, as well as rafted, clustered, and isolated clasts indicates deposition in a more proximal depositional environment than is inferred for the underlying formations, dominated by high density turbidity current, likely within a restricted basin fill complex (Johansson and Stow, 1995). The base of the Port Union Formation is marked by an isolated ~2 m thick unit with highly convolute bedding. Sediment slumping does not become common until the Little Catalina Formation, and as such the interpretation of this isolated strata as a seismoturbidite seems likely (cf. Druschke et al., 2009; Mason et al., 2013).

The overlying Little Catalina Formation, is dominated by dark grey thinly bedded mudstones with inferred to represent deposition of thin  $T_{(C)DE}$  turbidites. Metre-thick slumped units, comprising convolute beds of these thin turbidites, suggests deposition on an unstable slope (cf. MacNaughton et al., 2000).

The Trinity Bay North Group of the Catalina Dome consists of a deep-water marine sedimentary succession that completely lacks evidence for wave-generated ripples, palaeosols, or fluvial facies. Patchy mm-scale mineral growths interpreted as laumontized accretionary lapilli tuff and scoria have been used to infer deposition of these rocks on land (Retallack, 2014). These structures are demonstrated herein to be post-depositional patchy carbonate cements, on the basis of detailed thin section analysis and staining for carbonates (Figure 2.42). Claims of hummocky cross-stratification (Retallack, 2014) are likewise refuted herein.

The dominance of turbidite beds throughout the succession, the inclusion of slumped units, possible deep-marine equivalents of cap carbonates, and the absence of wave-generated sedimentary features supports the interpretation of deposition within a deep-marine environment, as has been previously suggested (O'Brien and King, 2005; Hofmann et al., 2008; Mason et al., 2013).

## **CONCLUSIONS**

The MPER stratigraphic succession represents a shallowing upwards siliciclastic succession likely deposited in a backarc basin. The Drook and lower Briscal formations record sedimentation associated with the initial rifting and development of the basin. The basin then transitioned to backarc spreading and strong island arc volcanism, as shown by the increased sedimentation rate and tuffite horizons of the upper Briscal and Mistaken Point formations. The Trepassey and Fermeuse formations record the stage of basin maturity, with seafloor spreading beginning to cease and sediments prograding into the basin.

The Catalina Dome succession likewise records a shallowing upwards siliciclastic succession. More information is required to better understand the depositional environment of individual formations.

Detailed examination of tuffite deposits within the MPER succession not only adds vital context to geochronological data yielded from these horizons, but also challenges previous models of fossil preservation. Internal structures within these units suggest deposition as an ashy turbidite, likely felling frondose organisms immediately prior to burial, and negating the need for fronds to have pseudo-procumbent life position.

Evidence presented by Retallack in support of assigning a sub-aerial depositional environment to parts of the MPER and Catalina Dome sections is found to be without merit. Claims of shallow marine sedimentary structures cannot be assessed on the basis of figured material, or can be explained as the product of deep marine processes.

Geochemical proxies, used to infer palaeosol facies are shown to have been used far beyond the limits of their original methodology, and techniques for the analysis of modern soils are applied to Ediacaran deposits without discussion of how half a billion years of post-deposition processes may affect the results obtained. There is no evidence of shallow marine sedimentary structures, or sub-aerial exposure such as desiccation cracks.

The MPER and Catalina Dome successions were most likely deposited in deep marine environments, below the photic zone. This rules out photoautotrophic affinities for the Ediacara biota present.

## **ACKNOWLEDGEMENTS**

This research was supported by the Natural Environment Research Council (grant number NE/J5000045/1) and a NIGFSC award. Alex Liu and Tom Hearing are thanked for their help and assistance in gathering the data. Peter J. Matthews is thanked for assistance in slabbing of large samples. The people of Portugal Cove South, and Trepassey are thanked for their hospitality. The Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, provided permits to conduct research within the Mistaken Point Ecological Reserve. Access for research to fossil localities within the Mistaken Point Ecological Reserve is by permit only. Grid references for localities are not published, in accordance with MPER research permit conditions, but can be obtained from the author directly. Readers are advised that the

fossils around Cape Race are protected by the Paleontological Resource Regulations 67/11, under the Historic Resources Act, 1990.

## REFERENCES

- Bamforth, E.L., and Narbonne, G.M., 2009, New Ediacaran Rangeomorphs from Mistaken Point, Newfoundland, Canada: *Journal of Paleontology*, v. 83, no. 6, p. 897–913.
- 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*, v. 82, no. 4, p. 763–777.
- Benus, A.P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland): *Trace Fossils, Small Shelly Fossils and the Precambrian Cambrian Boundary: Proceedings, 1987, Memorial University (New York State Museum and Geological Survey Bulletin)*, p. 8–9.
- Berger, W.H., 1974, Deep-Sea Sedimentation, *in* Burk, C.A. and Drake, C.L. eds., *The Geology of Continental Margins*, Springer Berlin Heidelberg, p. 213–241.
- Berner, R.A., and Raiswell, R., 1984, C/S method for distinguishing freshwater from marine sedimentary rocks: *Geology*, v. 12, no. 6, p. 365–368, doi: 10.1130/0091-7613(1984)12<365:CMFDFD>2.0.CO;2.
- Brasier, M.D., Antcliffe, J.B., and Callow, R.H., 2011, Evolutionary trends in remarkable fossil preservation across the Ediacaran–Cambrian transition and the impact of metazoan mixing: *Taphonomy*, p. 519–567.
- Canfield, D.E., Poulton, S.W., and Narbonne, G.M., 2007, Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life: *Science*, v. 315, no. 5808, p. 92–95.
- Carey, S., and Sigurdsson, H., 1984, A model of volcanogenic sedimentation in marginal basins: *Geological Society, London, Special Publications*, v. 16, no. 1, p. 37–58, doi: 10.1144/GSL.SP.1984.016.01.04.
- Castelltort, S., Nagel, S., Mouthereau, F., Lin, A.T.-S., Wetzel, A., Kaus, B., Willett, S., Chiang, S.-P., and Chiu, W.-Y., 2011, Sedimentology of early Pliocene sandstones in the south-western Taiwan foreland: Implications for basin physiography in the early stages of collision: *Journal of Asian Earth Sciences*, v. 40, no. 1, p. 52–71, doi: 10.1016/j.jseas.2010.09.005.
- Clapham, M.E., and Narbonne, G.M., 2002, Ediacaran epifaunal tiering: *Geology*, v. 30, no. 7, p. 627–630, doi: 10.1130/0091-7613(2002)030<0627:EET>2.0.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*, v. 29, no. 4, p. 527–544, doi: 10.1666/0094-8373(2003)029<0527:POTOKA>2.0.CO;2.

- Cronin, B., Owen, D., Hartley, A., and Kneller, B., 1998, Slumps, debris flows and sandy deep-water channel systems: implications for the application of sequence stratigraphy to deep water clastic sediments: *Journal of the Geological Society*, v. 155, no. 3, p. 429–432, doi: 10.1144/gsjgs.155.3.0429.
- Dalrymple, R.W., Gehling, J.G., and Narbonne, G.M., 1999, Storm dominated sedimentation in a tectonically active basin: Implications for the paleoecology of the Ediacaran biota at Mistaken Point, Newfoundland, *in* *Geol. Soc. Amer. Abstr. Progs*, p. 362.
- Dickson, J. a. D., 1965, A Modified Staining Technique for Carbonates in Thin Section: *Nature*, v. 205, no. 4971, p. 587–587, doi: 10.1038/205587a0.
- Draut, A.E., and Clift, P.D., 2013, Differential preservation in the geologic record of intraoceanic arc sedimentary and tectonic processes: *Earth-Science Reviews*, v. 116, p. 57–84, doi: 10.1016/j.earscirev.2012.11.003.
- Druschke, P., Hanson, A.D., and Wells, M.L., 2009, Structural, stratigraphic, and geochronologic evidence for extension predating Palaeogene volcanism in the Sevier hinterland, east-central Nevada: *International Geology Review*, v. 51, no. 7–8, p. 743–775, doi: 10.1080/00206810902917941.
- Faugères, J.-C., Gonthier, E., and Stow, D.A.V., 1984, Contourite drift molded by deep Mediterranean outflow: *Geology*, v. 12, no. 5, p. 296–300, doi: 10.1130/0091-7613(1984)12<296:CDMBDM>2.0.CO;2.
- Flude, L.I., and Narbonne, G.M., 2008, Taphonomy and ontogeny of a multibranch Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland: *Canadian Journal of Earth Sciences*, v. 45, no. 10, p. 1095–1109.
- Ford, T.E., 1958, Precambrian fossils from Charnwood Forest: *Proceedings of the Yorkshire Geological Society*, v. 31, p. 211–217.
- Fugelli, E.M.G., and Olsen, T.R., 2007, Delineating confined slope turbidite systems offshore mid-Norway: The Cretaceous deep-marine Lysing Formation: *AAPG Bulletin*, v. 91, no. 11, p. 1577–1601, doi: 10.1306/07090706137.
- Gardiner, S., and Hiscott, R.N., 1988, Deep-water facies and depositional setting of the lower Conception Group (Hadrynian), southern Avalon Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 25, no. 10, p. 1579–1594, doi: 10.1139/e88-151.
- Ghisalberti, M., Gold, D.A., Laflamme, M., Clapham, M.E., Narbonne, G.M., Summons, R.E., Johnston, D.T., and Jacobs, D.K., 2014, Canopy Flow Analysis Reveals the Advantage of Size in the Oldest Communities of Multicellular Eukaryotes: *Current Biology*, v. 24, no. 3, p. 305–309, doi: 10.1016/j.cub.2013.12.017.
- Habicht, K.S., Gade, M., Thamdrup, B., Berg, P., and Canfield, D.E., 2002, Calibration of Sulfate Levels in the Archean Ocean: *Science*, v. 298, no. 5602, p. 2372–2374, doi: 10.1126/science.1078265.

- Harazim, D., Callow, R.H.T., and Mcilroy, D., 2013, Microbial mats implicated in the generation of intrastratal shrinkage (“synaeresis”) cracks: *Sedimentology*, v. 60, no. 7, p. 1621–1638, doi: 10.1111/sed.12044.
- Haughton, P., Davis, C., McCaffrey, W., and Barker, S., 2009, Hybrid sediment gravity flow deposits – Classification, origin and significance: *Marine and Petroleum Geology*, v. 26, no. 10, p. 1900–1918, doi: 10.1016/j.marpetgeo.2009.02.012.
- Hiscott, R.N., Pickering, K.T., Bouma, A.H., Hand, B.M., Kneller, B.C., Postma, G., and Soh, W., 1997, Basin-Floor Fans in the North Sea: Sequence Stratigraphic Models vs. Sedimentary Facies: Discussion: *AAPG Bulletin*, v. 81, no. 4, p. 662–665.
- Hofmann, H.J., O’Brien, S.J., and King, A.E., 2008, Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada: *Journal of Paleontology*, v. 82, no. 1, p. 1–36, doi: 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*, v. 44, no. 1, p. 25–41.
- James, N.P., Collins, L.B., Bone, Y., and Hallock, P., 1999, Subtropical carbonates in a temperate realm; modern sediments on the Southwest Australian shelf: *Journal of Sedimentary Research*, v. 69, no. 6, p. 1297–1321, doi: 10.2110/jsr.69.1297.
- Jenkins, R.J.F., 1992, Functional and Ecological Aspects of Ediacaran Assemblages, *in* Lipps, J.H. and Signor, P.W. eds., *Origin and Early Evolution of the Metazoa*, *Topics in Geobiology* 10, Springer US, p. 131–176.
- Jenkins, R.J.F., 1985, The Enigmatic Ediacaran (Late Precambrian) Genus *Rangea* and Related Forms: *Paleobiology*, v. 11, no. 3, p. 336–355.
- Johansson, M., and Stow, D.A.V., 1995, A classification scheme for shale clasts in deep water sandstones: Geological Society, London, Special Publications, v. 94, no. 1, p. 221–241, doi: 10.1144/GSL.SP.1995.094.01.15.
- King, A.F., 1990, Geology of the St. John’s area: Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador.
- Kneller, B.C., and Branney, M.J., 1995, Sustained high-density turbidity currents and the deposition of thick massive sands: *Sedimentology*, v. 42, no. 4, p. 607–616, doi: 10.1111/j.1365-3091.1995.tb00395.x.
- Konhauser, K.O., 2006, *Introduction to Geomicrobiology*: Wiley.
- Ku, T.C.W., Kay, J., Browne, E., Martini, A.M., Peters, S.C., and Chen, M.D., 2008, Pyritization of iron in tropical coastal sediments: Implications for the development of iron, sulfur, and carbon diagenetic properties, Saint Lucia, Lesser Antilles: *Marine Geology*, v. 249, no. 3–4, p. 184–205, doi: 10.1016/j.margeo.2007.12.001.

- Laflamme, M., and Darroch, S.A.F., 2015, Palaeobiology: Ecological Revelations in Ediacaran Reproduction: *Current Biology*, v. 25, no. 21, p. R1047–R1050, doi: 10.1016/j.cub.2015.09.041.
- 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 microfossil record: *Palaeontology*, v. 54, no. 3, p. 607–630, doi: 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*, v. 169, no. 4, p. 395–403, doi: 10.1144/0016-76492011-094.
- Lowe, D.R., 1982, Sediment gravity flows; II, Depositional models with special reference to the deposits of high-density turbidity currents: *Journal of Sedimentary Research*, v. 52, no. 1, p. 279–297, doi: 10.1306/212F7F31-2B24-11D7-8648000102C1865D.
- Ludlam, S.D., 1974, Fayetteville Green Lake, New York. 6. The role of turbidity currents in lake sedimentation: *Limnol. Oceanogr.*, v. 19, no. 4, p. 656–664.
- MacNaughton, R.B., Narbonne, G.M., and Dalrymple, R.W., 2000, Neoproterozoic slope deposits, Mackenzie Mountains, northwestern Canada: implications for passive-margin development and Ediacaran faunal ecology: *Canadian Journal of Earth Sciences*, v. 37, no. 7, p. 997–1020.
- Marlow, J.J., Steele, J.A., Ziebis, W., Thurber, A.R., Levin, L.A., and Orphan, V.J., 2014, Carbonate-hosted methanotrophy represents an unrecognized methane sink in the deep sea: *Nature Communications*, v. 5, p. 5094, doi: 10.1038/ncomms6094.
- Mason, S.J., Narbonne, G.M., Dalrymple, R.W., and O'Brien, S.J., 2013, Palaeoenvironmental analysis of Ediacaran strata in the Catalina Dome, Bonavista Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 50, no. 2, p. 197–212, doi: 10.1139/cjes-2012-0099.
- Matthews, J.J., 2011, The Palaeontology and Palaeoenvironments of the Ferryland Siliciclastic Sequence: Unpublished Masters Thesis, University of Oxford.
- McIlroy, D., Green, O.R., and Brasier, M.D., 2001, Palaeobiology and evolution of the earliest agglutinated Foraminifera: Platysolenites, Spirosolenites and related forms: *Lethaia*, v. 34, no. 1, p. 13–29, doi: 10.1080/002411601300068170.
- Menon, L.R., McIlroy, D., Liu, A.G., and Brasier, M.D., 2016, The dynamic influence of microbial mats on sediments: fluid escape and pseudofossil formation in the Ediacaran Longmyndian Supergroup, UK: *Journal of the Geological Society*, p. 2015–36, doi: 10.1144/jgs2015-036.
- Mulder, T., Razin, P., and Faugeres, J.-C., 2009, Hummocky cross-stratification-like structures in deep-sea turbidites: Upper Cretaceous Basque basins (Western Pyrenees, France): *Sedimentology*, v. 56, no. 4, p. 997–1015, doi: 10.1111/j.1365-3091.2008.01014.x.

- Mutti, E., Tinterri, R., Benevelli, G., Biase, D. di, and Cavanna, G., 2003, Deltaic, mixed and turbidite sedimentation of ancient foreland basins: *Marine and Petroleum Geology*, v. 20, no. 6–8, p. 733–755, doi: 10.1016/j.marpetgeo.2003.09.001.
- Myrow, P.M., 1995, Neoproterozoic Rocks of the Newfoundland Avalon Zone: *Precambrian Research*, v. 73, no. 1–4, p. 123–136.
- Nance, R.D., Murphy, J.B., and Keppie, J.D., 2002, A Cordilleran model for the evolution of Avalonia: *Tectonophysics*, v. 352, no. 1–2, p. 11–31.
- Narbonne, G.M., 2005, THE EDIACARA BIOTA: Neoproterozoic Origin of Animals and Their Ecosystems: *Annual Review of Earth and Planetary Sciences*, v. 33, no. 1, p. 421–442, doi: 10.1146/annurev.earth.33.092203.122519.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: *Geology*, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- O'Brien, S.J., and King, A.F., 2005, Late Neoproterozoic (Ediacaran) stratigraphy of Avalon Zone sedimentary rocks, Bonavista Peninsula, Newfoundland: *Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey*, p. 6–1.
- Óskarsson, B.V., Riishuus, M.S., and Arnalds, Ó., 2012, Climate-dependent chemical weathering of volcanic soils in Iceland: *Geoderma*, v. 189–190, p. 635–651, doi: 10.1016/j.geoderma.2012.05.030.
- Pattison, S.A.J., 2005, Storm-Influenced Prodelta Turbidite Complex in the Lower Kenilworth Member at Hatch Mesa, Book Cliffs, Utah, U.S.A.: Implications for Shallow Marine Facies Models: *Journal of Sedimentary Research*, v. 75, no. 3, p. 420–439, doi: 10.2110/jsr.2005.033.
- Peterson, K.J., Waggoner, B., and Hagadorn, J.W., 2003, A fungal analog for Newfoundland Ediacaran fossils? *Integrative and Comparative Biology*, v. 43, no. 1, p. 127–136, doi: 10.1093/icb/43.1.127.
- Poulton, S.W., and Raiswell, R., 2002, The low-temperature geochemical cycle of iron: From continental fluxes to marine sediment deposition: *American Journal of Science*, v. 302, no. 9, p. 774–805, doi: 10.2475/ajs.302.9.774.
- Premuzic, E.T., Benkovitz, C.M., Gaffney, J.S., and Walsh, J.J., 1982, The nature and distribution of organic matter in the surface sediments of world oceans and seas: *Organic Geochemistry*, v. 4, no. 2, p. 63–77, doi: 10.1016/0146-6380(82)90009-2.
- Raiswell, R., and Berner, R.A., 1986, Pyrite and organic matter in Phanerozoic normal marine shales: *Geochimica et Cosmochimica Acta*, v. 50, no. 9, p. 1967–1976, doi: 10.1016/0016-7037(86)90252-8.
- Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., and Wåhlin, A., 2014, Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations: *Marine Geology*, v. 352, p. 111–154, doi: 10.1016/j.margeo.2014.03.011.

- Retallack, G.J., 2013, Ediacaran Gaskiers Glaciation of Newfoundland reconsidered: *Journal of the Geological Society*, v. 170, no. 1, p. 19–36, doi: 10.1144/jgs2012-060.
- Retallack, G.J., 2016, Ediacaran sedimentology and paleoecology of Newfoundland reconsidered: *Sedimentary Geology*, v. 333, p. 15–31, doi: 10.1016/j.sedgeo.2015.12.001.
- Retallack, G.J., 2014, Volcanosedimentary paleoenvironments of Ediacaran fossils in Newfoundland: *Geological Society of America Bulletin*, v. 126, no. 5–6, p. 619–638, doi: 10.1130/B30892.1.
- Retallack, G.J., 1994, Were the Ediacaran Fossils Lichens: *Paleobiology*, v. 20, no. 4, p. 523–544.
- Seilacher, A., 1992, Vendobionta and Psammocorallia - Lost Constructions of Precambrian Evolution: *Journal of the Geological Society*, v. 149, p. 607–613.
- Seilacher, A., Grazhdankin, D., and Legouta, A., 2003, Ediacaran biota: The dawn of animal life in the shadow of giant protists: *Paleontological Research*, v. 7, no. 1, p. 43–54, doi: 10.2517/prpsj.7.43.
- Sheldon, N.D., Retallack, G.J., and Tanaka, S., 2002, Geochemical Climofunctions from North American Soils and Application to Paleosols across the Eocene-Oligocene Boundary in Oregon: *The Journal of Geology*, v. 110, no. 6, p. 687–696, doi: 10.1086/342865.
- Shepard, F.P., Marshall, N.F., McLoughlin, P.A., and Sullivan, G.G., 1979, *Currents in Submarine Canyons and Other Seavalleys*:
- Skipton, D.R., Dunning, G.R., and Sparkes, G.W., 2013, Late Neoproterozoic arc-related magmatism in the Horse Cove Complex, eastern Avalon Zone, Newfoundland: *Canadian Journal of Earth Sciences*, v. 50, no. 4, p. 462–482, doi: 10.1139/cjes-2012-0090.
- Sparks, R.S.J., and Wilson, C.J.N., 1983, Flow-head deposits in ash turbidites: *Geology*, v. 11, no. 6, p. 348–351, doi: 10.1130/0091-7613(1983)11<348:FDIAT>2.0.CO;2.
- Sperling, E.A., Peterson, K.J., and Laflamme, M., 2011, Rangeomorphs, Thectardis (Porifera?) and dissolved organic carbon in the Ediacaran oceans: *Geobiology*, v. 9, no. 1, p. 24–33, doi: 10.1111/j.1472-4669.2010.00259.x.
- Stow, D.A.V., and Faugères, J.-C., 2008, Chapter 13 Contourite Facies and the Facies Model, *in* Camerlenghi, M.R. and A. ed., *Developments in Sedimentology, Contourites*, Elsevier, p. 223–256.
- Stow, D.A.V., and Johansson, M., 2000, Deep-water massive sands: nature, origin and hydrocarbon implications: *Marine and Petroleum Geology*, v. 17, no. 2, p. 145–174, doi: 10.1016/S0264-8172(99)00051-3.

- Stow, D. a. V., and Piper, D.J.W., 1984, Deep-water fine-grained sediments: facies models: Geological Society, London, Special Publications, v. 15, no. 1, p. 611–646, doi: 10.1144/GSL.SP.1984.015.01.38.
- Stow, D.A.V., Reading, H.G., and Collinson, J.D., 1996, Deep seas: Sedimentary environments: processes, facies and stratigraphy, v. 3, p. 395–453.
- Stow, D.A.V., and Shanmugam, G., 1980, Sequence of structures in fine-grained turbidites: Comparison of recent deep-sea and ancient flysch sediments: *Sedimentary Geology*, v. 25, no. 1, p. 23–42, doi: 10.1016/0037-0738(80)90052-4.
- Stow, D.A.V., and Tabrez, A.R., 1998, Hemipelagites: processes, facies and model: Geological Society, London, Special Publications, v. 129, no. 1, p. 317–337, doi: 10.1144/GSL.SP.1998.129.01.19.
- Sumner, D.Y., 2009, Decimetre-Thick Encrustations of Calcite and Aragonite on the Sea-Floor and Implications for Neoproterozoic and Neoproterozoic Ocean Chemistry, *in* *Precambrian Sedimentary Environments*, Blackwell Publishing Ltd., p. 107–120.
- Talling, P.J., Amy, L.A., Wynn, R.B., Peakall, J., and Robinson, M., 2004, Beds comprising debrite sandwiched within co-genetic turbidite: origin and widespread occurrence in distal depositional environments: *Sedimentology*, v. 51, no. 1, p. 163–194, doi: 10.1111/j.1365-3091.2004.00617.x.
- Tokuhashi, S., 1996, Shallow-marine turbiditic sandstones juxtaposed with deep-marine ones at the eastern margin of the Niigata Neogene backarc basin, central Japan: *Sedimentary Geology*, v. 104, no. 1–4, p. 99–116, doi: 10.1016/0037-0738(95)00123-9.
- Tripsanas, E.K., Piper, D.J.W., Jenner, K.A., and Bryant, W.R., 2008, Submarine mass-transport facies: new perspectives on flow processes from cores on the eastern North American margin: *Sedimentology*, v. 55, no. 1, p. 97–136, doi: 10.1111/j.1365-3091.2007.00894.x.
- Wignall, P.B., Newton, R., and Brookfield, M.E., 2005, Pyrite framboid evidence for oxygen-poor deposition during the Permian–Triassic crisis in Kashmir: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 216, no. 3–4, p. 183–188, doi: 10.1016/j.palaeo.2004.10.009.
- Williams, H., and King, A.F., 1979, Trepassey map area, Newfoundland: Geological Survey of Canada, Energy, Mines, and Resources Canada.
- Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, J.G., and Clapham, M.E., 2003, Palaeoenvironmental analysis of the late Neoproterozoic Mistaken Point and Trepassey formations, southeastern Newfoundland: *Canadian Journal of Earth Sciences*, v. 40, no. 10, p. 1375–1391.
- Wood, P.A., and Smith, A.J., 1958, The Sedimentation and Sedimentary History of the Aberystwyth Grits (upper Llandoveryan): *Quarterly Journal of the Geological Society*, v. 114, no. 1–4, p. 163–195, doi: 10.1144/gsjgs.114.1.0163.

# Chapter 4: Geochronology of the Mistaken Point Ecological Reserve and the Catalina Dome

---

## ABSTRACT

New U-Pb (zircon) ages from key stratigraphic volcanogenic horizons within the ~2300 m thick Ediacaran succession in and around the Mistaken Point Ecological Reserve (MPER) provide an improved chronostratigraphic framework for the Ediacaran macro- and trace-fossil assemblage. This provides an essential temporal constraint for comparison and correlation with other broadly contemporaneous fossiliferous successions worldwide in order to understand evolutionary and ecological development. Furthermore, U-Pb (zircon) ages from two horizons in the Catalina Dome, Bonavista Peninsula allow development of the chronostratigraphic framework for the macrofossil assemblage present in this succession, and demonstrate that much of the Catalina Dome is older than previously envisaged through lithostratigraphic correlation with the rocks at Mistaken Point. A U-Pb (zircon) age from MPER indicates that the trace fossils there are older than  $565.17 \pm 0.44$  Ma. This age is therefore a minimum for what is considered one of the oldest reputable examples of locomotion. The oldest evidence for animals in the Catalina Dome succession is constrained by a U-Pb (zircon) age of  $566.43 \pm 0.73$  Ma from ~50 m below a surface containing *Haootia quadriformis*, a tentative cnidarian. This new chronostratigraphic framework permits the integration of lithostratigraphic and palaeontological datasets for the first time, and provides valuable constraints on the rise of the Ediacara biota.

## **INTRODUCTION**

The late Ediacaran siliciclastic successions around Mistaken Point Ecological Reserve (MPER) and the Catalina Dome, both of Newfoundland, Canada, are well known for their exceptionally preserved macrofossil assemblages and have been central to development of theories related to the nature of the Ediacaran biota (Narbonne, 2004; Liu et al., 2011; Darroch et al., 2013; Mitchell et al., 2015). Understanding the causes of the emergence, evolution, and extinction of the Ediacaran biota, and their relationship to environmental change requires the construction of an accurate, highly-resolved chronostratigraphic framework upon which biostratigraphic, taphonomic, sedimentological, and environmental data can be integrated. This has to be achieved region by region with the ultimate goal being objective integration of environmental and palaeobiological proxy data worldwide. The fossil assemblages of MPER and the Catalina Dome contain key discoveries including the oldest frondose organisms (Narbonne and Gehling, 2003), the oldest evidence of locomotion (Liu et al., 2010), and the oldest evidence of muscular tissue (Liu et al., 2014). This chapter presents new radio-isotopic data and from these develops a chronostratigraphic framework for the fossiliferous successions of MPER and the Catalina Dome, allowing the temporal constraints on these two sections to be compared for the first time, and underpinning comparison with other late Ediacaran fossil bearing assemblages.

## **PRIOR DATING OF THE MPER SUCCESSION**

This study builds upon a legacy of investigations for the MPER and Catalina Dome successions, including radio-isotopic dating of volcanic layers to constrain the age of key fossiliferous layers. Maximum ages for the MPER succession comes from dates from the underlying glaciogenic Gaskiers Formation and the basal Drook Formation of around 582 Ma (Bowring et al. 2002). These are non-published dates, the results have only been

presented in abstract form therefore it is not possible to identify whether they are  $^{238}\text{U}$ - $^{206}\text{Pb}$  or  $^{207}\text{Pb}/^{206}\text{Pb}$  dates and the vintage of the U/Pb tracer calibration. Within this non-published dataset a date of ~579 Ma was presented for an ash bed within the fossiliferous section of the Drook Formation. Another important prior constraint is the report of a ~565 Ma 'U-Pb' data from an ash bed (the 'E' Surface) within the Mistaken Point Formation. Again, the description of this data is limited to a personal communication (G. Dunning, in Benus, 1988). Whilst these two studies demonstrate the potential utility of U-Pb (zircon) dating of ash layers from the MPER, the lack of full publication of radio-isotopic analyses and sample location information limits the usefulness of such data and hence the need for this study to be undertaken.

#### **U-Pb GEOCHRONOLOGY ANALYTICAL METHODS**

Radio-isotopic dates from these successions are based upon U-Pb (zircon) geochronology of tuffs that occur at certain levels within the successions of interest. U-Pb (zircon) geochronology of tuffs is established as the most robust method for absolute dating of these successions, where inter-stratified volcanics occur (e.g. Grotzinger et al., 1995; Martin et al., 2000; Noble et al., 2015). This study uses high-accuracy single zircon dating using U-Pb (zircon) Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-ID-TIMS) method to date a number of ash beds throughout the successions. These dates provide maximum/minimum constraints on key fossiliferous intervals with the MPER and Catalina Dome successions and allow an improved quantification of sediment accumulation rates within each basin.

*Mineral Separation:* Samples of 5 – 25 kg were jaw crushed and disk milled. Having been sieved to remove particles >355  $\mu\text{m}$ , heavy mineral concentrates were prepared using a Rogers Table, Frantz LB-1 magnetic separator, and methylene iodide heavy liquids. Zircon

grains were then selected by hand for analysis from the non-magnetic heavy mineral fraction based upon external morphology, and lack of inclusions and internal textures indicating the presence of xenocrystic cores. Cathodeluminescence (CL) imaging of the internal zonation of zircon was carried out on a subset of samples.

*U-Pb (zircon) Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-ID-TIMS)*: To eliminate the effect of post-crystallisation Pb-loss, zircons selected for analysis by isotope dilution (ID) thermal ionisation mass spectrometry (TIMS) were subjected to a process of thermal annealing and chemical leaching pre-treatment known as “chemical abrasion” (Mattinson, 2005). This approach is established as routine for U-Pb analyses by ID-TIMS having been repeatedly demonstrated as more effective than mechanical abrasion (Bowring et al., 2007), although still not 100% effective all of the time (e.g. Huyskens et al., 2016). Bulk zircon fractions were thermally annealed in a muffle furnace to  $900 \pm 20^\circ\text{C}$  for ~ 60 hours in quartz beakers. Following optical examination with transmitted light selected zircons (single crystals and fragments) were selected, photographed and then transferred to 300  $\mu\text{l}$  Teflon PFA microcapsules, which were placed within a Parr pressure vessel, and leached in 29 M HF with trace  $\text{HNO}_3$  for 12 hours at  $\sim 180^\circ\text{C}$ . The leachate was then removed and the zircons rinsed in ultrapure  $\text{H}_2\text{O}$ , fluxed on a hotplate at  $\sim 80^\circ\text{C}$  for 3 hours in 6 M HCl, ultrasonically cleaned for 30 minutes, and finally placed back on the hotplate for an additional 30 minutes. The HCl solution was then removed and the zircon crystals were finally rinsed in ultrapure 4M  $\text{HNO}_3$  prior to the addition of spike with mixed EARTHTIME  $^{233}\text{U}$ - $^{235}\text{U}$ - $^{205}\text{Pb}$  tracer. The zircons were dissolved in  $\sim 120 \mu\text{l}$  of 29 M HF with a trace amount of 30%  $\text{HNO}_3$  at  $\sim 220^\circ\text{C}$  for at least 60 hours, with the microcapsules housed within Parr vessels. The zircon digests were then dried to fluorides, which were subsequently converted to chlorides in 3 M HCl at  $\sim 180^\circ\text{C}$  overnight.

U and Pb were separated using standard HCl-based anion-exchange chromatographic procedures on 0.05 ml PTFE columns manufactured at the NERC Isotope Geosciences Laboratory (NIGL). Pb and U isotope ratios were measured using the NIGL Thermo-Electron Triton Thermal Ionisation Mass-Spectrometer (TIMS), which is used solely for low-blank U-Pb geochronology. Pb and U were loaded together on a single Re filament in a phosphoric acid – silica gel mixture (Gerstenberger and Haase, 1997). Pb isotopes were measured by peak-hopping on a single SEM detector. U isotope measurements were made in the static Faraday mode.

$^{206}\text{Pb}/^{238}\text{U}$  dates were calculated using the  $^{238}\text{U}$  and  $^{235}\text{U}$  decay constants of Jaffey et al. (1971) and a value of  $^{238}\text{U}/^{235}\text{U}_{\text{zircon}} = 137.818 \pm 0.045$  (Hiess et al., 2012) was used in the data reduction calculations. U/Pb were determined via isotope dilution using the gravimetric calibration of the EARTHTIME mixed U/Pb tracer (Condon et al., 2015; McLean et al., 2015) and using the data reduction and uncertainty propagation algorithms implemented in the U-Pb REDUX software (Bowring et al., 2011; McLean et al., 2011). For U-Pb data sets of this age, the  $^{206}\text{Pb}/^{238}\text{U}$  dates are the most precise and robust, assuming the chemical abrasion has been effective in eliminating the effects of Pb-loss. In contrast, the  $^{207}\text{Pb}$ -based dates ( $^{207}\text{Pb}/^{235}\text{U}$  and  $^{207}\text{Pb}/^{206}\text{Pb}$ ) are less precise with  $2\sigma$  uncertainties on the order of 2 Myr and hence are used only to assess concordance of the U-Pb (zircon) systematics.

## **INTERPRETIVE FRAMEWORK**

The interpretation of U-Pb (zircon) data obtained from each of the samples necessarily requires that a judgement be made on those zircon U-Pb analyses (i.e., dates) that are thought to represent the age of eruption (and therefore deposition of the tuffaceous material within the preserved succession), and those that do not (i.e., analyses of older,

xenocrystic materials, and/or analyses perturbed by Pb-loss). In this study zircon U-Pb dates from each sample showed significant scatter over 2-5 Myr, in excess of analytical uncertainty. Potential causes of this scatter include post-depositional Pb-loss (discussed above); pre-eruptive processes, either through the recycling of older xenocrysts or prolonged crystallisation prior to eruption; and post-eruption reworking during transport and deposition of ash. This type of age variation with ID-TIMS U-Pb (zircon) data sets is typical (Schmitz and Davydov, 2012; Sahy et al., 2015), especially in volcanically active basins when the background supply of zircon is juvenile.

Several viable frameworks exist for the interpretation of U-Pb geochronology datasets. The most common approach is to derive a weight mean date (Ludwig, 1991) from the largest population of youngest ages that yield a Mean Square Weighted Deviation (MSWD) value within the 95% confidence interval. This is predicated on the assumption that if Pb loss does manifest itself in an analysis it is unlikely to be reproducible (e.g. Bowring et al., 2007) and that older dates reflect pre-eruptive processes and/or inheritance of older zircon. The range of MSWD values deemed to be acceptable is a product of the precision of each of the included dates, and the number of dates included in calculation. An MSWD value within the prescribed acceptable range indicates that statistically, no age variation can be detected within the chosen population, recognising the individual levels of precision of each date may obscure real age variation. The benefit of including the highest number of dates thought to represent a coherent population is that it provides a more complete likeness of the expected normal distribution around the true age of eruption. A weakness of this approach is that increasing  $n$  has the effect of reducing the weighted mean uncertainty to a point where it may not be realistic and may underestimate the true uncertainty.

A recent alternative interpretive framework is the selection of the ‘youngest date’ to best approximate the age of deposition of an ash layer, whereby it is assumed that the youngest date obtained corresponds to the youngest zircon in the sample, and all older dates reflect pre-eruptive zircon dates (e.g. Schoene et al., 2010). The weakness of this framework is that results are not, by definition, reproducible and therefore robustness of the single analyses cannot be determined from the sample dataset alone. This further raises the question of whether the youngest date does indeed represent the eruptive age, or whether this has been perturbed by open-system processes (e.g. Pb-loss).

In reality these are two end-member interpretative frameworks and depending on the dataset there will be a number of intermediate options (e.g. youngest two dates, youngest three dates). In this study we discuss these two end member interpretive frameworks for assigning depositional ages to the tuff layers, ignoring the intermediate options

## **GEOCHRONOLOGICAL SAMPLES AND U-PB RESULTS**

Samples were collected under permit, issued by the Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador. Targeted tuffaceous horizons were identified in the field based on their light buff to grey-green colour, and tendency to be more cleaved than the surrounding lithologies. Other indicators include dark speckling caused by authigenic chlorite growth, and the co-location of fossil remains which are often found preserved beneath volcanoclastic horizons. Tuffaceous samples were collected for geochronological analysis, and where cleavage and collection regulations allowed, a sample for slabbing was also obtained. Detailed sedimentological description of the samples is given in Chapter 3.

## Samples and dates from Mistaken Point Ecological Reserve

Six samples were analysed from the Mistaken Point Ecological Reserve. The locations and stratigraphic levels of these samples are given in Figure 4.1. The results of the analyses are summarised in Figure 4.2.

*DRK-10*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the DRK-10 tuffite ranged from 573.61 – 577.58 Ma (n=9). The four youngest dates gave a weighted mean age of  $574.44 \pm 0.51$ , with an MSWD of 2.8, which is considered to best approximate the age of deposition of the tuffite at this level.

*DRK-1*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the DRK-1 tuffite ranged from 571.17 – 577.20 Ma (n=18). The 5 youngest dates gave a weighted mean age of  $571.40 \pm 0.18$ , with an MSWD of 0.83. This is indistinguishable from the youngest date.

*BRS-1*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the BRS-1 tuffite ranged from 566.42 – 571.14 Ma (n=8). The youngest date was excluded due to it being significantly younger than the remaining population of data and not reproduced. The four youngest analyses, excluding z3, gave a weighted mean age of  $567.77 \pm 0.23$  Ma, with an MSWD of 1.9.

*MP-14*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the MP-14 tuffite ranged from 564.15 – 598.84 Ma (n=16). The youngest date (z16) was interpreted as having undergone post-crystallisation Pb-loss. The oldest analysis likely represents inherited/reworked material. The seven youngest analyses, excluding z16, gave a weighted mean age of  $565.23 \pm 0.15$ , with an MSWD of 1.7.

*LC-1*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the LC-1 tuffite ranged from 564.72 – 567.27 Ma (n=11). The three youngest dates gave a weighted mean age of  $565.17 \pm 0.44$ , with an MSWD of 1.8.

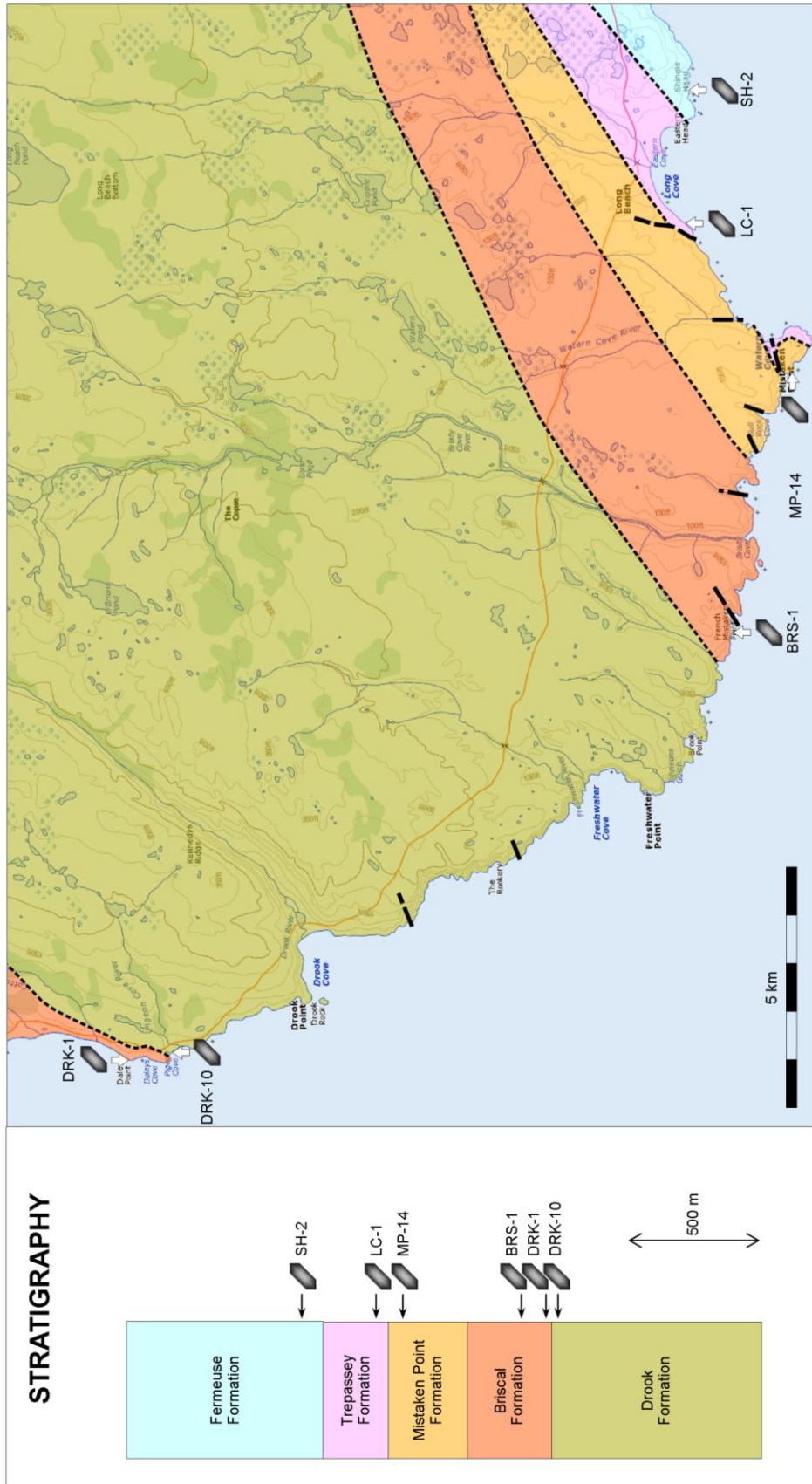


FIGURE 4.1. Diagram showing the stratigraphic and geographic positions of geochronological samples taken from within the Mistaken Point Ecological Reserve.

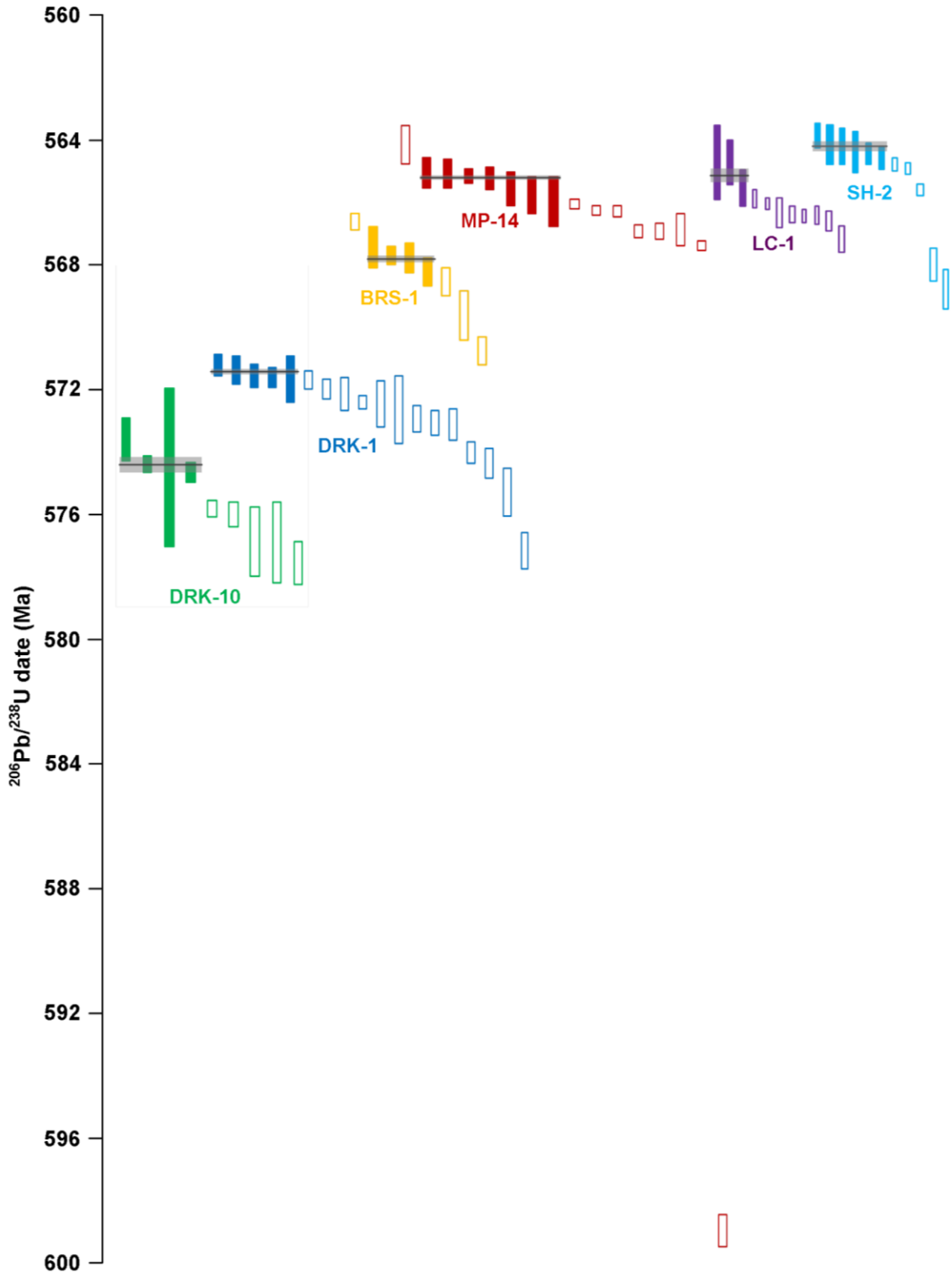


FIGURE 4.2. U-Pb data for samples from the Mistaken Point Ecological Reserve. For each sample, filled bars represent analyses included in the weighted mean calculation. Hollow bars represent data excluded from the weighted mean. The weighted mean age is shown by the dark grey line, and the uncertainty of that age is shown in the light grey bar.

*SH-2*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the SH-2 tuffite ranged from 563.73 – 569.06 Ma (n=11). The six youngest dates gave a weighted mean age of  $564.20 \pm 0.33$ , with an MSWD of 1.6.

A full dataset for these samples is presented in Table 4.1 (at end of chapter).

### **Samples and dates from the Catalina Dome**

Two samples were analysed from the Catalina Dome. The locations and stratigraphic levels of these samples are given in Figure 4.3. The results of the analyses are summarised in Figure 4.4.

*MRC-6*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the MRC-6 tuffite ranged from 570.95 – 574.30 Ma (n=4), with the three youngest ages giving a weighted mean age of  $571.00 \pm 0.37$  Ma, and an MSWD of 0.044.

*HF14-6*:  $^{206}\text{Pb}/^{238}\text{U}$  dates from the HF14-6 tuffite ranged from 565.92 – 608.02 Ma (n=6), with the three youngest ages giving a weighted mean age of  $566.43 \pm 0.73$  Ma, with an MSWD of 2.9.

A full dataset for these samples is presented in Table 4.1 (at end of chapter).

## **DISCUSSION**

### **A New Chronostratigraphic Framework for MPER**

For the first time, the wider contexts of tuffaceous deposits, and the dates yielded from them can be understood through detailed observations of outcrops, as well as slabbed and polished sections. The sedimentology of the tuffites is discussed in detail in Chapter 3.

Several of the tuffites sampled for geochronological analysis exhibit signs of sub-marine reworking of the volcanoclastic sediments, including cross-lamination, shale clasts, and units with an upper boundary that transitions into tuffite-free material. Samples DRK-10

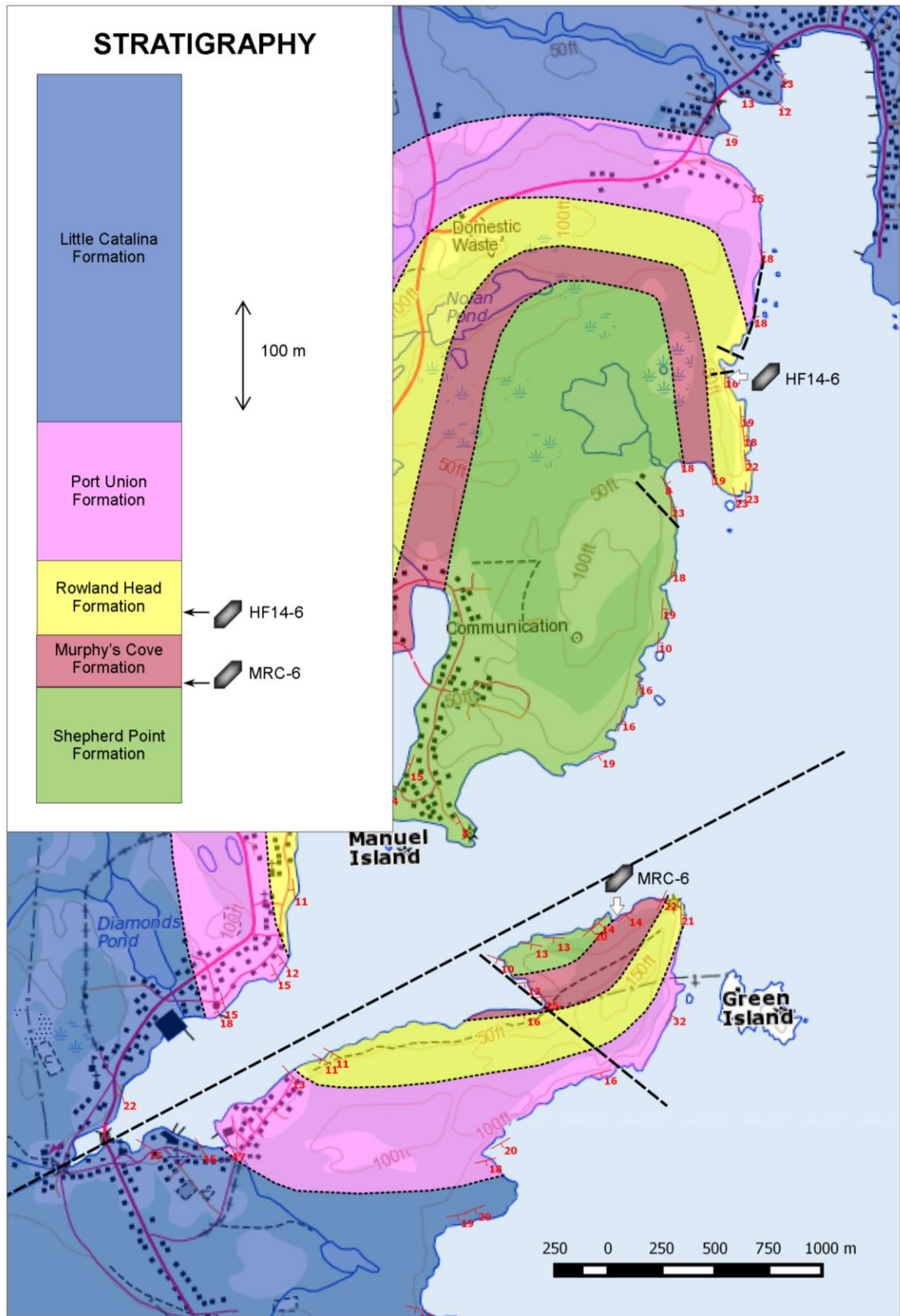


FIGURE 4.3. Diagram showing the stratigraphic and geographic positions of the geochronological samples taken from the Catalina Dome area.

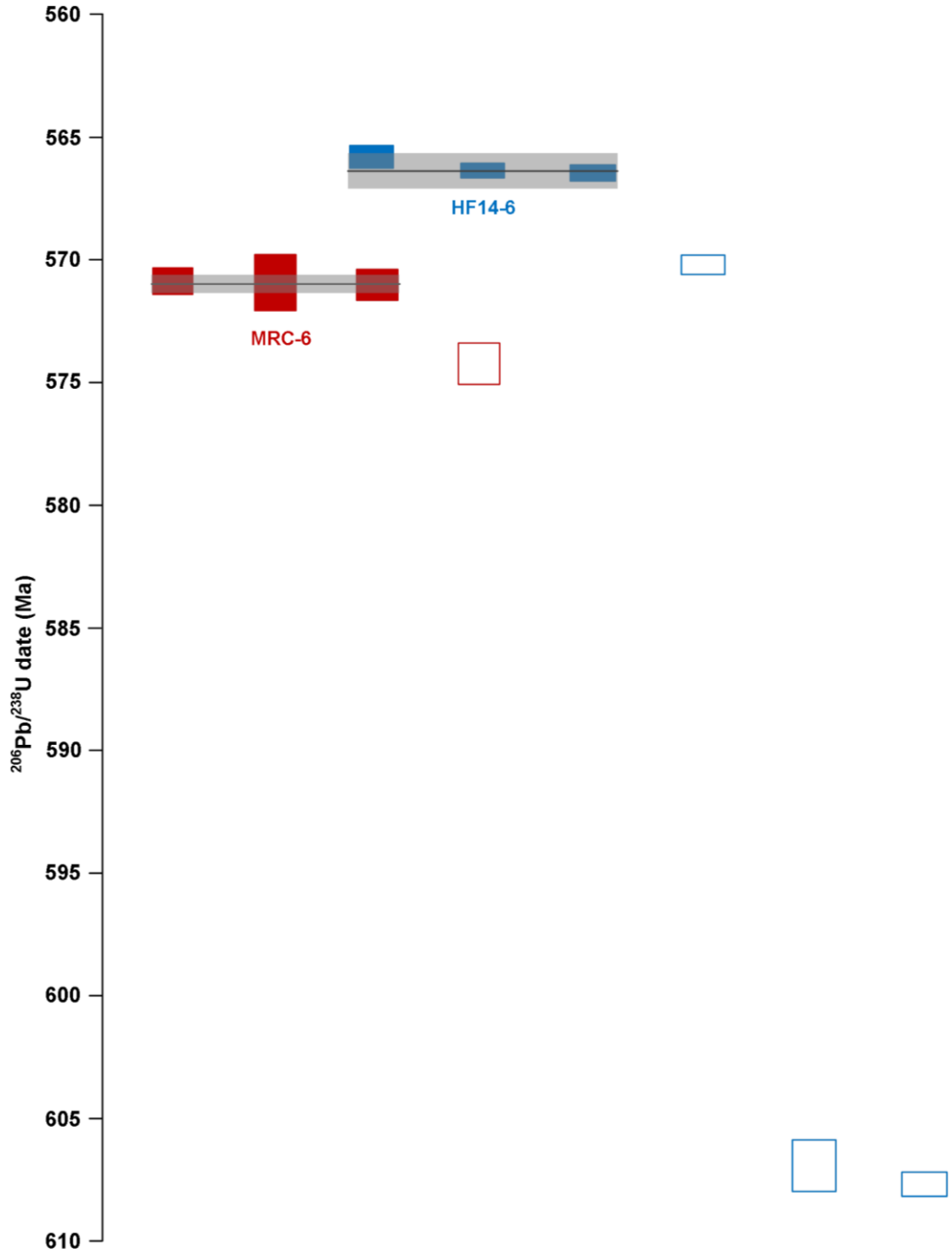


FIGURE 4.4. U-Pb data for samples from the Catalina Dome. For each sample, filled bars represent analyses included in the weighted mean calculation. Hollow bars represent data excluded from the weighted mean. The weighted mean age is shown by the dark grey line, and the uncertainty of that age is shown in the light grey bar.

and DRK-1, show signs of being deposited as volcanoclastic dominated turbidites. While this requires an interval between eruption and final resedimentation, this is thought to be relatively short – lithification has not occurred following the primary sedimentation, and shale clasts in the final deposit have a non-tuffaceous composition. The DRK-10 and DRK-1 dates are therefore interpreted as depositional ages. With no internal sedimentological data available for the BRS-1 sample, the same interpretation is applied. This interpretation is similar to that made for U-Pb (zircon) dating of similar tuffites in other basins where a priori constraints allow for a test of the U-Pb (zircon) dating (e.g. Schmitz and Davydov, 2012; Wotzlaw et al., 2014), and where there is a lag between a zircon dates and sedimentation, excluding clearly inherited zircon dates, it is on the order ~100 kyr (Wotzlaw et al., 2014).

Sample DRK-10 is sampled from the same horizon believed to be the origin of material that yielded an age of  $578.8 \pm 0.5$  Ma (unpublished data from Bowring in Van Kranendonk et al., 2008). This date is significantly older than the ~574 Ma data from this study, however the lack of exact reporting of the data and sample context limits any precise comparison.

It was not possible to collect a sample of BRS-1 for slabbing, but from the field observations, this unit is interpreted as an ashy turbidite.

The volcanoclastics directly above the E-Surface at the Mistaken Point ‘Yale’ and ‘Queens’ Outcrops are directly overlain by a 5 mm thick lithic and crystal tuff, with very little finer material, save for the chlorite matrix (Figure 2.15B). This stratum is directly overlain by a normally graded 10 cm thick tuffite with signs of laminations in places (Figure 3.3). This sequence of a fines-poor lithic/crystal tuff capped by a normally graded tuffaceous unit has been described from the Mediterranean ash turbidite deposits

associated with the Minoan eruption of Santorini (Sparks and Wilson, 1983). If this comparison is justified, the 5 mm lithic/crystal tuff is interpreted as a flow-head deposit, deposited rapidly by the front of the turbidity current, onto which the more conventional turbidite is then deposited. The MP-14 date is therefore interpreted as a depositional age, noting the same caveats as for DRK-10, DRK-1, and BRS-1.

Sample MP-14 is sampled from the same horizon believed to be the origin of material that yielded an age of  $565 \pm 3$  Ma (Benus, 1988). Without knowing the methodology, this previous datum may be a  $^{206}\text{Pb}/^{207}\text{Pb}$  age, and therefore not directly comparable to the new data presented herein.

Due to pervasive modern weathering the internal fabric of sample LC-1 cannot be easily observed. Caution is further advised as the interpreted age for MP-14, including the associated  $2\sigma$  uncertainties, lie within the uncertainties of the LC-1 result. Interpretation of this data as a deposition age would require a rapid, near 8-fold increase in sediment accumulations rate, based on compacted thicknesses (Figure 4.5). However with no direct evidence to the contrary, the LC-1 sample is interpreted as the age of eruption/deposition.

The SH-2 sample shows convolute and disturbed internal laminations, and is situated within a slump scar, where it is overlain by a slumped unit. The tuffaceous SH-2 unit likely acted as the décollement for the overlying slump unit, and was therefore previously deposited upslope and semi-lithified. The SH-2 date is interpreted as a maximum age (Table 4.2).

The robustness of the selected interpretive framework for the geochronological data was tested by analysing the impact of using the alternative ‘youngest age’ framework. For the DRK-10, DRK-1, LC-1, and SH-2 samples there is no statistical difference between the age given by the youngest date and that provided by the weighted mean of the youngest

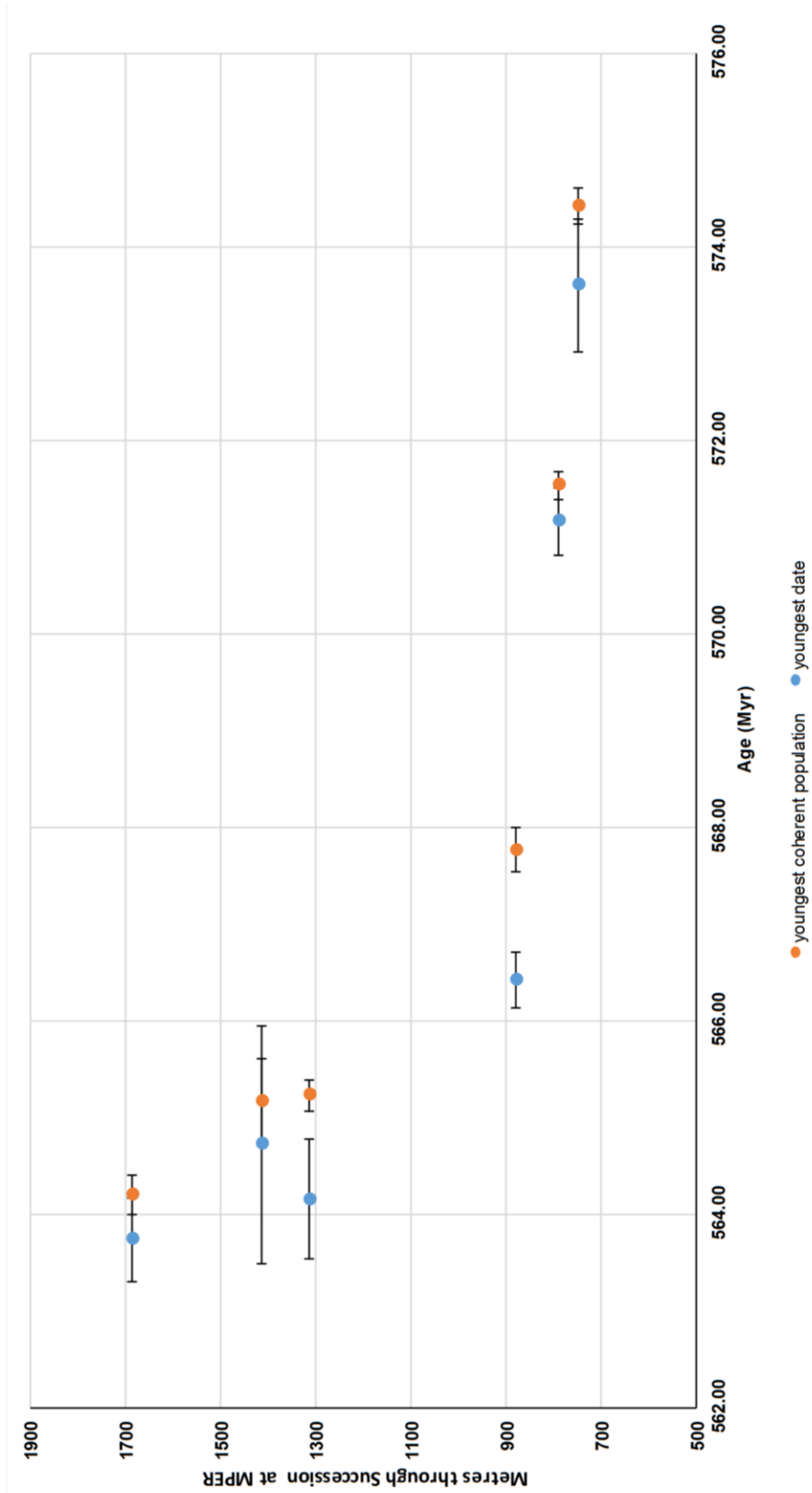


FIGURE 4.5. Age model for the rocks of the Mistaken Point Ecological Reserve. Dates given by weighted mean of youngest coherent population in orange. Dates given by youngest date given in blue. Analytical uncertainties shown.

coherent population (Figure 4.5; Table 4.3). Statistical equivalence is shown by an overlap in the  $2\sigma$  uncertainties of the compared dates.

Sample	Stratigraphic Position	Weighted Mean $^{206}\text{Pb}/^{238}\text{U}$ date (Ma)	$\pm X$	$\pm Y$	$\pm Z$	N	MSWD	Interpretation
SH-2	Fermeuse Formation	564.20	0.20	0.25	0.65	6/11	1.6	Maximum age
LC-1	Trepassey Formation	565.17	0.44	0.46	0.76	3/11	1.8	Eruption/Deposition
MP-14	Mistaken Point Formation	565.23	0.16	0.22	0.64	7/16	1.7	Eruption/Deposition
BRS-1	Briscal Formation	567.77	0.23	0.27	0.66	4/8	1.9	Eruption/Deposition
DRK-1	Briscal Formation	571.40	0.14	0.22	0.65	5/18	0.83	Eruption/Deposition
DRK-10	Drook Formation	574.43	0.19	0.24	0.66	4/9	2.8	Eruption/Deposition

TABLE 4.2. Summary of interpreted U-Pb (zircon) dates from the Mistaken Point Ecological Reserve. X – internal or analytical uncertainty (Myr). Y – quadratic addition of tracer calibration error. Z – quadratic addition of both trace calibration and  $^{238}\text{U}$  decay constant errors. MSWD – mean square weighted deviation

Sample	Youngest $^{206}\text{Pb}/^{238}\text{U}$ date (Ma)	$\pm X$	$\Delta t$	$\Omega$
SH-2	563.73	0.43	0.47	0.47
LC-1	564.7	1.2	0.5	1.3
MP-14	564.15	0.62	1.08	0.64
BRS-1	566.42	0.29	1.35	0.37
DRK-1	571.17	0.35	0.37	0.37
DRK-10	573.61	0.69	0.82	0.72

TABLE 4.3. Comparison of the date obtained from the youngest date with that of weighted mean of the youngest coherent population with an acceptable MSWD. X - the analytical uncertainty (Myr) for the youngest date.  $\Delta t$  - the difference (Myr) between the youngest date and the weighted mean.  $\Omega$  - the analytical uncertainties in both dates combined in quadrature.

Samples BRS-1 and MP-14 notably don't show statistical equivalence between dates provided by the two frameworks. This reflects the exclusion of the youngest zircon from the weighted mean calculation from each of these samples due to them being isolated from what was interpreted as the youngest coherent population. The use of the 'youngest date'

framework would not radically change the stratigraphy, but noting the sedimentological qualifiers previously mentioned, it does introduce a small stratigraphic inconsistency considering the LC-1 sample is stratigraphically above MP-14.

The youngest coherent population approach is preferred as it includes the range of results that would be expected from the crystallisation of zircons during a single eruption, and we suggest that the younger non-reproducible U-Pb dates reflect incomplete elimination of Pb-loss in those zircons analysed. The weighted mean date uncertainties in this study are likely not underestimated as  $n$  for each sample is limited and the precision of the weighted mean date is comparable to the most precise single date uncertainty. The difference between the two end-member interpretative frameworks has a negligible impact on the overall chronostratigraphic interpretation of the succession (Figure 4.5).

### **A Chronostratigraphic Framework for the Catalina Dome**

No previous geochronological data has been published for the rocks of the Catalina Dome, and all previously presented ages for fossiliferous horizons were based on lithostratigraphic correlation with the rocks of Mistaken Point, and the implicit assumption that chronostratigraphic correlations can be inferred directly from lithostratigraphic extrapolations.

Field observations gave no indication that the chosen geochronological samples had undergone redeposition or sedimentary reworking, but closer examination was precluded by the pervasive cleavage. The calculated dates are interpreted as ages of eruption and deposition, there being no evidence to the contrary (Table 4.4). This interpretation is reached with caution, following the studies on tuffite deposition in the Mistaken Point Ecological Reserve, described in Chapter 2.

Sample	Stratigraphic Position	$^{206}\text{Pb}/^{238}\text{U}$ date (Ma)	$\pm X$	$\pm Y$	$\pm Z$	N	MSWD	Interpretation
HF14-6	Catalina Formation	566.43	0.2	0.25	0.65	3/6	2.9	Eruption/Deposition
MRC-6	Murphy's Cove Formation	571.00	0.38	0.41	0.73	3/4	0.04	Eruption/Deposition

TABLE 4.4. Summary of interpreted U-Pb (zircon) dates from the Catalina Dome. X – internal or analytical uncertainty (Myr). Y – quadratic addition of tracer calibration error. Z – quadratic addition of both trace calibration and  $^{238}\text{U}$  decay constant errors. MSWD – mean square weighted deviation

The robustness of the selected interpretative framework for the geochronological data was tested by analysing the impact of using the ‘youngest age’ framework. For both samples there is no statistical difference between the age given by the youngest date, and that provided by the weighted mean of the youngest coherent population (Table 4.5).

Sample	Youngest $^{206}\text{Pb}/^{238}\text{U}$ date (Ma)	$\pm X$	$\Delta t$	$\Omega$
HF14-6	565.92	0.47	0.51	0.51
MRC-6	570.95	0.53	0.05	0.65

TABLE 4.5. Comparison of the date obtained from the youngest date with that of weighted mean of the youngest coherent population with an acceptable MSWD. X - the analytical uncertainty (Myr) for the youngest date.  $\Delta t$  - the difference (Myr) between the youngest date and the weighted mean.  $\Omega$  - the analytical uncertainties in both dates combined in quadrature.

The youngest coherent population approach is preferred as it includes the range of results that would be expected from the crystallisation of zircons during a single eruption, however the weighted mean date uncertainties may be underestimated. The difference between the two end-member interpretative frameworks has a negligible impact on the overall chronostratigraphic interpretation of the succession (Figure 4.4).

## CONCLUSIONS

The application of high-precision  $^{206}\text{Pb}/^{238}\text{U}$  (zircon) ID-TIMS geochronology to multiple levels within the late Ediacaran rocks of the Mistaken Point Ecological Reserve, Newfoundland, has permitted the construction of a more robust and better resolved chronostratigraphy for this fossiliferous succession. Similarly, analysis of two horizons

from the Catalina Dome, Bonavista Peninsula, Newfoundland has allowed for the construction of the first geochronological framework for this important fossiliferous succession.

The new data presented for the Mistaken Point Ecological Reserve slightly amends the currently used chronostratigraphy. The previous age of  $578.8 \pm 0.5$  Ma (unpublished data from Bowring in Van Kranendonk et al., 2008) for the 'Pizza Disk bed' (DRK-10) is revised to  $574.44 \pm 0.51$  Ma. The oldest large complex multicellular organisms, specimens of *Trepassia wardae*, are ~50 m below this horizon.

The age of the E-Surface (MP-14) is revised from  $565 \pm 3$  Ma (Benus, 1988) to  $565.23 \pm 0.15$  Ma. Four other dates are provided, covering the majority of the fossiliferous strata within MPER. Increased chronological resolution around the Trepassey and Fermeuse formations shows an increased sedimentation rate at this point in the interval, compared to elsewhere in the succession. This supports geochemical data suggesting increased sedimentation rates at this point (Canfield et al., 2007). The age model for the Mistaken Point Ecological Reserve (Figure 4.5) is consistent with that of a sedimentary sequence deposited within a back arc basin (Chapter 3). If this palaeoenvironmental setting is correct, then the Drook and lower Briscal formations record sedimentation associated with the initial rifting and development of the basin. At ~567 Ma the basin transitioned to backarc spreading and strong island arc volcanism, as shown by the increased sedimentation rate and tuffite horizons of the upper Briscal and Mistaken Point formations. The Trepassey and Fermeuse formations record the stage of basin maturity, with seafloor spreading beginning to cease and sediments prograding into the basin, a progression that occurred ~564 Ma.

Two dates for the Catalina Dome succession have been acquired. A horizon near the base of the Murphy's Cove Formation has an age of  $571.00 \pm 0.37$  Ma, and an age of  $566.43 \pm 0.73$  Ma is given to a horizon in the lower Rowland Head Formation. These ages allow for the first direct chronostratigraphic comparison between the Catalina Dome and Mistaken Point Ecological Reserve sections. Though data is limited for the Catalina Dome succession, it would appear that both successions were deposited at roughly the same time. Within MPER, the boundary between the Mistaken Point and Trepassey formations is slightly younger than the 565.23 Ma age from the MP-14 sample taken from the 'E' Surface. At the Catalina Dome, the boundary between the Mistaken Point and Trepassey formations, using the former stratigraphy of O'Brien and King (2005), which is now the boundary between the Murphy's Cove and Rowland Head formations, has an age of  $\sim 567.9$  Ma (Figure 4.6). This age is calculated by interpolating between the HF14-6 and MRC-6 ages, assuming a constant sedimentation rate. The base of the Mistaken Point Formation within MPER has an approximate age of 566.6 Ma, whereas the base of the Mistaken Point Formation in the Catalina Dome, as defined by O'Brien and King (2005), must be older than 571 Ma since the transition lies within the new Shepherd Point Formation erected herein, and is below the MRC-6 horizon.

The Trinity Bay North Group of the Catalina Dome, and the fossils found there are older than has been previously estimated. Greater chronostratigraphic resolution is still required at the bottom and top of the section, and the rare and often thin tuffites within this area should be further explored for their chronostratigraphic potential. The lack of further dated horizons at the Catalina Dome precludes the calculation of sedimentation rate trends at this locality.

These new dates reveal that evidence of metazoans, through locomotary trails in MPER, and the tentative cnidarian *Haootia quadriiformis* in the Catalina Dome, both appear in

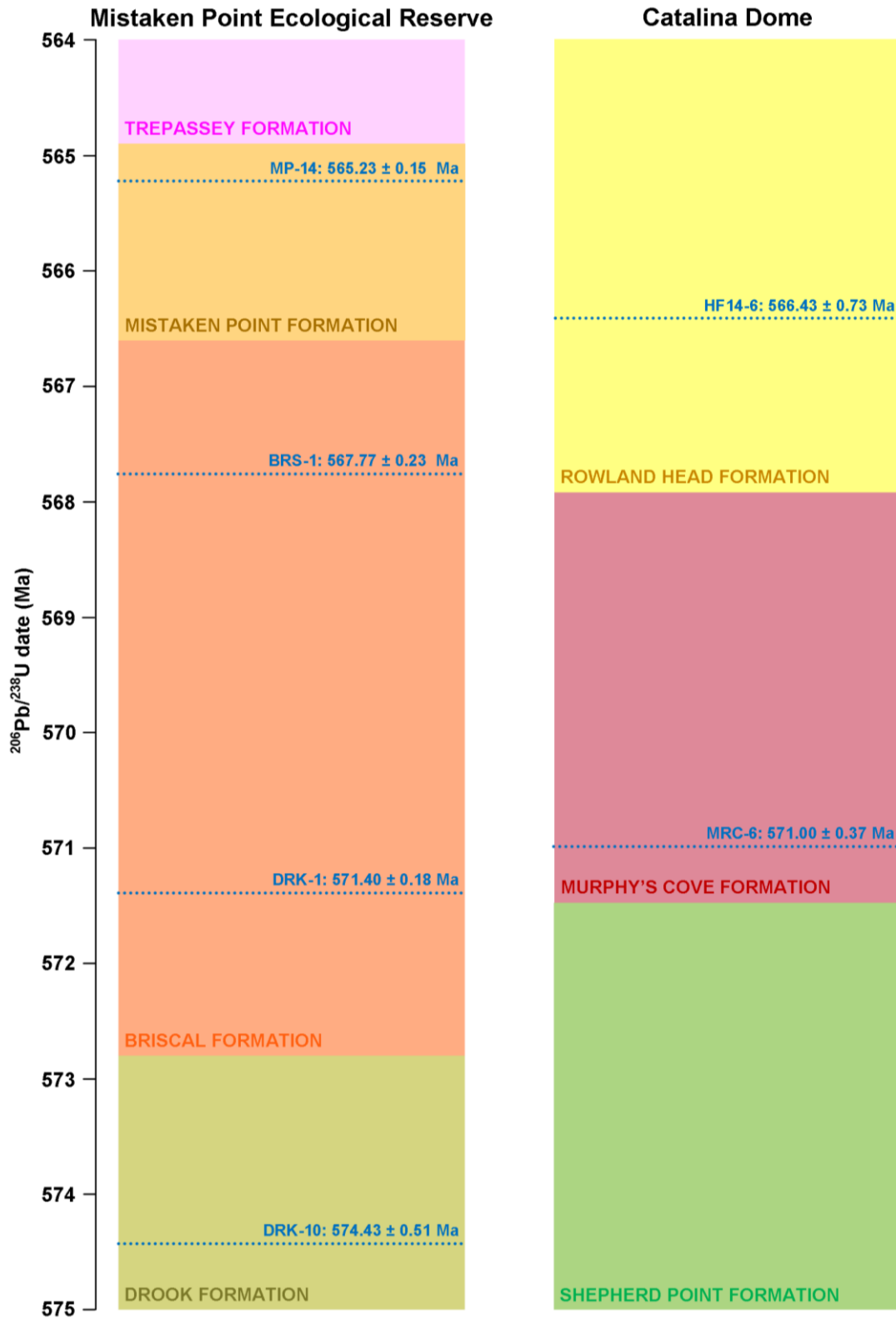


FIGURE 4.6. Chronostratigraphic correlation of the lower part of the Catalina Dome section with that in the Mistaken Point Ecological Reserve. The age of formation boundaries have been interpolated/extrapolated from the data available for that section.

their respective sections around 565 Ma, providing valuable constraints on the rise of metazoans. This is expanded upon further in Chapter 5.

The independent geochronological frameworks for the MPER and Catalina Dome, and the observation they are contemporaneous advance the sub-basin or wedge hypothesis (Figure 2.47) to explain the stratigraphic relationship between the two sections, and discredits the onlap and truncation hypotheses (Figure 2.47).

## **ACKNOWLEDGEMENTS**

This research was supported by the Natural Environment Research Council (grant number NE/J5000045/1) and a NIGFSC award. Alex Liu and Tom Hearing are thanked for their help and assistance in gathering the data. The people of Portugal Cove South, Trepassey, and Trinity Bay North are thanked for their hospitality. The Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, provided permits to conduct research within the Mistaken Point Ecological Reserve. Access for research to fossil localities within the Mistaken Point Ecological Reserve is by permit only. Readers are advised that the fossils around the Catalina Dome are protected by the Paleontological Resource Regulations 67/11, under the Historic Resources Act, 1990.

## **REFERENCES**

- Benus, A.P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland): Trace Fossils, Small Shelly Fossils and the Precambrian Cambrian Boundary: Proceedings, 1987, Memorial University (New York State Museum and Geological Survey Bulletin), p. 8–9.
- Bowring, S.A., Grotzinger, J.P., Condon, D.J., Ramezani, J., Newall, M.J., and Allen, P.A., 2007, Geochronologic constraints on the chronostratigraphic framework of the neoproterozoic Huqf Supergroup, Sultanate of Oman: *American Journal of Science*, v. 307, no. 10, p. 1097–1145.

- Bowring, J.F., McLean, N.M., and Bowring, S.A., 2011, Engineering cyber infrastructure for U-Pb geochronology: Tripoli and U-Pb\_Redux: *Geochemistry, Geophysics, Geosystems*, v. 12, no. 6.
- Canfield, D.E., Poulton, S.W., and Narbonne, G.M., 2007, Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life: *Science*, v. 315, no. 5808, p. 92–95.
- Condon, D.J., Schoene, B., McLean, N.M., Bowring, S.A., and Parrish, R.R., 2015, Metrology and Traceability of U-Pb Isotope Dilution Geochronology (EARTHTIME Tracer Calibration Part I): *Geochimica et Cosmochimica Acta*,.
- Darroch, S.A.F., Laflamme, M., and Clapham, M.E., 2013, Population structure of the oldest known macroscopic communities from Mistaken Point, Newfoundland: *Paleobiology*, v. 39, no. 4, p. 591–608, doi: 10.1666/12051.
- Gerstenberger, H., and Haase, G., 1997, A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations: *Chemical Geology*, v. 136, no. 3–4, p. 309–312, doi: 10.1016/S0009-2541(96)00033-2.
- Grotzinger, J.P., Bowring, S.A., Saylor, B.Z., and Kaufman, A.J., 1995, Biostratigraphic and Geochronological Constraints on Early Animal Evolution: *Science*, v. 270, no. 5236, p. 598–604.
- Hiess, J., Condon, D.J., McLean, N., and Noble, S.R., 2012,  $^{238}\text{U}/^{235}\text{U}$  Systematics in Terrestrial Uranium-Bearing Minerals: *Science*, v. 335, no. 6076, p. 1610–1614, doi: 10.1126/science.1215507.
- Huyskens, M.H., Zink, S., and Amelin, Y., 2016, Evaluation of temperature-time conditions for the chemical abrasion treatment of single zircons for U–Pb geochronology: *Chemical Geology*, v. 438, p. 25–35, doi: 10.1016/j.chemgeo.2016.05.013.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971, Precision Measurement of Half-Lives and Specific Activities of  $^{235}\text{U}$  and  $^{238}\text{U}$ : *Physical Review C*, v. 4, p. 1889–1906, doi: 10.1103/PhysRevC.4.1889.
- 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 of London B: Biological Sciences*, v. 281, no. 1793, p. 20141202, doi: 10.1098/rspb.2014.1202.
- 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 microfossil record: *Palaeontology*, v. 54, no. 3, p. 607–630, doi: 10.1111/j.1475-4983.2010.01024.x.
- 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*, v. 38, no. 2, p. 123–126.

- Ludwig, K.R., 1991, ISOPLOT; a plotting and regression program for radiogenic-isotope data; version 2.53: U.S. Geological Survey, Open-File Report USGS Numbered Series 91-445.
- Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A., and Kirschvink, J.L., 2000, Age of Neoproterozoic bilaterian body and trace fossils, White Sea, Russia: Implications for metazoan evolution: *Science*, v. 288, no. 5467, p. 841–845.
- Mattinson, J.M., 2005, Zircon U–Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: *Chemical Geology*, v. 220, no. 1–2, p. 47–66, doi: 10.1016/j.chemgeo.2005.03.011.
- McLean, N.M., Bowring, J.F., and Bowring, S.A., 2011, An algorithm for U-Pb isotope dilution data reduction and uncertainty propagation: *Geochemistry, Geophysics, Geosystems*, v. 12, no. 6.
- McLean, N.M., Condon, D.J., Schoene, B., and Bowring, S.A., 2015, Evaluating uncertainties in the calibration of isotopic reference materials and multi-element isotopic tracers (EARTHTIME Tracer Calibration Part II): *Geochimica et Cosmochimica Acta*.
- 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*, v. 524, no. 7565, p. 343–346, doi: 10.1038/nature14646.
- Narbonne, G.M., 2004, Modular construction of early ediacaran complex life forms: *Science*, v. 305, no. 5687, p. 1141–1144, doi: 10.1126/science.1099727.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: *Geology*, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- 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*, v. 127, no. 1–2, p. 250–265, doi: 10.1130/B31013.1.
- O’Brien, S.J., and King, A.F., 2005, Late Neoproterozoic (Ediacaran) stratigraphy of Avalon Zone sedimentary rocks, Bonavista Peninsula, Newfoundland: Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, p. 6–1.
- Sahy, D., Condon, D.J., Terry Jr., D.O., Fischer, A.U., and Kuiper, K.F., 2015, Synchronizing terrestrial and marine records of environmental change across the Eocene–Oligocene transition: *Earth and Planetary Science Letters*, v. 427, p. 171–182, doi: 10.1016/j.epsl.2015.06.057.
- Schmitz, M.D., and Davydov, V.I., 2012, Quantitative radiometric and biostratigraphic calibration of the Pennsylvanian–Early Permian (Cisuralian) time scale and pan-

Euramerican chronostratigraphic correlation: Geological Society of America Bulletin, v. 124, no. 3–4, p. 549–577, doi: 10.1130/B30385.1.

Schoene, B., Guex, J., Bartolini, A., Schaltegger, U., and Blackburn, T.J., 2010, Correlating the end-Triassic mass extinction and flood basalt volcanism at the 100 ka level: *Geology*, v. 38, no. 5, p. 387–390, doi: 10.1130/G30683.1.

Sparks, R.S.J., and Wilson, C.J.N., 1983, Flow-head deposits in ash turbidites: *Geology*, v. 11, no. 6, p. 348–351, doi: 10.1130/0091-7613(1983)11<348:FDIAT>2.0.CO;2.

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*: , p. 23–36.

Wotzlaw, J.-F., Hüsing, S.K., Hilgen, F.J., and Schaltegger, U., 2014, High-precision zircon U–Pb geochronology of astronomically dated volcanic ash beds from the Mediterranean Miocene: *Earth and Planetary Science Letters*, v. 407, p. 19–34, doi: 10.1016/j.epsl.2014.09.025.

Table 4.1 Geochronology Data Tables

Fraction	Dates							Composition				Isotopic Ratios							
	206Pb 238U a	$\pm 2\sigma$ abs	207Pb 235U b	$\pm 2\sigma$ abs	207Pb 206Pb b	$\pm 2\sigma$ abs	% disc c	Th/ U d	Pb* (pg) e	Pbc (pg) f	Pb*/ Pbc g	206Pb/ 204Pb h	207Pb/ 206Pb i	$\pm 2\sigma$ %	207Pb/ 235U i	$\pm 2\sigma$ %	206Pb 238U ia	$\pm 2\sigma$ %	Corr. coef.
<b>SH-2</b>																			
<b>z15</b>	<b>563.73</b>	<b>0.43</b>	563.55	0.21	563.2	1.7	-0.09	0.61	45.6	0.21	219.1	12786.4	0.058920	0.073	0.74197	0.05	0.091387	0.080	0.33
<b>z16</b>	<b>564.05</b>	<b>0.70</b>	563.72	0.84	562.7	3.1	-0.22	0.51	26.7	0.24	110.4	6614.3	0.058908	0.140	0.74225	0.19	0.091440	0.130	0.68
<b>z9</b>	<b>564.09</b>	<b>0.63</b>	564.06	0.72	564.3	2.6	0.05	0.55	48.0	0.38	125.3	7431.2	0.058950	0.113	0.74284	0.17	0.091447	0.116	0.71
<b>z14</b>	<b>564.30</b>	<b>0.73</b>	563.79	0.84	562.1	3.5	-0.38	0.55	48.0	0.61	78.8	4677.2	0.058891	0.157	0.74238	0.19	0.091483	0.135	0.58
<b>z19</b>	<b>564.36</b>	<b>0.39</b>	564.44	0.45	565.1	1.6	0.15	0.50	58.6	0.21	283.7	17022.7	0.058973	0.067	0.74349	0.10	0.091492	0.071	0.72
<b>z12</b>	<b>564.51</b>	<b>0.40</b>	564.42	0.63	564.4	2.7	-0.01	0.48	21.5	0.23	92.6	5594.3	0.058953	0.118	0.74345	0.15	0.091519	0.074	0.56
z3	564.71	0.22	564.71	0.42	565.1	1.6	0.08	0.54	63.0	0.43	146.9	8738.5	0.058971	0.068	0.74395	0.10	0.091552	0.040	0.69
z5	564.88	0.21	564.73	0.57	564.5	2.6	-0.06	0.44	76.5	1.04	73.5	4493.2	0.058955	0.113	0.74399	0.13	0.091581	0.039	0.48
z1	565.59	0.19	565.58	0.38	565.9	1.6	0.06	0.55	78.9	0.57	138.4	8199.2	0.058993	0.068	0.74545	0.09	0.091701	0.035	0.53
z2	568.20	0.56	567.68	0.68	565.9	2.5	-0.39	0.57	67.4	0.77	88.1	5205.2	0.058994	0.110	0.74906	0.16	0.092144	0.103	0.68
z7	569.06	0.68	568.20	0.71	565.1	2.2	-0.69	0.47	48.3	0.48	100.3	6079.4	0.058972	0.097	0.74996	0.16	0.092290	0.125	0.78
<b>LC-1</b>																			
<b>z6B</b>	<b>564.72</b>	<b>1.23</b>	565.25	1.62	567.7	6.4	0.55	0.55	88.9	3.30	27.0	1615.8	0.059044	0.294	0.74488	0.37	0.091553	0.228	0.61
<b>z10</b>	<b>564.74</b>	<b>0.73</b>	564.70	0.72	564.9	2.2	0.04	0.62	178.0	0.92	193.2	11248.5	0.058967	0.095	0.74394	0.17	0.091557	0.136	0.80
<b>z6A</b>	<b>565.57</b>	<b>0.61</b>	565.80	0.80	567.1	3.1	0.28	0.58	74.1	1.24	59.7	3524.7	0.059026	0.139	0.74583	0.19	0.091698	0.112	0.64
z8	565.94	0.31	565.75	0.42	565.3	1.6	-0.10	0.66	127.7	0.62	207.0	11937.3	0.058978	0.064	0.74574	0.10	0.091761	0.057	0.68
z2	566.09	0.19	566.05	0.42	566.2	1.8	0.04	0.58	103.7	0.92	112.1	6596.7	0.059003	0.074	0.74626	0.10	0.091786	0.035	0.62
z1	566.41	0.48	567.00	2.85	569.7	14.1	0.60	0.57	92.3	7.60	12.1	732.4	0.059098	0.646	0.74790	0.66	0.091840	0.088	0.17
z3	566.46	0.29	566.36	0.47	566.3	1.9	-0.01	0.65	222.1	1.81	122.6	7094.2	0.059005	0.081	0.74680	0.11	0.091848	0.054	0.61
z5	566.48	0.22	566.51	0.63	567.0	3.0	0.10	0.61	126.8	2.05	61.9	3628.4	0.059022	0.134	0.74705	0.14	0.091852	0.040	0.31
z11	566.50	0.30	566.30	0.41	565.8	1.5	-0.11	0.62	158.4	0.74	212.8	12376.7	0.058991	0.060	0.74668	0.09	0.091855	0.056	0.69
z7	566.69	0.33	566.43	0.39	565.7	1.5	-0.16	0.69	62.0	0.34	181.2	10368.5	0.058988	0.059	0.74691	0.09	0.091888	0.060	0.66
z12	567.27	0.43	566.94	0.56	566.0	2.2	-0.21	0.56	119.8	1.25	95.6	5662.5	0.058996	0.095	0.74780	0.13	0.091985	0.078	0.62
<b>E-Surface (MP-1 and MP-14) N.B. MP-1 samples noted by -1</b>																			
<b>z16</b>	<b>564.15</b>	<b>0.62</b>	564.65	1.29	567.0	5.2	0.51	0.63	7.8	0.20	38.1	2227.9	0.059023	0.239	0.74385	0.30	0.091458	0.115	0.64

<b>z15</b>	<b>565.04</b>	<b>0.50</b>	566.00	1.27	570.2	5.6	0.91	0.65	9.1	0.20	45.2	2630.1	0.059110	0.254	0.74616	0.29	0.091608	0.093	0.52
<b>z5-1</b>	<b>565.04</b>	<b>0.47</b>	565.81	1.45	569.2	6.3	0.75	0.40	7.2	0.46	15.6	985.7	0.059084	0.289	0.74584	0.33	0.091608	0.086	0.60
<b>z2</b>	<b>565.14</b>	<b>0.21</b>	565.46	0.74	567.0	3.7	0.35	0.88	15.2	0.26	59.4	3256.7	0.059025	0.165	0.74524	0.17	0.091626	0.039	0.19
<b>z12</b>	<b>565.20</b>	<b>0.37</b>	565.58	1.60	567.4	7.5	0.41	0.54	26.6	1.14	23.3	1399.5	0.059036	0.345	0.74545	0.37	0.091635	0.068	0.41
<b>z4</b>	<b>565.53</b>	<b>0.53</b>	564.52	2.98	560.7	14.6	-0.84	0.71	17.6	1.10	16.0	930.4	0.058854	0.669	0.74362	0.69	0.091692	0.097	0.25
<b>z6-1</b>	<b>565.77</b>	<b>0.59</b>	565.48	1.67	564.6	7.3	-0.20	1.00	27.5	2.21	12.5	683.1	0.058959	0.334	0.74528	0.38	0.091732	0.109	0.57
<b>z4-1</b>	<b>565.97</b>	<b>0.79</b>	566.53	1.57	569.1	6.4	0.57	0.48	6.4	0.41	15.5	958.6	0.059082	0.292	0.74708	0.36	0.091765	0.145	0.63
z1	566.19	0.31	566.32	0.73	567.2	3.4	0.19	0.58	19.4	0.30	64.7	3823.3	0.059029	0.153	0.74672	0.17	0.091802	0.057	0.37
z14	566.41	0.33	567.10	1.59	570.2	7.8	0.68	0.49	11.2	0.50	22.6	1378.2	0.059110	0.358	0.74806	0.37	0.091841	0.062	0.19
z13	566.44	0.34	566.56	0.90	567.4	3.9	0.18	0.59	15.2	0.28	54.2	3195.0	0.059034	0.177	0.74713	0.21	0.091845	0.063	0.56
z9	567.11	0.42	566.90	1.88	566.4	9.1	-0.11	0.68	19.0	0.94	20.3	1178.8	0.059007	0.418	0.74771	0.43	0.091958	0.078	0.27
z7-1	567.18	0.52	566.83	0.85	565.8	3.1	-0.23	0.41	25.6	0.64	40.0	2481.1	0.058991	0.139	0.74760	0.19	0.091970	0.097	0.72
z5	567.35	1.01	566.63	1.40	564.1	4.8	-0.57	0.55	16.5	0.21	77.8	4619.7	0.058944	0.217	0.74725	0.32	0.091999	0.186	0.75
z6	567.52	0.32	567.26	0.67	566.6	3.2	-0.16	0.78	84.2	1.14	73.7	4135.5	0.059012	0.144	0.74834	0.15	0.092028	0.058	0.31
z1-1	598.84	0.51	598.83	1.03	599.1	4.0	0.06	0.52	13.0	0.46	28.2	1711.7	0.059903	0.182	0.80354	0.23	0.097346	0.088	0.65

**BRS-1**

<b>z3</b>	<b>566.42</b>	<b>0.29</b>	566.41	0.55	566.7	2.4	0.05	0.94	36.0	0.19	190.5	10279.9	0.059015	0.107	0.74687	0.13	0.091841	0.053	0.48
<b>z6</b>	<b>567.35</b>	<b>0.77</b>	567.38	3.96	567.7	19.4	0.08	1.39	10.2	0.92	11.1	559.8	0.059044	0.892	0.74855	0.91	0.092000	0.141	0.21
<b>z9</b>	<b>567.65</b>	<b>0.31</b>	566.60	0.80	562.7	4.1	-0.87	0.77	22.7	0.43	52.4	2954.3	0.058907	0.186	0.74720	0.18	0.092050	0.057	0.10
<b>z5</b>	<b>567.72</b>	<b>0.55</b>	568.67	2.59	572.8	12.7	0.90	0.98	7.7	0.48	16.0	870.9	0.059181	0.582	0.75077	0.59	0.092061	0.101	0.20
<b>z2</b>	<b>568.25</b>	<b>0.49</b>	568.17	1.17	568.2	5.4	0.00	0.83	14.4	0.39	36.6	2039.1	0.059056	0.247	0.74991	0.27	0.092152	0.090	0.38
z4	568.60	0.52	567.46	2.51	563.2	12.3	-0.95	0.84	5.7	0.31	18.1	1018.2	0.058921	0.563	0.74868	0.58	0.092211	0.096	0.22
z8	569.84	0.89	571.41	2.99	578.0	14.3	1.42	0.88	8.7	0.65	13.3	745.5	0.059322	0.658	0.75550	0.68	0.092421	0.163	0.27
z7	571.14	0.54	572.29	2.83	577.1	13.8	1.05	0.88	6.5	0.48	13.7	764.6	0.059300	0.635	0.75702	0.65	0.092642	0.098	0.20

**DRK-1**

<b>z20A</b>	<b>571.17</b>	<b>0.35</b>	570.74	1.14	569.3	5.8	-0.31	0.77	13.1	0.31	42.3	2389.2	0.059087	0.264	0.75433	0.26	0.092646	0.064	0.04
<b>z21</b>	<b>571.32</b>	<b>0.48</b>	572.55	2.50	577.7	12.1	1.11	1.19	7.6	0.44	17.2	894.1	0.059315	0.554	0.75747	0.57	0.092672	0.087	0.26
<b>z19</b>	<b>571.48</b>	<b>0.37</b>	572.40	0.64	576.4	2.5	0.86	0.69	92.5	0.70	132.1	7566.4	0.059279	0.109	0.75722	0.15	0.092700	0.068	0.65
<b>z13</b>	<b>571.56</b>	<b>0.33</b>	570.23	0.71	565.2	3.2	-1.11	0.74	30.8	0.63	49.2	2808.6	0.058976	0.142	0.75345	0.16	0.092713	0.061	0.45
<b>z7</b>	<b>571.60</b>	<b>0.74</b>	572.11	3.39	574.5	15.3	0.52	0.54	18.5	3.72	5.0	315.1	0.059227	0.701	0.75671	0.78	0.092719	0.135	0.61
<b>z23</b>	571.63	0.29	572.83	1.25	577.9	6.1	1.10	1.10	20.7	0.61	33.8	1775.3	0.059320	0.277	0.75796	0.29	0.092724	0.053	0.22
<b>z1</b>	571.93	0.34	571.70	0.57	571.1	2.0	-0.13	0.68	78.1	1.05	74.4	4301.9	0.059135	0.087	0.75600	0.13	0.092775	0.062	0.76

z8	572.08	0.52	572.11	1.27	572.5	5.3	0.08	1.34	14.8	0.63	23.5	1180.9	0.059172	0.243	0.75671	0.29	0.092801	0.096	0.60
z18	572.36	0.23	572.31	0.65	572.4	2.9	0.02	0.88	16.8	0.21	79.5	4357.7	0.059170	0.127	0.75706	0.15	0.092848	0.042	0.51
z11	572.41	0.74	571.72	3.21	569.3	14.4	-0.54	0.99	7.1	1.11	6.4	359.6	0.059086	0.662	0.75604	0.74	0.092856	0.134	0.61
z4	572.60	1.12	571.76	4.26	568.8	17.8	-0.66	0.63	46.1	2.27	20.3	1202.8	0.059072	0.818	0.75611	0.97	0.092889	0.204	0.81
z16	572.92	0.43	572.51	1.54	571.2	7.4	-0.29	0.55	14.7	0.56	26.1	1560.6	0.059138	0.339	0.75740	0.35	0.092944	0.079	0.26
z17	573.04	0.40	572.45	1.68	570.4	7.8	-0.45	0.86	11.6	0.47	24.8	1377.8	0.059116	0.358	0.75729	0.38	0.092964	0.074	0.41
z18A	573.11	0.51	574.46	2.66	580.1	13.0	1.21	0.98	4.9	0.29	17.0	924.3	0.059380	0.595	0.76078	0.61	0.092976	0.093	0.18
z22	574.01	0.36	574.01	1.89	574.3	9.2	0.06	1.01	14.6	0.63	23.3	1252.0	0.059222	0.423	0.76001	0.43	0.093128	0.065	0.16
z3	574.35	0.49	573.32	1.26	569.6	5.3	-0.83	0.73	20.1	0.97	20.8	1201.3	0.059093	0.242	0.75881	0.29	0.093186	0.089	0.61
z5	575.29	0.78	574.15	1.49	569.8	5.8	-0.95	1.45	20.4	1.00	20.4	1006.4	0.059101	0.263	0.76023	0.34	0.093346	0.141	0.68
z9	577.20	0.60	577.81	0.86	580.5	3.0	0.59	0.62	55.6	1.04	53.6	3153.8	0.059392	0.136	0.76660	0.20	0.093670	0.108	0.72

**DRK-10**

z12	<b>573.61</b>	<b>0.69</b>	573.32	0.90	572.4	3.4	-0.20	1.65	14.4	0.17	86.7	4027.4	0.059171	0.154	0.75881	0.21	0.093060	0.126	0.64
z2	<b>574.38</b>	<b>0.26</b>	574.11	0.99	573.3	4.8	-0.18	1.36	26.6	0.59	45.2	2233.7	0.059194	0.216	0.76017	0.23	0.093191	0.047	0.24
z7	<b>574.50</b>	<b>2.56</b>	574.51	2.39	574.8	3.4	0.07	1.31	24.1	0.35	69.2	3445.5	0.059236	0.153	0.76087	0.55	0.093211	0.466	0.96
z10	<b>574.68</b>	<b>0.32</b>	574.42	1.01	573.6	4.4	-0.17	1.37	32.5	0.62	52.7	2598.8	0.059204	0.199	0.76072	0.23	0.093242	0.059	0.57
z3	575.84	0.27	575.68	0.85	575.3	3.8	-0.09	1.41	21.7	0.34	63.4	3092.5	0.059249	0.171	0.76290	0.19	0.093439	0.049	0.50
z8	576.02	0.42	574.90	1.91	570.7	9.4	-0.92	1.42	28.0	1.15	24.2	1192.7	0.059125	0.429	0.76155	0.44	0.093468	0.076	0.16
z4	576.88	1.11	576.22	2.22	573.8	10.4	-0.53	1.77	14.3	0.54	26.4	1207.9	0.059209	0.475	0.76384	0.51	0.093615	0.201	0.34
z1	576.92	1.28	576.13	1.15	573.3	2.6	-0.63	1.41	27.9	0.29	95.0	4625.1	0.059194	0.117	0.76368	0.26	0.093621	0.231	0.89
z9	577.58	0.67	576.43	1.33	572.2	5.7	-0.93	1.24	17.2	0.46	37.8	1922.6	0.059164	0.260	0.76420	0.30	0.093733	0.122	0.50

**HF14-6**

z2	<b>565.92</b>	<b>0.47</b>	566.24	0.53	567.9	1.6	0.36	0.44	188.7	0.82	231.0	14079.7	0.059048	0.066	0.74659	0.12	0.091757	0.086	0.81
z1	<b>566.51</b>	<b>0.29</b>	566.51	0.37	566.9	1.2	0.07	0.42	194.1	0.45	429.7	26328.1	0.059020	0.046	0.74705	0.08	0.091858	0.053	0.78
z4	<b>566.58</b>	<b>0.35</b>	566.98	0.39	568.9	1.1	0.43	0.46	192.6	0.63	308.0	18677.2	0.059076	0.044	0.74786	0.09	0.091868	0.064	0.81
z7	570.35	0.39	569.64	0.46	567.1	1.6	-0.57	0.85	110.6	0.59	188.0	10363.8	0.059026	0.070	0.75244	0.11	0.092508	0.072	0.70
z6	607.26	1.04	607.17	0.89	607.1	1.5	-0.01	0.58	56.8	0.25	226.1	13278.9	0.060125	0.061	0.81842	0.19	0.098781	0.180	0.94
z3	608.02	0.51	607.86	0.67	607.6	3.6	-0.06	0.50	32.2	0.27	119.9	7195.8	0.060139	0.163	0.81967	0.15	0.098910	0.089	0.08

**MRC-6**

z5	<b>570.95</b>	<b>0.53</b>	571.96	1.09	576.3	4.9	0.94	0.61	38.8	0.95	40.8	2398.7	0.059277	0.226	0.756454	0.250	0.09261	0.10	0.42
z1	<b>570.98</b>	<b>1.13</b>	571.02	6.32	571.5	30.6	0.10	0.73	4.6	0.70	6.5	384.5	0.059145	1.405	0.754819	1.446	0.09261	0.21	0.27

z4	<b>571.07</b>	<b>0.63</b>	571.91	2.24	575.5	10.8	0.79	0.63	14.4	0.85	16.9	998.5	0.059256	0.498	0.756358	0.513	0.09263	0.12	0.23
z2	574.30	0.83	574.88	4.14	577.4	20.0	0.55	1.04	3.6	0.33	10.9	592.4	0.059307	0.918	0.761511	0.942	0.09318	0.15	0.24

- a Corrected for initial Th/U disequilibrium using radiogenic 208Pb and Th/U[magma] = 3.5000.
- b Isotopic dates calculated using the decay constants  $\lambda_{238} = 1.55125E-10$  and  $\lambda_{235} = 9.8485E-10$  (Jaffey et al. 1971).
- c % discordance =  $100 - (100 * (206Pb/238U \text{ date}) / (207Pb/206Pb \text{ date}))$
- d Th contents calculated from radiogenic 208Pb and the 230Th-corrected 206Pb/238U date of the sample, assuming concordance between the U-Pb and Th-Pb systems.
- e Total mass of radiogenic Pb.
- f Total mass of common Pb.
- g Ratio of radiogenic Pb (including 208Pb) to common Pb.
- h Measured ratio corrected for fractionation and spike contribution only.
- i Measured ratios corrected for fractionation, tracer and blank.

# Chapter 5: Towards a Stratigraphic Framework for the Ediacaran of Avalonia

---

## ABSTRACT

A revised lithostratigraphy, and new chronostratigraphic constraints for the fossiliferous late Ediacaran successions of Newfoundland prompts a reanalysis of Avalonian stratigraphy. The Newfoundland sections at Mistaken Point and the Catalina Dome both show an early fossil assemblage containing the rangeomorphs *Vinlandia* and *Trepassia* (<582 to ~575 Ma). Shortly after, around 575 Ma, there is a rapid increase in taxonomic diversity, suggesting an ‘Ediacaran Explosion’. Evidence for metazoan behaviour first appears at both Mistaken Point and the Catalina Dome ~565 Ma. The interval from 545 – 565 Ma, containing the disappearance of rangeomorphs across Avalonia, remains poorly constrained chronostratigraphically and as a result is poorly understood. All known Ediacaran rangeomorphs are found in deep-marine deposits. Potential exists for the creation of several Avalonian biostratigraphic zones, though further investigation is required.

## INTRODUCTION

The Ediacaran rocks of Newfoundland and the United Kingdom contain a rich assemblage of soft-bodied macrofossils, representing the point in time when “life got big” (Narbonne and Gehling, 2003). These successions were deposited offshore from the palaeocontinent of Avalonia (Murphy and Nance, 1989), with a palaeo-latitude of 40–65° south (Torsvik, 2003; Samson et al., 2005; Thompson et al., 2007; Li et al., 2008; Pisarevsky et al., 2008).

Modern geographical areas that formed part of Avalonia during the Ediacaran, in addition to eastern Newfoundland and southern United Kingdom, include the Low Countries, southern Ireland, a section of Spain, Nova Scotia, and New Brunswick (Cocks et al., 1997). This chapter focuses on the rocks of Newfoundland and the United Kingdom as these contain the oldest complex macrofossil assemblages, and have diverse lithostratigraphic successions that span the majority of the Ediacaran interval.

The lithostratigraphic and chronostratigraphic correlation of the various Ediacaran successions is essential to both understanding the rise and eventual fall of the Ediacara biota, and the ongoing work to subdivide the Ediacaran Period itself. This chapter reviews the current state of Ediacaran stratigraphy in Newfoundland and the United Kingdom, combining previous data with those presented in the previous chapters, and uses this as a framework on which to compare and contrast the distribution of fossil taxa found in these successions. The implications for understanding the evolution of the Ediacara biota are considered.

## **STRATIGRAPHIC SECTIONS**

The Avalonian Ediacaran rocks of Newfoundland and Britain record ~90 Myr of stratigraphy comprising volcanics, deep-marine, shallow-marine, and fluvial lithologies. The successions, their interpreted palaeoenvironments, and chronostratigraphic constraints are shown in Figure 5.1 and is summarised below.

### **Bonavista Peninsula, Newfoundland**

As described in Chapter 2, the rocks of the Catalina Dome, eastern Bonavista Peninsula, have been reanalysed and placed in the newly erected Trinity Bay North Group. These rocks represent a shallowing upwards succession within a basin fill complex. Those rocks

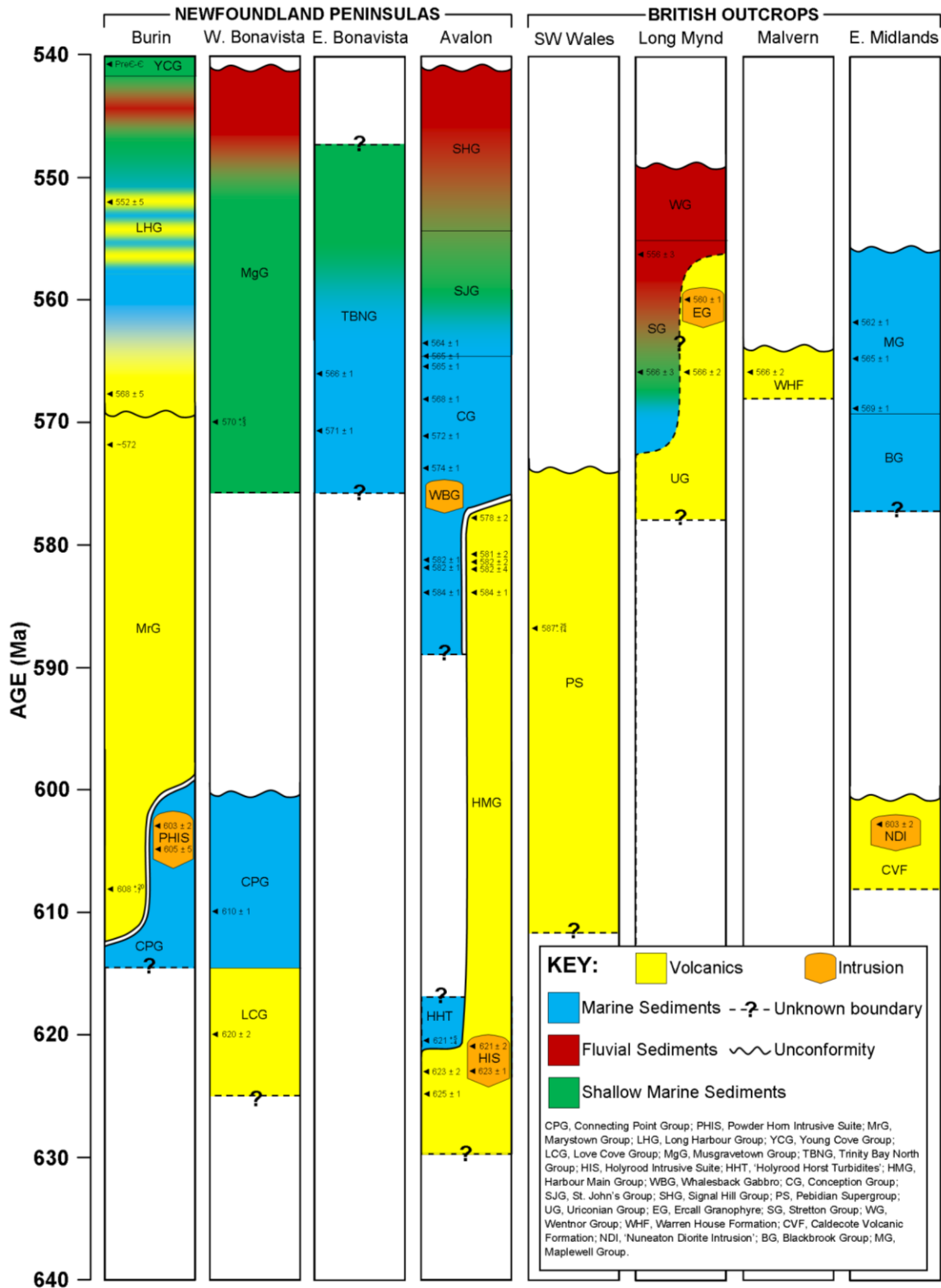


FIGURE 5.1. Correlation chart for the Avalonian Ediacaran successions of Newfoundland and Britain. The Llangynog Inlier is not shown due to lack of geochronological data. The East Midlands section represents the successions seen at Nuneaton and in Charnwood Forest. Geochronology from this volume, and Patchett and Jocelyn, 1979; Krogh et al., 1988; O'Brien et al., 1989; Tucker and Pharaoh, 1991; Dec et al., 1992; O'Brien, 1994; O'Brien et al., 1995; Israel, 1998; O'Brien et al., 1999; Hinchey, 2001; Compston et al., 2002; Sparkes et al., 2005; Gradstein et al., 2012; Skipton et al., 2013; Noble et al., 2015. Ages and uncertainties rounded to nearest Myr.

directly above the Trinity Bay North Group, previously placed within the Signal Hill Group will necessarily need revising, however this is outside the scope of this study.

A fault zone running north-south from Spillars Cove to English Harbour separates the newly defined Trinity Bay North Group and associated rocks, from the successions of the western Bonavista Peninsula – comprising the Musgravetown, Connecting Point, and Love Cove Groups.

The Musgravetown Group comprises the Cannings Cove, Bull Arm, Big Head, Rocky Harbour, and Crown Hill Formations on the Bonavista Peninsula. With a basal succession of cobble conglomerates overlain by subaerial volcanic rocks, through siliceous siltstones and a mixtite unit, the Musgravetown Group is then dominated by shallow marine and deltaic siltstones and sandstones. A rhyolite near the top of the Bull Arm Formation has yielded a U-Pb zircon age of  $570^{+5}_{-3}$  Ma (O'Brien et al., 1989).

In the west of the Peninsula, the Musgravetown Group unformably overlies the Connecting Point Group (O'Brien, 1994), a thick succession of turbiditic marine clastic rocks. A tuff from the middle of the succession has a reported age of  $610 \pm 1$  Ma (Dec et al., 1992). The Connecting Point Group conformably overlies the Love Cove Group (Dec et al., 1992), which comprises pyroclastic flow deposits and tuffs, and has a reported age of  $620 \pm 2$  Ma from a rhyolite within the unit (O'Brien et al., 1989).

### **Burin Peninsula, Newfoundland**

The vast majority of the peninsula is cored by the Marystown Group, comprising various subaerial volcanic and associated plutonic rocks, from basaltic to rhyolitic compositions (O'Brien et al., 1999). A tuff from the Marystown Group has been dated to  $608^{+20}_{-7}$  Ma

(Krogh et al., 1988), and a pyroclastic rock has yielded an age of ~572 Ma (O'Brien et al., 1999).

The Marystown Group overlies the Connecting Point Group, represented by similar lithologies to that on the Bonavista Peninsula. Here it is intruded by the Powder Horn Intrusive Suite. A gabbro from the suite has been dated to  $603 \pm 2$  Ma, and a felsic dyke to  $605 \pm 5$  Ma (Hinchey, 2001).

Unconformably overlying the Marystown Group is the Long Harbour Group, comprising volcanic, marine, deltaic, and fluvial facies. A rhyolite from near the base of the Group has yielded a U-Pb zircon age of  $568 \pm 5$  Ma, and a rhyolite nearer the top of the Group has given a U-Pb zircon age of  $552 \pm 3$  Ma (O'Brien et al., 1995). In the north-east of the peninsula the Musgravetown Group overlies the Marystown Group

Conformably overlying the Long Harbour Group is the Young Cove Group, representing deltaic and shallow marine environments, part of which acts as the global stratotype of the Precambrian-Cambrian boundary.

### **Avalon Peninsula, Newfoundland**

The Hawke Hills Tuff, dated to  $729 \pm 7$  Ma (Israel, 1998), is the oldest known rock from the Avalon Peninsula and considerably older than the successive units. The Holyrood Intrusive Suite, sometimes found intruded into the Hawke Hills Tuff (O'Brien et al., 2001), is composed of granites, quartz monzonite, quartz diorite and gabbro, and minor aplite.

The outcrops of this suite form the core of the Avalon Peninsula, between the Holyrood and Topsail Faults. A U-Pb date of  $622.5 \pm 1.3$  Ma, based on the weighted average of three zircon analyses, was acquired from a medium-grained, quartz-phyric, biotite-hornblende granite, ~5.5 km southwest of the Oval Pit Mine (Sparkes et al., 2005). Four analyses from

a granite of the Holyrood Intrusive Suite yielded a U-Pb zircon date of  $620.5 \pm 2.1/-1.8$  Ma (Krogh et al., 1988).

Sparkes et al. (2005) also secured a date for the White Hills Intrusive Suite; a group of locally altered felsic to mafic intrusive rocks that are thought to correlate with the much larger Holyrood Intrusive Suite. A quartz-feldspar porphyry, thought to be the youngest component unit of the suite, yielded a U-Pb age of  $625 \pm 2.5$  Ma, based on the weighted average of six analyses, some of which contained multiple zircons.

The Harbour Main Group comprises rhyolitic intrusive and extrusive rocks, basaltic flows, gabbro, pyroclastics, sandstones, conglomerates, slates and tuffaceous siltstones. While it is now regarded unsuitable to describe the Harbour Main Group as a single lithostratigraphic entity (O'Brien et al., 2001), the term still has stratigraphic precedence, and remains a useful grouping to describe these mainly volcanoclastic units. The main outcrops are centred around the core of the Avalon Peninsula, and along the eastern shores of Conception Bay, as well as minor outcrops along the Topsail and Frenchman's Cove faults which trend north-south between their namesakes. The Harbour Main Group is dated to  $622.6 \pm 2.3/-2.0$  Ma (Krogh et al., 1988), based on three U-Pb zircon analyses.

However, a number of new dates significant to the wider regional context of the rise of the Ediacara biota have been published for the Harbour Main Group. Felsic volcanic rocks from the Oval Pit Mine have been dated to  $584 \pm 1$  Ma, based on the weighted average of five  $^{206}\text{Pb}/^{238}\text{U}$  ages. The age is thought to provide the lower age limit on a period of high-sulphidation alteration (Sparkes et al., 2005).

Sparkes et al., (2005) also provide a date for a crystal-rich ash-flow tuff from the Manuels Volcanic Suite, also historically part of the Holyrood Intrusive Suite. The  $^{206}\text{Pb}/^{238}\text{U}$  age of

582 ± 4 Ma is based on three analyses of the largest, clear, euhedral grains and is assumed to provide the eruption age of the ash-flow tuff.

The Horse Cove Complex is an informal composite unit comprising a mafic-to-felsic dyke swarm hosted by mafic volcanics and diorite intrusions (Sparkes, 2006). Four dates were obtained from a selection of lithologies from this unit using U-Pb CA-TIMS analysis of zircons (Skipton et al., 2013). The weighted mean of four  $^{206}\text{Pb}/^{238}\text{U}$  analyses from a granodiorite sample was 625 ± 1.4 Ma, and represents the age of the host rock within the complex. Four analyses from a rhyolitic dyke yielded a U-Pb (zircon) age of 581.7 ± 1.9 Ma. Three concordant analyses from a feldspar porphyry gave a U-Pb (zircon) age of 580.6 ± 2.0 Ma. An andesitic dyke yielded a U-Pb (zircon) age of 578.4 ± 2.3 Ma based on the weighted mean on two analyses. These final dates relate to dykes that intrude the granodiorite and also, in places, crosscut each other, and represent the youngest known units from the Harbour Main Group.

All turbidites on the Avalon Peninsula have previously been mapped as being within the Conception and St. John's Groups. However, questions have been raised about the stratigraphic affinity of those turbidites within and around the Holyrood Horst. These grey and green sedimentary rocks lie unconformably on the Hawke Hills Tuff, contain granitoid detritus (O'Brien et al., 2001), and have been dated to 621 ± 5/-4 Ma (U-Pb) from a felsic tuff near the base of the exposure on the eastern shore of Holyrood Bay (Israel, 1998).

Previous dates for the deep-marine deposits of the Conception Group have been provided by Gradstein et al. (2012), all of which are drawn from Bowring's data, but not accompanied by any methodology, locality, or wider data breakdown. A date of 582.1 ± 0.5 Ma is given for the "*basal Drook Formation*", 582.4 ± 0.5 Ma for "*midway through Gaskiers Diamictite*", and 583.7 ± 0.5 Ma for "*near top of Mall Bay Formation*".

The Drook Formation is intruded by the fine and coarse grained gabbro of the Whalesback Gabbro. This unit has no published chronological data, and its presence solely within the lower parts of the Drook Formation makes it an important target for future geochronological analysis.

An age of  $578.8 \pm 0.5$  Ma, often cited as Van Kranendonk et al. (2008), though the data itself is drawn from an abstract by Bowring, is given for a horizon from the Drook Formation. Little information is given on the samples precise location, though it is widely regarded to relate to the large ashy deposit that lies directly above the 'Pizza Disc Bed', Pigeon Cove, MPER. The methodology and wider data associated with this age are unpublished.

The other age of  $565 \pm 3$  Ma is from the top of the Mistaken Point Formation, and was presented in an abstract (Benus, 1988). The details of the sample are given as "*a 10 cm-thick tuff in the lower part of the type section of the Mistaken Point Formation*" and the method quoted as "*U-Pb determinations of zircons*". It is widely believed that the horizon being referred to is the E-Surface outcrop at Mistaken Point. The detailed methodology and wider data associated with this are unpublished. No published dates exist for samples younger than this on the Avalon Peninsula until one enters the Phanerozoic.

These historic dates for the Drook and Mistaken Point Formations are supplemented by the new data presented in Chapter 4.

The Conception Group is overlain by the St. John's Group comprising the Trepassey, Fermeuse, and Renew's Head Formations, interpreted to have been deposited in slope and deltaic environmental settings (Matthews, 2011).

The Signal Hill Group comprises siltstones, sandstones and conglomerates exhibiting wave ripples and desiccation cracks – the first evidence for shallow marine and subaerial deposits in the succession (Matthews, 2011). Tuffaceous horizons are rare, but a number discovered during the course of this study hold potential for constraining the age of these deposits. The Signal Hill Group is unconformably overlain by the Lower Cambrian quartzites of the Random Formation.

The west of the Avalon Peninsula, specifically the St. Mary's Peninsula has been mapped as belonging to the Musgravetown Group, as is found on the Bonavista Peninsula. This group is tentatively correlated with the Signal Hill Group (King et al., 1988), and thought to be devoid of fossils. Very early descriptions of *Aspidella* from rocks north of Collinet Harbour (Jukes, 1843) now assigned to the Musgravetown Group require either the amendment of the map and local stratigraphy, or this to be the first evidence of the Ediacara biota within the Group. Further palaeontological study of the Musgravetown Group is required.

### **Long Mynd, England**

The oldest rocks within the area belong to the Uriconian Group, a unit comprising lavas and tuffaceous rocks with compositions from basalt through andesite and dacite to rhyolite (Thorpe, 1972). A rhyolite from the eastern side of the Stretton Fault yielded an interpreted eruption age of  $566 \pm 2$  Ma, based on three U-Pb zircon analyses (Tucker and Pharaoh, 1991). Further north at the Wrekin, the Uriconian Group is intruded by the Ercall Granophyre, a small granitic pluton that is unconformably overlain by the quartzites of the Lower Cambrian (Cope and Gibbons, 1987). The Ercall Granophyre has an interpreted emplacement age of  $560 \pm 1$  Ma, based on four U-Pb multi-zircon analyses (Tucker and Pharaoh, 1991).

The Longmyndian Supergroup comprises a ~6000 m thick succession of siliciclastic rocks with rare volcanoclastic horizons. The Longmyndian Supergroup was considered to unconformably overly the Uriconian Group (Cobbold, 1927), but those contacts visible in surface outcrops have been shown to be faulted (Pauley, 1991). The lower Stretton Group of the supergroup comprises the Ragleth Tuff, Stretton Shale, Burway, Synalds, Lightspout, and Portway Formations and shows a shallowing upwards succession from marine mudstones, through turbidites and deltaic sandstones, to alluvial plain deposits (Pauley, 1990). The overlying Wentnor Group comprises the Bayston-Oakwood and Bridges Formations, representing braided alluvial sandstones, conglomerates, and siltstones (Pauley, 1990).

*Beltanelliformis*, *Intrites*, and *Medusinites* have been described from the Stretton Group (McIlroy et al., 2005), but their biogenicity has since been questioned (Menon et al., 2016). No rangeomorphs or other complex macroscopic forms are known from the Long Mynd succession.

Compston et al. (2002) provided two U-Pb zircon ages for the Longmyndian rocks around Church Stretton. A bentonite from the Stretton Shale Formation was sampled, and analysed using the SHRIMP technique. The largest peak on the probability-density plot gave an age of  $566 \pm 2.9$  Ma which was interpreted as the age of deposition. Two minor peaks at ~526 Ma and ~552 Ma were interpreted to have undergone post-crystallisation Pb-loss. This sample was obtained from the eastern side of the Church Stretton Fault, hindering accurate correlation into the extensive successions on the western side of the Fault.

The second horizon dated by Compston et al. (2002) was a lapilli tuff from the Lightspout Formation, near the Lightspout Waterfall. A U-Pb (zircon) age of deposition of  $555.9 \pm 2.9$

Ma was obtained, however the population was complex, with peaks on the probability-density plot at ~532 Ma, ~557 Ma, and ~581 Ma, and is open to alternative interpretations.

Rocks of the Longmyndian Supergroup are also exposed further south in a number of small inliers along the Church Stretton Fault. At the Old Radnor Inlier, Powys, Wales, the Yat Wood Formation has been erected and lithologically correlated to the middle part of the Stretton Group (Woodcock and Pauley, 1989). The sandstones and rare conglomerates of the Inlier are described as the Strinds Formation, litho-correlated with the Bayston-Oakwood Formation (Woodcock and Pauley, 1989). These outcrops are juxtaposed to the basic and intermediate intrusive igneous rocks of the Stanner Hanter Complex. A granite from this has an interpreted  $^{206}\text{Pb}/^{238}\text{U}$  zircon age of  $710 \pm 1.5$  Ma, making it the oldest known rock in southern Britain (Schofield et al., 2010).

### **Charnwood Forest, England**

The Charnwood Forest outcrops, centred around Charnwood Forest, Leicestershire, comprise deep-marine deposits of the Blackbrook Group (Ives Head and Blackbrook Reservoir Formations) and Maplewell Group (Beacon Hill and Bradgate Formations).

SHRIMP U-Pb zircon data for the Charnwood Forest outcrops is provided by Compston et al. (2002). A coarse tuff from the Beacon Hill Formation has an interpreted age of  $566.1 \pm 3.1$  Ma. The main probability-density age from the analyses was at  $590.5 \pm 1.6$  Ma, but this was interpreted as representing inherited material. The Park Breccia Member, near the base of the Bradgate Formation, dated from a coarse tuff matrix to slump breccia, has an interpreted age of  $559.3 \pm 2.0$  Ma. As well as containing 600+ Ma inherited grains, there was a probability-density peak age at  $548.7 \pm 1.9$  Ma (interpreted as an artefact of Pb loss) and a peak at  $573.2 \pm 1.0$  (evaluated as representing an inherited age-group). This horizon is a few metres below the Memorial Crags fossil locality.

The Park Breccia was resampled and zircons analysed with U-Pb CA-ID-TIMS methods by Noble et al. (2015), and based on seven analyses a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $561.85 \pm 0.34$  Ma was provided. Noble et al. also refined the previous age for the Beacon Hill Formation to  $565.22 \pm 0.33$  Ma. In addition, a date of  $569.08 \pm 0.45$  Ma was obtained from the Benscliffe Breccia at the base of the Beacon Hill Formation, and three youngest U-Pb (zircon) dates from the Ives Head Formation were given as  $\sim 612$  Ma.

Save for ivesheadiomorphs, which are known throughout the succession, fossils are restricted to the higher Maplewell Group, where examples of *Charnia*, *Bradgatia*, *Primocandelabrum*, *Charniodiscus*, and *Aspidella* can be found across five stratigraphic horizons dated at  $< 562$  Ma (Noble et al., 2015).

### **Llangynog Inlier, Wales**

The Llangynog Inlier of South Wales is a small set of poorly exposed outcrops of the Coomb Volcanic Formation, comprising rhyolites, basalts, and tuffs interbedded with volcanoclastic sediments (Cope and Bevins, 1993). Ediacaran discoidal impressions such as *Cyclomedusa* are known from the top of the section (Cope, 1977). No geochronological data has yet been published from this succession.

### **South West Wales**

The Peibidian Supergroup, exposed in the St. David's area of Wales and overlain by Lower Cambrian sediments, comprises a  $\sim 2000$  m thick succession of trachytic and andesitic tuffs and local conglomeratic tuffaceous sediments (Pharaoh and Gibbons, 1994). The St. David's Granophyre, part of the Supergroup, yielded a U-Pb zircon age of  $587^{+25}_{-14}$  Ma from seven analyses, and was interpreted as the age of magmatic crystallisation (Patchett and Jocelyn, 1979). No fossils are known from this succession.

### **Malvern Hills, England**

The Precambrian rocks of the Malvern Hills can be divided into those of the Malvern Complex, and the Warren House Formation. The former comprises diorites and granites, and some metamorphosed equivalents (Lambert and Holland, 1971). A deformed granite from the complex has an interpreted age of emplacement at  $677 \pm 2$  Ma based on four multi-zircon U-Pb analyses (Tucker and Pharaoh, 1991). The Warren House Formation comprises basalts, altered intermediate and rhyolitic lavas, and felsic pyroclastic rocks. A rhyolitic crystal tuff yielded an interpreted eruption age of  $566 \pm 2$  Ma, based on three multi-zircon U-Pb analyses (Tucker and Pharaoh, 1991).

### **Nuneaton Inlier, England**

The Nuneaton Inlier of the English Midlands is represented in outcrop by the Caldecote Volcanic Formation (Brasier et al., 1978). The formation comprises crystal lapilli tuffs and tuffaceous siltstones, and is unconformably overlain by Lower Cambrian deposits. A minimum age for the formation is acquired from a granophyric diorite intrusion, which is dated to  $603 \pm 2$  Ma, based on two multi-zircon U-Pb analyses (Tucker and Pharaoh, 1991).

## **TOWARDS AN AVALONIAN EDIACARAN BIOSTRATIGRAPHY**

Understanding the causes of the emergence, evolution, and extinction of the Ediacara biota has been hampered due to a lack of a highly-resolved chronostratigraphic framework, upon which regionally restricted biostratigraphic, taphonomic, sedimentological and environmental data could be integrated. Using the data presented in Chapters 2 and 4, the stratigraphic distribution of taxa at the Catalina Dome and Mistaken Point Ecological

Reserve are compared and contrasted to explore the possibility of creating biozones within the Ediacaran of Avalonia.

### **Catalina Dome**

Stratigraphic ranges for a number of key taxa were presented in Hofmann et al. (2008), following their comprehensive palaeontological studies in the area. In addition, new localities discovered and documented in the course of this study, as well as others (Liu, 2011; Liu et al., 2014; Liu et al., 2016) precipitate the need for a re-evaluation.

Figure 5.2 shows the stratigraphic distribution of taxa in the Catalina Dome, alongside the new chronologic framework presented in Chapter 4. New discoveries show the Port Union Formation to be much more fossiliferous, in both abundance and diversity, than previously envisaged. Fossils are also much more common in the Rowland Head Formation (Hofmann et al., 2008) than previously thought.

### **Mistaken Point Ecological Reserve Area**

The stratigraphic ranges for selected taxa within the Mistaken Point area have been produced by collating published data (Narbonne and Gehling, 2003; Clapham et al., 2004; Narbonne et al., 2005; Gehling and Narbonne, 2007; Bamforth et al., 2008; Bamforth and Narbonne, 2009; Bamforth and Narbonne, 2009; Brasier and Antcliffe, 2009; Liu et al., 2010; Liu et al., 2012), unpublished data (Liu, 2011), and new fossil localities discovered during this study.

Figure 5.3 shows the stratigraphic distribution of taxa in and around the Mistaken Point Ecological Reserve, alongside the new chronologic framework presented in Chapter 4. Major additions include the discovery of several fossiliferous horizons in the Briscal Formation that extend the ranges of *Beothukis*, *Fractofusus*, and *Primocandelabrum* to a

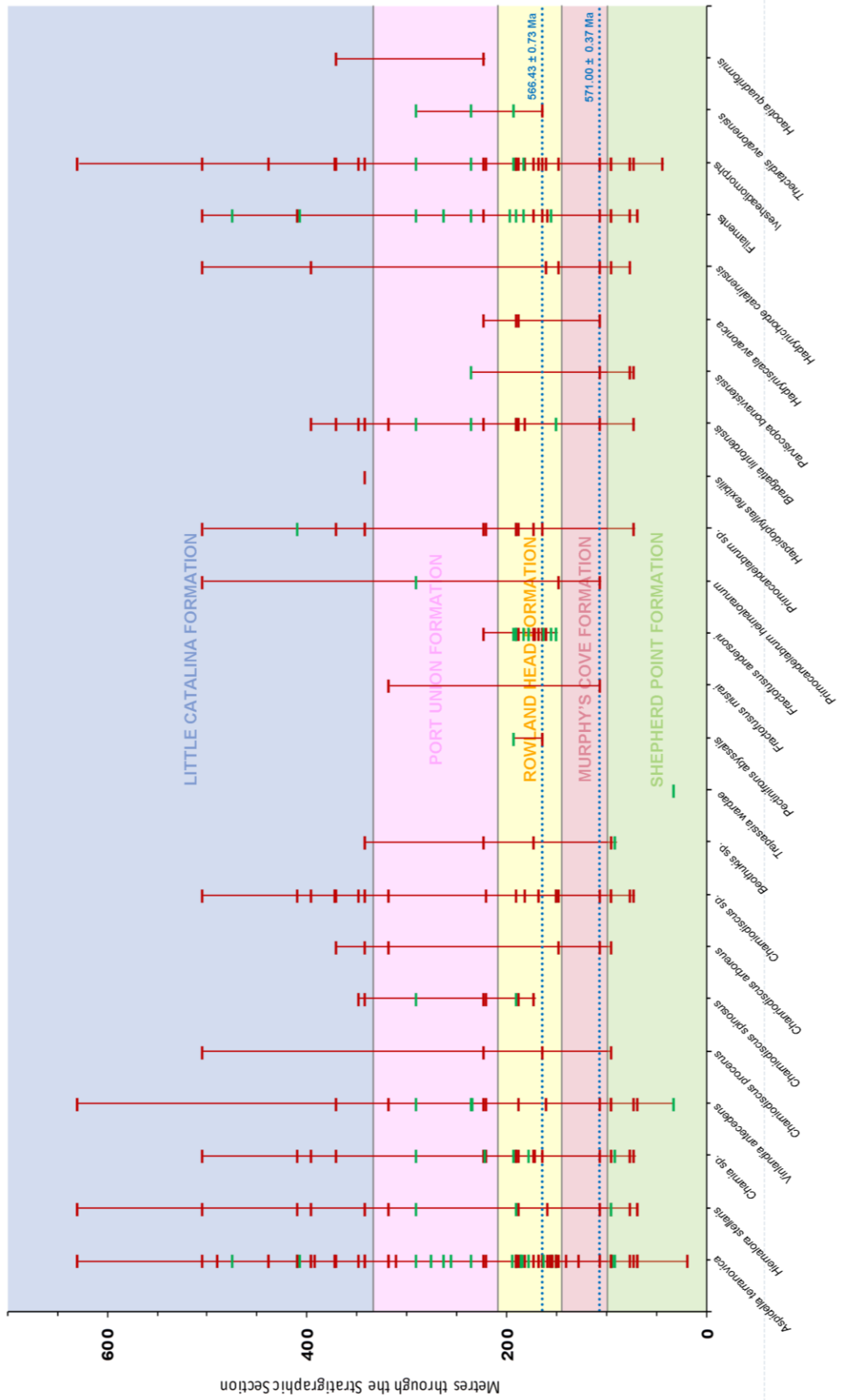


FIGURE 5.2. Diagram showing the stratigraphic distribution of taxa in and around the Catalina Dome, Bonavista Peninsula. Previously documented occurrences are in red. Green markers denote new fossil occurrences.

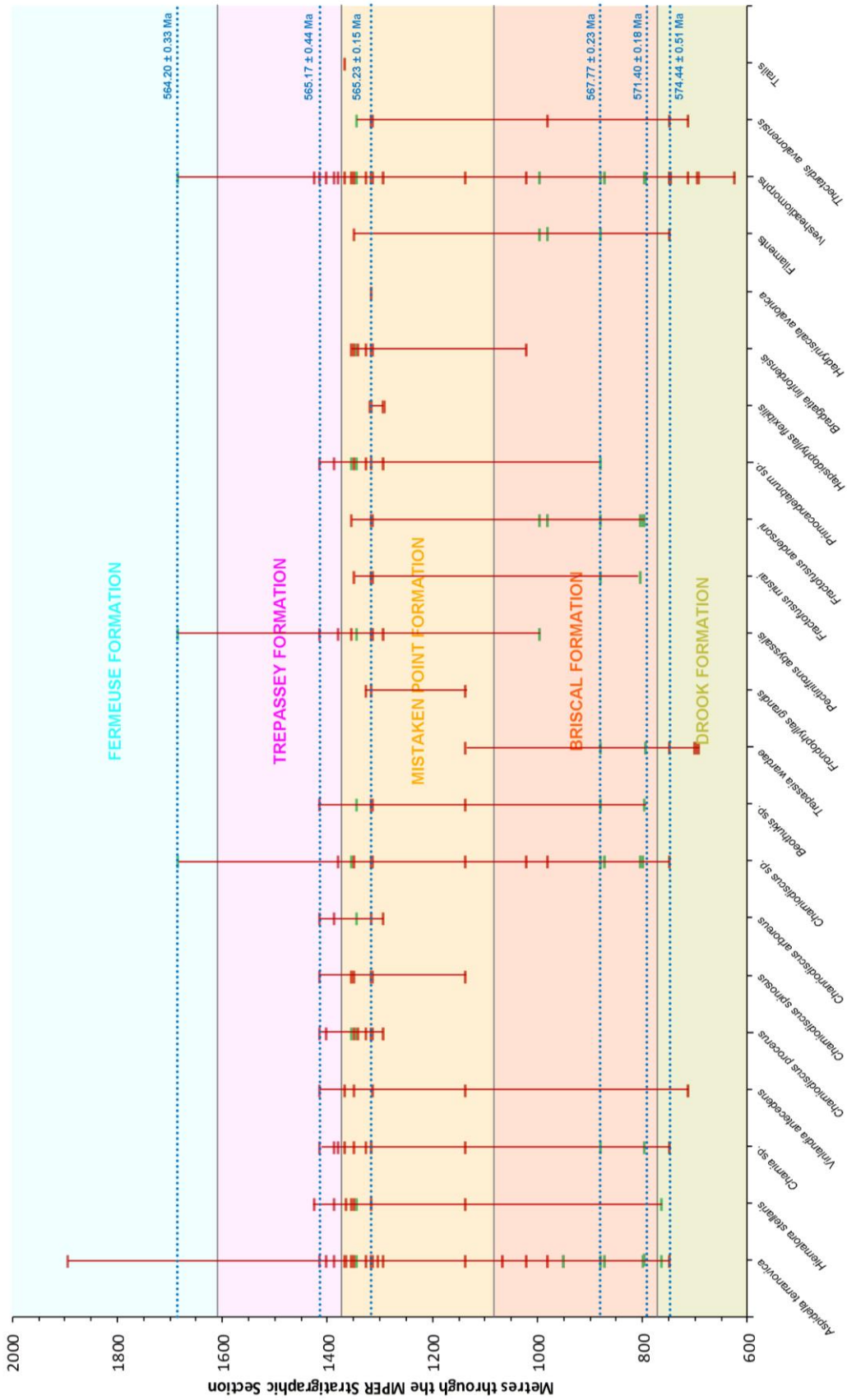


FIGURE 5.3. Diagram showing the stratigraphic distribution of taxa in and around the Mistaken Point Ecological Reserve. Previously documented occurrences are in red. Green markers denote new fossil occurrences.

lower point in the stratigraphy. A lack of known fossil surfaces in the upper Trepassey Formation is likely a product of the lack of outcrop in Long Cove. The dataset may also be biased by the distributions of taxa within the Fermeuse Formations being reliant on a small number of fossiliferous surfaces.

### **Other Avalonian Localities**

Ediacaran fossils are also known from other outcrops on the Avalon Peninsula, Newfoundland, including Spaniard's Bay (Narbonne, 2004; Ichaso et al., 2007; Brasier et al., 2013), St. Schott's, the Carbonear Dome, and the east coast of the peninsula. The fossils in these outcrops are not considered here as their positions within their respective stratigraphies; the correlation of that stratigraphy with those presented here; and their chronostratigraphic position cannot be verified.

Fossils of the Charnwood Forest outcrops are only known from five horizons stratigraphically restricted to the top of the succession (Liu, 2011). Their distribution is shown in Figure 5.4.

Stratigraphic distributions of taxa within the Longmyndian outcrops are not presented here due to lack of rangeomorph fossils, poor age control on the succession, and the questionable biotic affinity of those structures that are present (Menon et al., 2016).

## **DISCUSSION**

The Ediacaran of Avalonia is dominated by volcanic lithologies with subordinate glaciogenic lithologies pre~575 Ma, with broad scale shallowing-upwards successions capping these through to the Precambrian-Cambrian boundary.

Geochemical studies have been used to suggest that the Harbour Main Group of Newfoundland and the Uriconian Group, Long Mynd, are correlatives and formed part of a

continuous tectonic belt (Papezik, 1970). Chronostratigraphic constraints however are not yet conclusive in showing these two units to be coeval (Figure 5.1).

The possibility of ~620 Ma Conception Group-like turbidites from the north of the Avalon Peninsula raises questions regarding the lithologically correlation of other units on the Peninsula. Within the area mapped as ~620 Ma deep-marine deposits by O'Brien et al (2001) lies an outcrop regarded by others as the ~580 Ma Gaskiers Formation, from which geochemical studies on the cap carbonate of the Gaskiers Formation have been based (Myrow and Kaufman, 1999). Mapping to the north of St. John's, Newfoundland has recognised a red mixtite within the lower part of the Drook Formation, classified as the Bauline Member, and tentatively suggested as a correlative for the Gaskiers Formation (King, 1990). Further work to test the litho- and chrono-stratigraphic affinities of these units is required, as well as studies to better constrain the north-south diachroneity of the Ediacaran sediments.

A 40 cm thick bed of carbonate from the Rocky Harbour Formation, Musgravetown Group, has been suggested as a correlative of the cap carbonate that lies at the top of the Gaskiers Formation (Normore, 2010). The lack of Gaskiers glaciation correlatives in many of the sections supports the idea that this was not a global event (Gradstein et al., 2012) or could reflect lack of preservation of time equivalent rock section and/or glacial facies. Further work to investigate the extent of the Gaskiers glacial event, especially within the British Avalonian sections, should be pursued.

Several broad themes can be extracted from the comparison of stratigraphic fossil-distribution data for the Catalina Dome and MPER sections. The first assemblage of structures to appear in both localities includes *Vinlandia*, *Trepassia*, and the taphomorphs ivesheadiomorphs. These emerge very approximately 575 Ma, and are preserved in

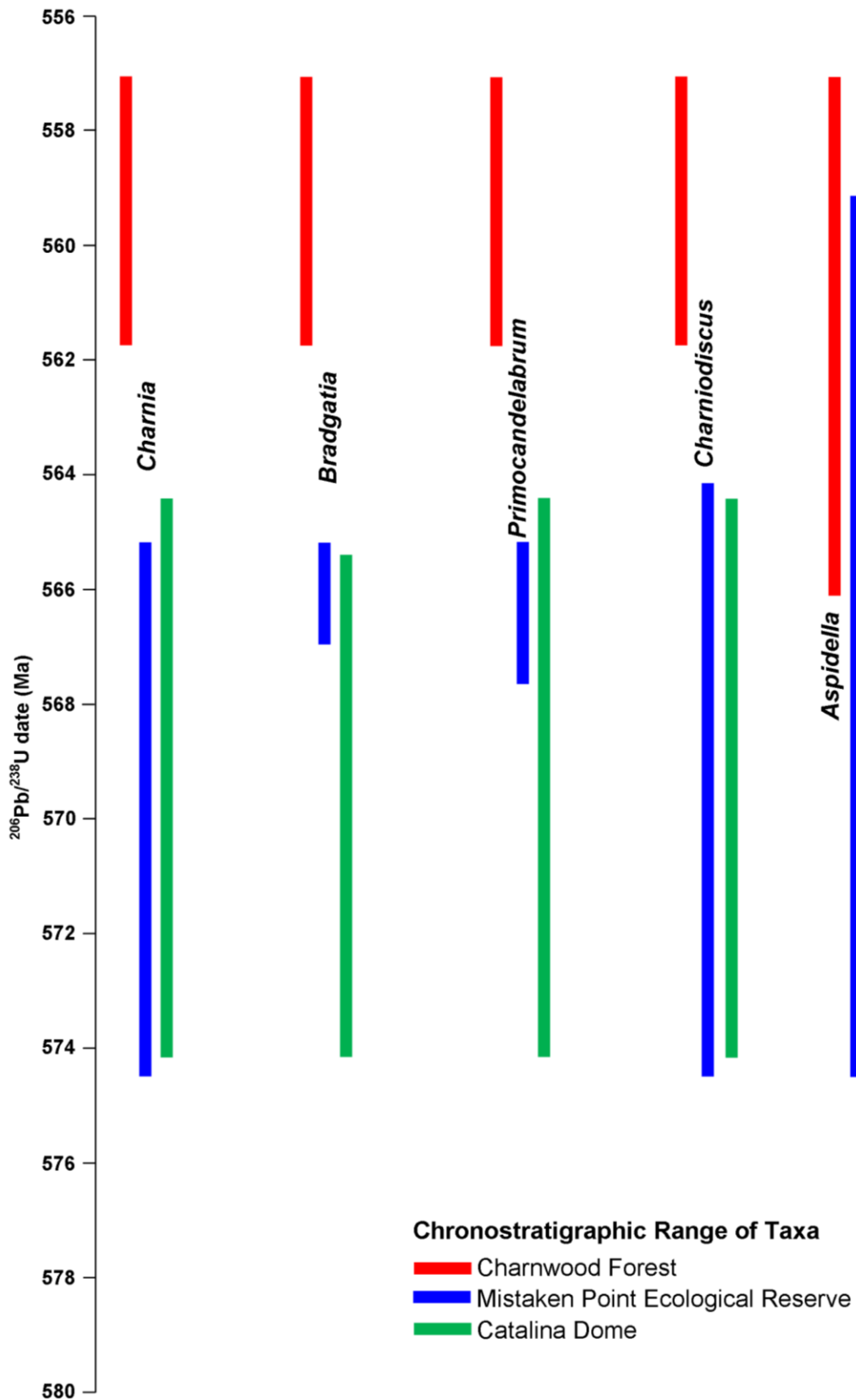


Figure 5.4. Chronostratigraphic distribution of shared taxa from Charnwood Forest, UK, and MPER and Catalina Dome, Newfoundland. Data for Charnwood Forest from Figure 7 of Noble et al. 2015. Note that plotting of ranges requires interpolation and extrapolation around known chronostratigraphic markers. With only two chronostratigraphic benchmarks within the Catalina Dome section, the plotting of chronostratigraphic ranges is highly speculative and reliant on subjective decision making.

formations dominated by cherty siltstones likely deposited on the basin plain. Shortly after this the rapid appearance of *Hiemalora*, *Charnia*, *Charniodiscus*, and the filaments (cf. Liu et al., 2012) occurs, still within the cherty siltstones of the Drook and Shepherd Point formations.

At ~571 Ma, *Fractofusus* first appears in both sections, but notably in the quiet water siltstones of the Murphy's Cove Formation at the Catalina Dome, as opposed to the high-density turbidite sandstones and grits of the Briscal Formation in MPER.

The interval around 565 Ma marks the period of highest density of fossil-bearing surfaces in both sections. This broadly correlates with zones containing an increased number of tuffaceous horizons, and therefore this pattern may be taphonomic in origin and represent peak-volcanism across Avalonian during the time interval studied.

~565 Ma also notes the co-emergence in both sections of evidence for metazoan activity. The stauromedusan-like muscular form *Haootia quadriformis* first occurs ~50 m above the horizon dated to  $566.43 \pm 0.73$  Ma in the Catalina Dome, and ~50 m above the  $565.23 \pm 0.15$  Ma E-Surface at MPER are structures interpreted to be the oldest credible trace fossils (Liu et al., 2010).

Comparison above this level is hindered by a lack of chronostratigraphic benchmarks, and paucity of known fossiliferous horizons in the Trepassey and Fermeuse formations of MPER. Though the ages of these uppermost fossiliferous sections remains poorly constrained, both localities have discoidal, rangeomorph, and other forms of taxa that persists from the older basin-plain deposits, through into the slumped slope deposits of the Fermeuse and Little Catalina formations, and do not appear to be affected by these changing environments. The uppermost sections of the Catalina Dome section appear much more taxonomically diverse, than that in MPER, though this may be due to the

previously mentioned lack of outcrop and known fossiliferous horizons in the Trepassey and Fermeuse formations of MPER.

Many differences exist in the biotas seen at the two studied Newfoundland localities.

*Trepassia* and *Pectinifrons* are only known from a very small number of stratigraphically restricted horizons in the Catalina Dome, whereas they are known from a much larger part of the sections in MPER. *Parviscopa* and *Hadrynichorde* are known from multiple horizons in the Catalina Dome, but have never been discovered in MPER.

There is little evidence that the stratigraphic distribution of fossils within the Catalina Dome and MPER sections is environmentally controlled, with the majority of taxa being known from a range of deep-marine facies. The patchiness of taphonomic processes associated with tuff deposition can also be ruled out because, while smothering and casting tuffites do vary in abundance, they are found throughout the sections.

The observed ranges of taxa are therefore likely to be a product of both evolutionary turnover and outcrop accessibility biases. Graphic correlation between the two Newfoundland sections, showing the stratigraphic ranges of taxa shows broadscale similarities (Figure 5.5). Last occurrence data shows a clustering in the MPER section around the upper boundary of the Mistaken Point Formation, and in the Fermeuse Formation. This may simply be due to the lack of fossiliferous horizons in the Trepassey and Fermeuse formations. The disperse nature of the plotted first and last occurrence data on the graphic correlation suggests that either the taxa are unsuitable for biostratigraphy, or that the first and last occurrence data are not yet precise enough, and more field research is required (Figure 5.5). The current data show the majority of first occurrences of taxa within the bottom half of each stratigraphic section, and the last occurrences in the upper half of each section. This suggest that even if biostratigraphy were possible, taxon-range

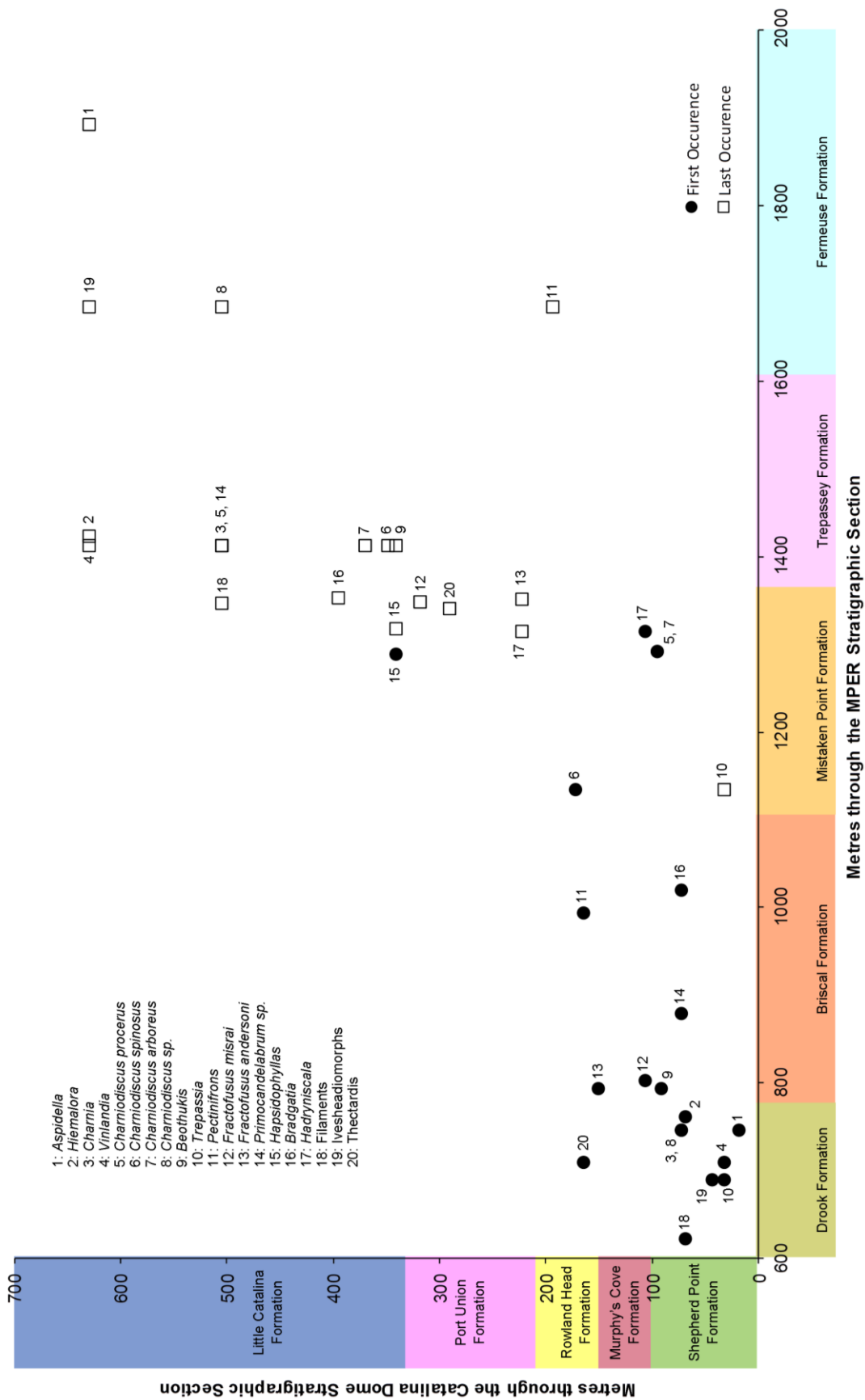


FIGURE 5.5: Graphic correlation of the MPER and Catalina Dome sections, showing the first and last occurrence of each taxon in both successions.

biozones may be of limited utility, and concurrent-range and interval-range biozones would need to be used. The formal creation of biostratigraphic zones is therefore considered to be premature at this time. Chronostratigraphic constraints on the upper extents of both successions will prove vital in testing the calibration of any potential biostratigraphy, and also integration with other successions such as those in the White Sea.

Comparison of the chronostratigraphic ranges of the shared taxa *Charnia*, *Bradgatia*, *Primocandelabrum*, *Charniodiscus*, and *Aspidella* between the sections at MPER, the Catalina Dome, and Charnwood Forest show distinct differences (Figure 5.4). It should be noted that the analysis is hampered by the lack of chronostratigraphic constraints in the upper part of the Catalina Dome section, and therefore the age of last occurrences within this section in particular have had to be extrapolated, and should therefore be treated with appropriate caution. Even so, it appears rangeomorph taxa are known from chronologically well-constrained, younger horizons at Charnwood Forest, than for the Newfoundland sections. This would appear to suggest the disappearance of these taxa in Newfoundland is not the product of evolutionary turnover. The Charnwood Forest fossils are only known from five horizons, and therefore there is a strong likelihood of outcrop bias affecting the current dataset. Further work to investigate the differences between the English and Newfoundland sections is required.

Palaeoecological studies on the latest Ediacaran fossil assemblages in Namibia have been used to suggest that the rise of animals is responsible for the extinction of the Ediacaran biota (Laflamme and Darroch, 2015). This is not evidenced in the Newfoundland sections, where metazoans appear at ~565 Ma in both sections, but the majority of other forms persist into the younger rocks, with only *Fractofusus andersoni* terminating in both localities upon the appearance of metazoans.

The absence of rangeomorphs from the Long Harbour Group on the Burin Peninsula and the Musgravetown Group in the west of the Bonavista Peninsula is of interest, when both have comparable, coeval, fossiliferous sections elsewhere deposited in similar environments (Figure 5.1). The majority of research on the Long Harbour and Musgravetown Groups has been through regional-scale mapping exercises, and the lack of a biota may therefore be representative of a sampling bias. Exploration of these units to confirm the absence of rangeomorphs, and if so, elucidate what may be controlling the biotic paucity is therefore necessary.

Similarly, the absence of rangeomorphs from the deep-marine section of the Long Mynd, and >562 Ma section of the Charnwood Forest outcrops is worthy of note, though this may be a product of lack of outcrop at these inland localities.

The youngest date yielded herein from the fossiliferous horizons of Newfoundland is  $564.20 \pm 0.33$  Ma. The lack of chronostratigraphic constraints for the rocks younger than this prevents global correlation with the significant fossil localities associated with the White Sea (558-550 Ma) and Nama (549-541 Ma) assemblages (Narbonne, 2005).

## **CONCLUSIONS**

Certain sections of the Ediacaran successions of Avalonia are well constrained chronostratigraphically, for example the Maplewell Group of the Charnwood Forest outcrops. However, the Ediacaran of Avalonia particularly suffers from the use of dates that are not accompanied by details of the analytical method used and the complete dataset (Benus, 1988; Van Kranendonk et al., 2008), or are not peer-reviewed (Benus, 1988; Israel, 1998). This hampers efforts at regional and global chronostratigraphic correlation by, for example, promoting the direct comparison of dates that may have been yielded from differing geochronological techniques.

New chronostratigraphic constraints on the fossiliferous successions of Newfoundland allows for direct comparison between the Mistaken Point and Catalina Dome sections, and that of Charnwood Forest for the first time. There is little correlation between the Newfoundland and English sections regarding the chronostratigraphic ranges of shared taxa. More data is required to reveal if the control on this is evolutionary, environmental, taphonomic, or due to sample bias.

There is a dearth of chronostratigraphic constraints across Avalonia between 545 Ma and 565 Ma. This time period not only includes the widespread disappearance of rangeomorphs, as seen in the Newfoundland and Charnwood Forest sections, but also the end of the Shuram anomaly: the largest carbon isotope excursion in the geological record (Le Guerroue, 2010; Grotzinger et al., 2011; Verdel et al., 2011). With a lack of target lithologies to chemostratigraphically correlate Avalonia with the Shuram Formation in Oman, and other equivalents worldwide, further chronostratigraphic studies are required. Increased resolution of the <565 Ma successions from Newfoundland is also essential for correlating with other global significant Ediacaran fossil localities, such as in Namibia (Grotzinger et al., 1995) and the White Sea (Martin et al., 2000), and understanding the apparent disappearance of the majority of Ediacaran taxa at the base of the Cambrian (Laflamme et al., 2013).

A wider geographical distribution of dates is also required within Avalonia to test the extent to which deposits are diachronous. All currently known Avalonian rangeomorphs are found within deep-marine deposits, and there is no evidence for biological-environmental association within the various deep-marine settings studied. Further dates higher in the Newfoundland and UK sections will allow for a better understanding of the controls on the stratigraphic distribution of taxa.

The rangeomorphs *Vinlandia* and *Trepassia* are the first complex forms to appear in both fossiliferous Newfoundland sections, closely followed by a rapid radiation of forms around 575 Ma, confirming the ‘Avalon Explosion’ (Shen et al., 2008) or ‘Ediacaran Explosion’ (Liu et al., 2012) hypothesis. The close temporal association of the end of the Gaskiers Glaciation with the rapid emergence of rangeomorphs has been used to suggest a possible global climatic driver for this ‘Avalon Explosion’ (Shen et al., 2008). New chronostratigraphic constraints on this radiation from MPER show a larger interval than previously thought between the Gaskiers Formation and the first rangeomorphs (see Chapter 4), however possible deep-marine cap-carbonate equivalents from the Catalina Dome (see Chapter 3) may reflect a longer duration to this terminal Neoproterozoic glacial event than previously thought.

The common occurrence of metazoans in both the MPER and Catalina Dome successions ~565 Ma offers an important benchmark for molecular clock and other evolutionary calculations reliant on fossil reference points. With the Newfoundland fossiliferous successions, especially those around MPER, now being some of the best chronostratigraphically constrained in the world, they will likely prove useful reference sections for future Ediacaran chronostratigraphy and palaeontological comparisons.

Potential exists for the creation of several biozones within the Ediacaran of Avalonian. Accurate litho- and chrono-stratigraphic correlation of the St. Schott’s Peninsula of Newfoundland, with the MPER and Catalina Dome sections, accompanied by accurate stratigraphic cataloguing of the fossil surfaces there may prove a valuable way to test the biostratigraphic ideas proposed and developed.

## ACKNOWLEDGEMENTS

This research was supported by the Natural Environment Research Council (grant number NE/J5000045/1). Alex Liu and Tom Hearing are thanked for their help and assistance in gathering the data. The Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, provided permits to conduct research within the Mistaken Point Ecological Reserve. Access for research to fossil localities within the Mistaken Point Ecological Reserve is by permit only. Readers are advised that the fossils around Cape Race, and those in the Catalina Dome are protected by the Paleontological Resource Regulations 67/11, under the Historic Resources Act, 1990.

## REFERENCES

- Bamforth, E.L., and Narbonne, G.M., 2009, New Ediacaran Rangeomorphs from Mistaken Point, Newfoundland, Canada: *Journal of Paleontology*, v. 83, no. 6, p. 897–913.
- 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*, v. 82, no. 4, p. 763–777.
- Benus, A.P., 1988, Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland): *Trace Fossils, Small Shelly Fossils and the Precambrian Cambrian Boundary: Proceedings, 1987, Memorial University (New York State Museum and Geological Survey Bulletin)*, p. 8–9.
- 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*, v. 166, p. 363–384.
- Brasier, M.D., Hewitt, R.A., and Brasier, C.J., 1978, On the Late Precambrian–Early Cambrian Hartshill Formation of Warwickshire: *Geological Magazine*, v. 115, no. 1, p. 21–36, doi: 10.1017/S0016756800040954.
- 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*, v. 231, p. 122–135, doi: 10.1016/j.precamres.2013.03.013.
- Clapham, M.E., Narbonne, G.M., Gehling, J.G., Greentree, C., and Anderson, M.M., 2004, *Thectardis avalonensis*: A new Ediacaran fossil from the Mistaken Point biota, Newfoundland: *Journal of Paleontology*, v. 78, no. 6, p. 1031–1036.

- Cobbold, E.S., 1927, The Stratigraphy and Geological Structure of the Cambrian Area of Comley, Shropshire: *Quarterly Journal of The Geological Society*, v. 83, p. 551–573, doi: 10.1144/GSL.JGS.1927.083.01-05.22.
- Cocks, L.R.M., Mckerrow, W.S., and Van Staal, C.R., 1997, The margins of Avalonia: *Geological Magazine*, v. 134, no. 5, p. 627–636, doi: null.
- Compston, W., Wright, A.E., and Toghiani, P., 2002, Dating the Late Precambrian volcanicity of England and Wales: *Journal of the Geological Society*, v. 159, p. 323–339, doi: 10.1144/0016-764901-010.
- Cope, J.C.W., 1977, Ediacara-Type Fauna from South-Wales: *Nature*, v. 268, no. 5621, p. 624–624.
- Cope, J.C.W., and Bevins, R.E., 1993, The Stratigraphy and Setting of the Precambrian Rocks of the Llangynog Inlier, Dyfed, South-Wales: *Geological Magazine*, v. 130, no. 1, p. 101–111.
- Cope, J.C.W., and Gibbons, W., 1987, New evidence for the relative age of the Ercall Granophyre and its bearing on the Precambrian-Cambrian boundary in southern Britain: *Geological Journal*, v. 22, no. 1, p. 53–60, doi: 10.1002/gj.3350220106.
- Dec, T., O'Brien, S.J., and Knight, I., 1992, Late precambrian volcanoclastic deposits of the avalonian eastport basin (newfoundland appalachians): petrofacies, detrital clinopyroxene geochemistry and palaeotectonic implications: *Precambrian Research*, v. 59, no. 3, p. 243–262, doi: 10.1016/0301-9268(92)90059-W.
- 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*, v. 44, no. 3, p. 367–387, doi: 10.1139/E07-003.
- Gradstein, F.M., Ogg, G., and Schmitz, M., 2012, *The Geologic Time Scale 2012 2-Volume Set*: Elsevier.
- Grotzinger, J.P., Bowring, S.A., Saylor, B.Z., and Kaufman, A.J., 1995, Biostratigraphic and Geochronological Constraints on Early Animal Evolution: *Science*, v. 270, no. 5236, p. 598–604.
- Grotzinger, J.P., Fike, D.A., and Fischer, W.W., 2011, Enigmatic origin of the largest-known carbon isotope excursion in Earth's history: *Nature Geoscience*, v. 4, no. 5, p. 285–292, doi: 10.1038/NGEO1138.
- Hinchey, J.G., 2001, An integrated geochemical, petrologic, geochronological, and metallogenic study of the Powder Horn Intrusive Suite and the associated Lodestar Prospect: a magmatic-hydrothermal auriferous breccia zone that links epithermal and porphyry systems, Northern Burin Peninsula, Newfoundland [Unpublished Masters Thesis]: Memorial University of Newfoundland.
- Hofmann, H.J., O'Brien, S.J., and King, A.E., 2008, Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada: *Journal of Paleontology*, v. 82, no. 1, p. 1–36, doi: 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*, v. 44, no. 1, p. 25–41.
- Israel, S., 1998, Geochronological, structural and stratigraphic investigation of a Precambrian unconformity between the Harbour Main Group and Conception Group, east coast Holyrood Bay, Avalon Peninsula, Newfoundland.: Unpublished B.Sc. Thesis, Memorial University, p. 78.
- Jukes, J.B., 1843, General Report of the Geological Survey of Newfoundland: Executed Under the Direction of the Government and Legislature of the Colony During the Years 1839 and 1840: J. Murray.
- King, A.F., 1990, Geology of the St. John's area: Geological Survey Branch, Department of Mines and Energy, Government of Newfoundland and Labrador.
- King, A.F., Colman-Sadd, S.P., Hayes, J.P., and Division, N.M.D., 1988, Geology of the Avalon Peninsula, Newfoundland:(parts of 1K, 1L, 1M, and 2C): Mineral Development Div., Dept. of Mines, Government of Newfoundland and Labrador.
- Krogh, T.E., Strong, D.F., O'Brien, S.J., and Papezik, V.S., 1988, Precise U–Pb zircon dates from the Avalon Terrane in Newfoundland: *Canadian Journal of Earth Sciences*, v. 25, no. 3, p. 442–453, doi: 10.1139/e88-045.
- Laflamme, M., and Darroch, S.A.F., 2015, Palaeobiology: Ecological Revelations in Ediacaran Reproduction: *Current Biology*, v. 25, no. 21, p. R1047–R1050, doi: 10.1016/j.cub.2015.09.041.
- 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*, v. 23, no. 2, p. 558–573, doi: 10.1016/j.gr.2012.11.004.
- Lambert, R.S.J., and Holland, J.G., 1971, The petrography and chemistry of the igneous complex of the Malvern Hills, England: *Proceedings of the Geologists' Association*, v. 82, no. 3, p. 323–IN5, doi: 10.1016/S0016-7878(71)80012-3.
- Le Guerroue, E., 2010, Duration and synchronicity of the largest negative carbon isotope excursion on Earth: The Shuram/Wonoka anomaly: *Comptes Rendus Geoscience*, v. 342, no. 3, p. 204–214, doi: 10.1016/j.crte.2009.12.008.
- Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., et al., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: *Precambrian Research*, v. 160, no. 1–2, p. 179–210, doi: 10.1016/j.precamres.2007.04.021.
- Liu, A.G., 2011, Understanding the Ediacaran assemblages of Avalonia: a palaeoenvironmental, taphonomic and ontogenetic study [Unpublished DPhil Thesis]: University of Oxford.

- 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*, v. 59, no. 1, p. 45–58, doi: 10.1111/pala.12206.
- Liu, A.G., Matthews, J.J., Menon, L.R., McIlroy, D., and Brasier, M.D., 2014, *Hootia quadriformis* n. gen., n. sp., interpreted as a muscular cnidarian impression from the Late Ediacaran period (approx. 560 Ma): *Proceedings of the Royal Society of London B: Biological Sciences*, v. 281, no. 1793, p. 20141202, doi: 10.1098/rspb.2014.1202.
- 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*, v. 38, no. 2, p. 123–126.
- 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*, v. 169, no. 4, p. 395–403, doi: 10.1144/0016-76492011-094.
- Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M.A., and Kirschvink, J.L., 2000, Age of Neoproterozoic bilaterian body and trace fossils, White Sea, Russia: Implications for metazoan evolution: *Science*, v. 288, no. 5467, p. 841–845.
- Matthews, J.J., 2011, *The Palaeontology and Palaeoenvironments of the Ferryland Siliciclastic Sequence: Unpublished Masters Thesis, University of Oxford.*
- McIlroy, D., Crimes, T.P., and Pauley, J.C., 2005, Fossils and matgrounds from the Neoproterozoic Longgrayndian Supergroup, Shropshire, UK: *Geological Magazine*, v. 142, no. 4, p. 441–455.
- Menon, L.R., McIlroy, D., Liu, A.G., and Brasier, M.D., 2016, The dynamic influence of microbial mats on sediments: fluid escape and pseudofossil formation in the Ediacaran Longmyndian Supergroup, UK: *Journal of the Geological Society*, p. 2015–36, doi: 10.1144/jgs2015-036.
- Murphy, J.B., and Nance, R.D., 1989, Model for the evolution of the Avalonian-Cadomian belt: *Geology*, v. 17, no. 8, p. 735–738, doi: 10.1130/0091-7613(1989)017<0735:MFTEOT>2.3.CO;2.
- Myrow, P.M., and Kaufman, A.J., 1999, A Newly Discovered Cap Carbonate Above Varanger-Age Glacial Deposits in Newfoundland, Canada: *Journal of Sedimentary Research*, v. 69, no. 3.
- Narbonne, G.M., 2004, Modular construction of early ediacaran complex life forms: *Science*, v. 305, no. 5687, p. 1141–1144, doi: 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*, v. 33, no. 1, p. 421–442, doi: 10.1146/annurev.earth.33.092203.122519.

- Narbonne, G.M., Dalrymple, R.W., Laflamme, M., Gehling, J.G., and Boyce, W.D., 2005, Life After Snowball: Mistaken Point Biota and the Cambrian of the Avalon, *in* NAPC 2005 Field Guide,.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: *Geology*, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- 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*, v. 127, no. 1–2, p. 250–265, doi: 10.1130/B31013.1.
- Normore, L.S., 2010, Geology of the Bonavista map-area (NTS 2C/11), Newfoundland: Current Research Report, p. 10–1.
- O'Brien, S.J., 1994, On the geological development of the Avalon Zone in the area between Ocean Pond and Long Islands, Bonavista Bay (parts of NTS 2C/5 and NTS 2C/12): Current research: Newfoundland Department of Mines and Energy, Geological Survey Branch, Report, p. 94–1.
- O'Brien, S.J., Dubé, B., and O'Driscoll, C.F., 1999, High-sulphidation, epithermal-style hydrothermal systems in late Neoproterozoic Avalonian rocks on the Burin Peninsula, Newfoundland: Implications for gold exploration: Current Research—Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report, p. 99–1.
- O'Brien, S.J., Dunning, G.R., Dube, B., Sparkes, B., Israel, S., and Ketchum, J., 2001, New insights into the Neoproterozoic geology of the central Avalon Peninsula (parts of NTS map areas 1N/6, 1N/7 and 1N/3), eastern Newfoundland: Current Research, Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, p. 169–189.
- O'Brien, S.J., Dunning, G.R., Knight, I., and Dec, T., 1989, Late Precambrian geology of the north shore of Bonavista Bay (Clode Sound to Lockers Bay): Newfoundland Department of Mines and Energy, Report of Activities, p. 49–50.
- O'Brien, S.J., O'Driscoll, C.F., Greene, B.A., and Tucker, R.D., 1995, Pre-Carboniferous geology of the Connaigre Peninsula and the adjacent coast of Fortune Bay, southern Newfoundland: Nfld Dept Nat Res Geol Surv Rept, p. 95–1.
- Papezik, V.S., 1970, Petrochemistry of volcanic rocks of the Harbour Main Group, Avalon Peninsula, Newfoundland: *Canadian Journal of Earth Sciences*, v. 7, no. 6, p. 1485–1498, doi: 10.1139/e70-141.
- Patchett, P.J., and Jocelyn, J., 1979, U–Pb zircon ages for late Precambrian igneous rocks in South Wales: *Journal of the Geological Society*, v. 136, no. 1, p. 13–19, doi: 10.1144/gsjgs.136.1.0013.
- Pauley, J.C., 1991, A revision of the stratigraphy of the longmyndian supergroup, welsh borderland, and of its relationship to the uriconian volcanic complex: *Geological Journal*, v. 26, no. 2, p. 167–183, doi: 10.1002/gj.3350260209.

- Pauley, J.C., 1990, Sedimentology, structural evolution and tectonic setting of the late Precambrian Longmyndian Supergroup of the Welsh Borderland, UK: Geological Society, London, Special Publications, v. 51, no. 1, p. 341–351, doi: 10.1144/GSL.SP.1990.051.01.22.
- Pharaoh, T.C., and Gibbons, W., 1994, Precambrian rocks in England and Wales south of the Menai Strait fault system, *in* Gibbons, W. and Harris, A.L. eds., A Revised Correlation of Precambrian Rocks in the British Isles, Geological Society, London, Special Report 22,.
- Pisarevsky, S.A., Murphy, J.B., Cawood, P.A., and Collins, A.S., 2008, Late Neoproterozoic and Early Cambrian palaeogeography: models and problems: Geological Society, London, Special Publications, v. 294, no. 1, p. 9.
- Samson, S.D., D’Lemos, R.S., Miller, B.V., and Hamilton, M.A., 2005, Neoproterozoic palaeogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages: *Journal of the Geological Society*, v. 162, no. 1, p. 65–71, doi: 10.1144/0016-764904-003.
- Schofield, D.I., Millar, I.L., Wilby, P.R., and Evans, J.A., 2010, A new, high precision U–Pb date from the oldest known rocks in southern Britain: *Geological Magazine*, v. 147, no. 1, p. 145–150, doi: 10.1017/S001675680999063X.
- Shen, B., Dong, L., Xiao, S., and Kowalewski, M., 2008, The Avalon Explosion: Evolution of Ediacara Morphospace: *Science*, v. 319, no. 5859, p. 81–84, doi: 10.1126/science.1150279.
- Skipton, D.R., Dunning, G.R., and Sparkes, G.W., 2013, Late Neoproterozoic arc-related magmatism in the Horse Cove Complex, eastern Avalon Zone, Newfoundland: *Canadian Journal of Earth Sciences*, v. 50, no. 4, p. 462–482, doi: 10.1139/cjes-2012-0090.
- Sparkes, G.W., 2006, Late Neoproterozoic geology of the east coast of Conception Bay, Newfoundland Avalon Zone: Current Research-Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report, p. 6–1.
- Sparkes, G.W., O’Brien, S.J., Dunning, G.R., and Dubé, B., 2005, U–Pb geochronological constraints on the timing of magmatism, epithermal alteration and low-sulphidation gold mineralization, eastern Avalon Zone, Newfoundland: Current research, p. 5–1.
- Thompson, M.D., Grunow, A.M., and Ramezani, J., 2007, Late Neoproterozoic paleogeography of the Southeastern New England Avalon Zone: Insights from U–Pb geochronology and paleomagnetism: *Geological Society of America Bulletin*, v. 119, no. 5–6, p. 681–696, doi: 10.1130/B26014.1.
- Thorpe, R.S., 1972, The geochemistry and correlation of the Warren House, the Uriconian and the Charnian Volcanic Rocks from the English Pre-Cambrian: *Proceedings of the Geologists’ Association*, v. 83, no. 3, p. 269–285, doi: 10.1016/S0016-7878(72)80035-X.
- Torsvik, T.H., 2003, The Rodinia Jigsaw Puzzle: *Science*, v. 300, no. 5624, p. 1379–1381, doi: 10.1126/science.1083469.

- Tucker, R.D., and Pharaoh, T.C., 1991, U-Pb zircon ages for Late Precambrian igneous rocks in southern Britain: *Journal of the Geological Society*, v. 148, no. 3, p. 435–443, doi: 10.1144/gsjgs.148.3.0435.
- 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*: , p. 23–36.
- Verdel, C., Wernicke, B.P., and Bowring, S.A., 2011, The Shuram and subsequent Ediacaran carbon isotope excursions from southwest Laurentia, and implications for environmental stability during the metazoan radiation: *Geological Society of America Bulletin*, v. 123, no. 7–8, p. 1539–1559, doi: 10.1130/B30369.1.
- Woodcock, N.H., and Pauley, J.C., 1989, The Longmyndian Rocks of the Old Radnor Inlier, Welsh Borderland: *Geological Journal*, v. 24, no. 2, p. 113–120, doi: 10.1002/gj.3350240204.

# Chapter 6: Post-Fossilization Processes and their implications for understanding Ediacaran macrofossil assemblages

---

## **ABSTRACT**

Fossil assemblages on the southern shore of Newfoundland's Avalon Peninsula preserve diverse examples of the enigmatic Ediacaran macrobiota, which offer some of the earliest evidence for large and complex multicellular life. These fossils are exposed on extensive bedding planes in extraordinary abundances, and census data taken from the assemblages has stimulated several palaeoecological studies that have been used to constrain the reproductive strategy and phylogenetic placement of these organisms. Mapping and stratigraphic correlation in Newfoundland reveals that some fossil surfaces can be tracked over several kilometres. These laterally extensive surfaces enable us to recognise that the mechanism by which the substrate overlying a fossil surface is removed may impose a first order control on the observed composition of a fossil assemblage. Weathering and erosion – along with factors associated with tectonics, metamorphism, and discovery – introduce oft-overlooked biases that are here grouped as 'post-fossilization processes'. The recognition that post-fossilization processes significantly influence fossil census data has implications for Ediacaran palaeoecology both in Newfoundland and beyond. The role of post-fossilization processes in differentially influencing the preservational fidelity of individual specimens on a given surface, and their potential for generating features that could be mistaken for original morphological characters, is also explored. It is further recognised that the study of post-fossilisation processes has significance to the field of

geoconservation, and the continued sustainability of these world-famous fossil localities that are currently being considered as a potential UNESCO world heritage site.

## **INTRODUCTION**

Fossils of large and complex soft-bodied organisms commonly referred to as the Ediacaran macrobiota are found globally in strata of the late Ediacaran Period (580–541 Ma; Fedonkin *et al.* 2007). These organisms, many of which are of uncertain phylogenetic position, have been considered by many to include some of the earliest animals (e.g. Narbonne *et al.* 2012). Some of the oldest Ediacaran macrofossils were discovered in what is now the Mistaken Point Ecological Reserve (MPER), southeastern Newfoundland (Fig. 1) in the late 1960's (Anderson & Misra 1968). The Mistaken Point fossil assemblages, ~580–560 Ma (Van Kranendonk *et al.* 2008), are dominated by a distinctive group of sessile, frondose organisms of enigmatic biological affinity termed the Rangeomorpha (Narbonne 2004). These forms occur alongside a small number of non-frondose taxa (reviewed in Liu *et al.* 2015b), and rare trace and body fossils that may indicate the presence of muscular metazoans (Liu *et al.* 2010, 2014, 2015a; Menon *et al.* 2013).

Palaeontological research into the Ediacaran macrobiota has often focused on the most beautiful, finely preserved, and complete fossil specimens, which are restricted to a relatively small number of localities worldwide. In Newfoundland, the MPER contains multiple fossil-bearing surfaces with high-quality preservation of thousands of individual organisms. Fossil census data from such bedding planes is increasingly being used to elucidate the population structure (Darroch *et al.* 2013), palaeoecology (Clapham *et al.* 2003), and even palaeobiology (Mitchell *et al.* 2015) of Ediacaran assemblages that are inferred to reflect palaeocommunities. These methodologies are based on the precept that the observed fossil assemblages are accurate representations of the original biological

communities, and are not affected by biases introduced by taphonomic or other secondary processes.

Knowledge of the taphonomic processes and conditions responsible for generating the observed fossils is required to correctly interpret fossil specimens, and the original taphonomic processes involved in the preservation of Ediacaran macrofossils are becoming increasingly well understood (e.g. Schiffbauer *et al.* 2014). Fossils in Newfoundland are typically preserved as casts and molds on the ancient seafloor beneath event beds that are often rich in volcanic material (Narbonne 2005). Bacterial sulfate reduction by microorganisms immediately following burial led to early diagenetic molding of the external morphology of both macro-organisms and surrounding microbial mats by iron sulfides (Gehling 1999; Liu 2016). These sulfides combined with further microbially produced hydrogen sulfide to form a framboidal pyrite ‘death mask’ around the soft tissues prior to extensive decay or sediment lithification (Gehling 1999; Liu 2016), capturing a high-fidelity impression of the external morphology of the organisms (see also Laflamme *et al.* 2011; Darroch *et al.* 2012).

Additional factors that exert influences on Ediacaran fossil assemblages remain less well understood. Notwithstanding the complications arising due to time averaging of Ediacaran fossil communities and the consideration of the presence of necromass (Liu *et al.* 2011, 2015b; Wilby *et al.* 2015), potential biases on the composition of fossil assemblages can be exerted by processes that took place after fossilization and lithification of the sediment. The implications of these for the interpretation of Ediacaran fossil assemblages at Mistaken Point are the primary focus of this paper.

## **THE ‘E’ SURFACE**

One of the best known and most extensively studied fossil horizons in Newfoundland is the Yale outcrop of the ‘E’ Surface at Mistaken Point (Landing *et al.* 1988, figure 10; Clapham *et al.* 2003; Figures 6.1–6.2). This outcrop preserves the fossilized impressions of over four thousand organisms, recording features of <0.5 mm in resolution, and its fossils have been the focus of studies into palaeoecology (Clapham *et al.* 2003; Darroch *et al.* 2013; Darroch *et al.* 2015; Liu *et al.* 2015b; Mitchell *et al.* 2015), taxonomy (Laflamme *et al.* 2004; Gehling & Narbonne 2007; Flude & Narbonne 2008; Bamforth & Narbonne 2009; Brasier & Antcliffe 2009; Brasier *et al.* 2012) and taphonomy (Seilacher 1992; Liu *et al.* 2011; Liu 2016). The Yale outcrop of the ‘E’ Surface (Figure 6.1) is also the principle locality that tour groups, run by MPER Staff, visit to observe the fossil horizons.

The ‘E’ Surface lies within the siltstone and mudstone dominated Mistaken Point Formation, which lies towards the top of the progradational Conception Group. The Mistaken Point Formation is dominated by green, grey and purple normally graded siltstones and mudstones, but characteristically includes thick sandstone turbidites with normal-grading and convolute-bedding, and fine- to medium-grained sandstones (e.g. Wood *et al.* 2003). Many bedding planes are overlain by light grey-green tuffs and tuffites that are preferentially cleaved compared to surrounding beds. These tuffs typically overlie fossil-bearing horizons.

### **Geology of the Yale outcrop of the ‘E’ Surface at Mistaken Point**

The Yale outcrop of the ‘E’ Surface (Figure 6.2a) lies near the top of the Mistaken Point Formation, within a distinctive stratigraphic succession that has been well documented in the literature (e.g. Landing *et al.* 1988, figures 10–11). The ‘E’ Surface lies approximately 2.5 m above the fossiliferous ‘D’ Surface, and is overlain by two thick green-grey tuffites

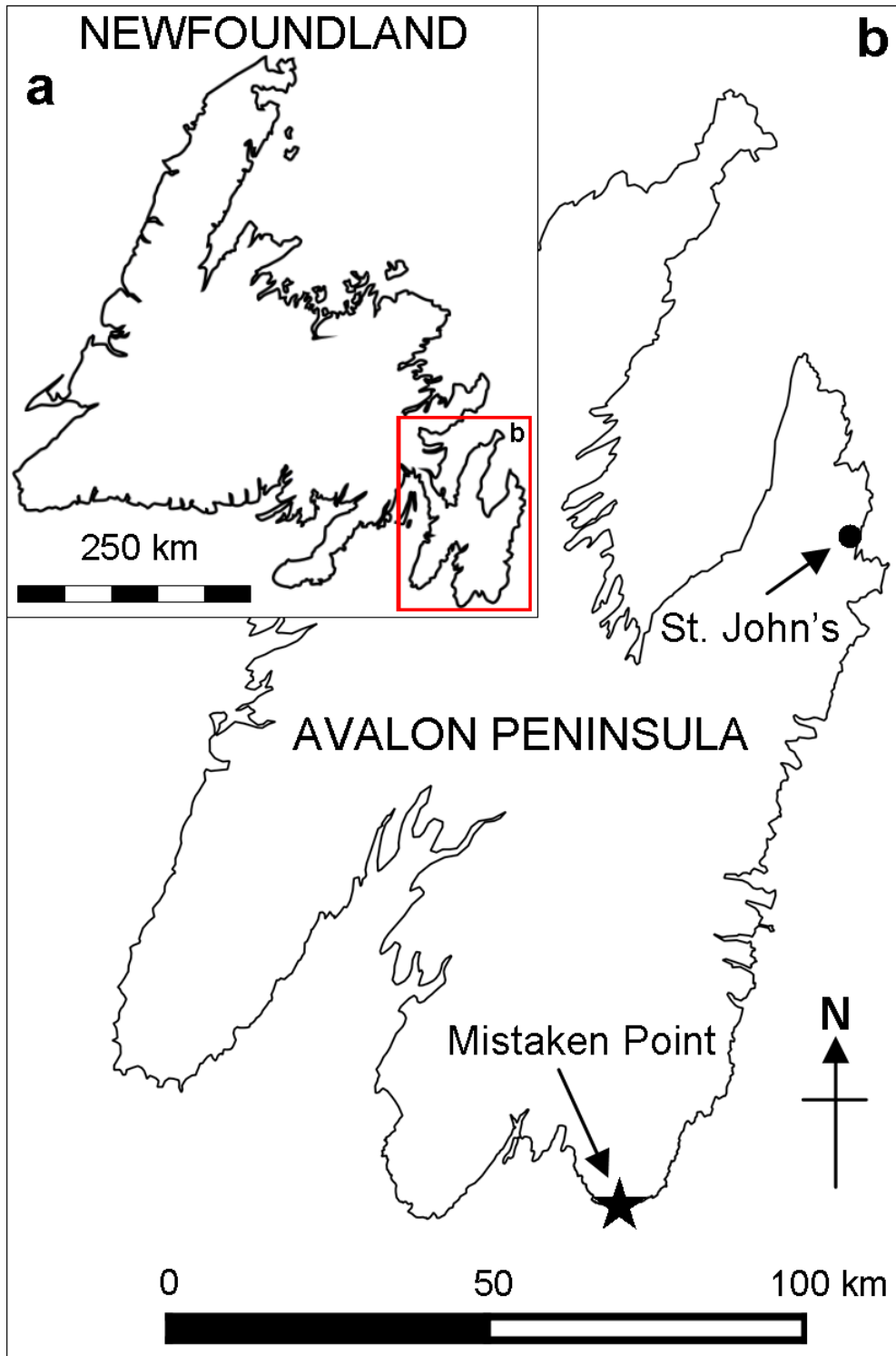


FIGURE 6.1. A) Map of Newfoundland and B) the Avalon Peninsula, showing the location of the Mistaken Point study area.

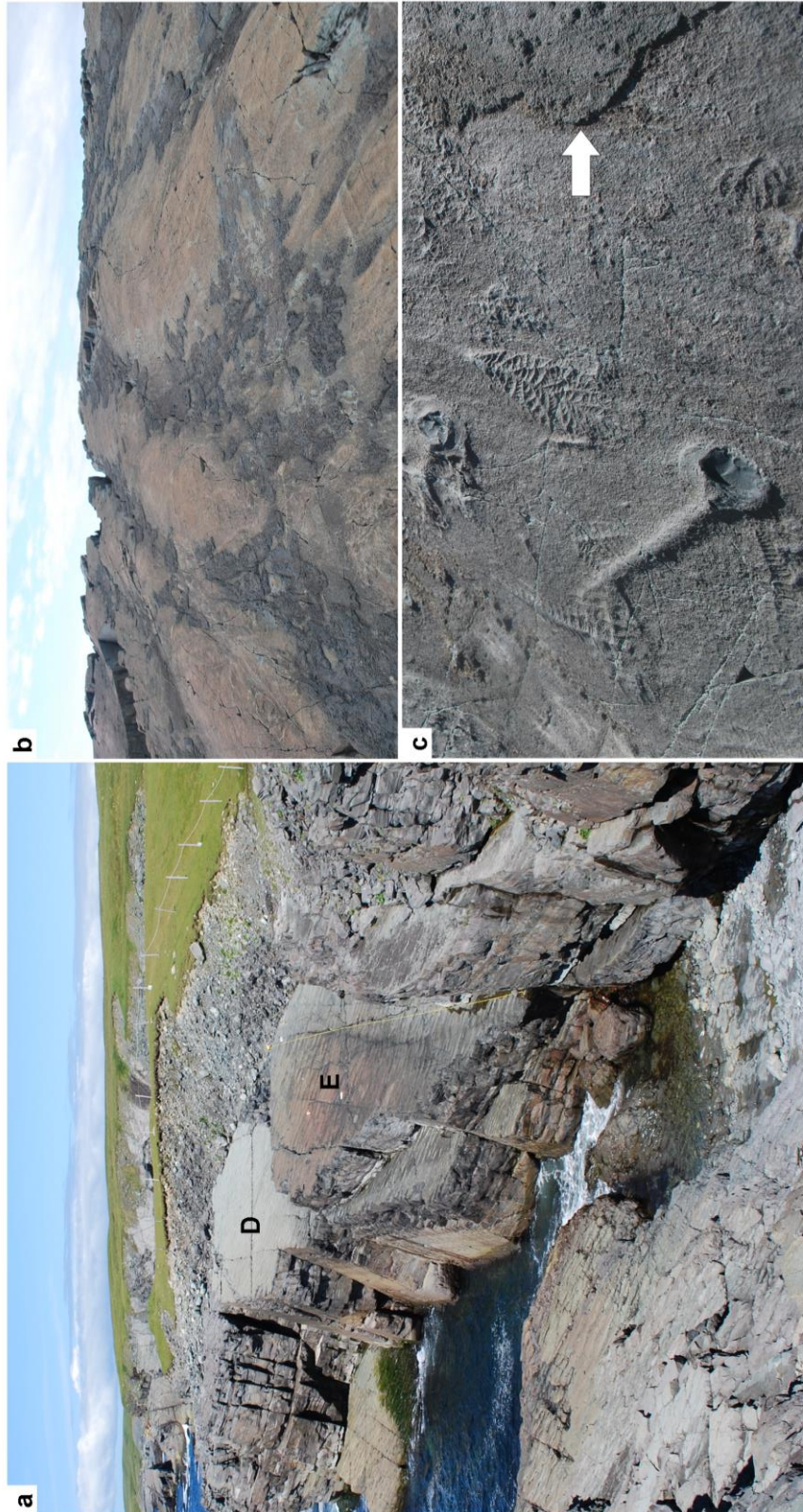


FIGURE 6.2. The Yale outcrop of the 'E' Surface at Mistaken Point. A) Overview of the Mistaken Point Yale locality, looking west. 'E' Surface marked E. 'D' Surface marked D. B) Looking up the trough of a 'tectonic ripple' on the Mistaken Point Yale 'E' Surface. Note how the remaining tuff (black) is largely confined to the topographic troughs. C) Example of fossils on the Mistaken Point Yale 'E' Surface outcrop. Note how the exposed surface is almost completely devoid of tuff, and those areas where tuff remains still retain a complete covering (white arrow).

approximately 20 cm thick (Figure 6.3). Above these tuffites lie a number of silty and sandy turbidites, the most distinctive of which is an approximately 80 cm thick sandstone bed with parallel lamination, rare rounded mudstone clasts, and patchy carbonate cementation. This sandstone bed fines upwards into a ~30 cm thick zone with contorted bedding that is also carbonate cemented in places (Figure 6.3). The contorted bedding is 95 cm below the 'E' Surface (Figure 6.3), and is considered to result from a period of post-depositional dewatering. Above this is a zone of cross-laminated fine-grained sandstone that grades into a purple siltstone, and the entire marker turbidite is topped by a ~2 cm thick mottled olive-green layer. Above the marker turbidite, and directly below the fossil horizon, is a ~15 cm thick bed of green laminated very coarse siltstone that fines upwards through grey-dark purple siltstone into a purple mudstone, which is topped by a ~2 cm thick mottled olive-green layer; the substrate on which organisms preserved on the 'E' Surface resided.

Directly above the 'E' Surface is a ~5 mm thick black, crystal tuff that is widely considered to have cast the fossil assemblage (Seilacher 1992). The crystal tuff is overlain by a ~10 cm thick, green, cleaved, normal-graded grey-green tuffite.

The sub-vertical portions of the contorted bedding in the marker turbidite are preferentially cleaved, probably due to grain sorting during fluid escape. Where the irregularly distributed cleavage within the contorted bed reaches the 'E' Surface, it is observed that it corresponds with undulating troughs on the surfaces (Figure 6.2b). These undulations of bedding, colloquially termed 'tectonic ripples', have previously been interpreted by some as asymmetric wave ripples (Williams & King 1979), but there is no evidence to suggest these undulations are ripples associated with a current or wave action (Wood *et al.* 2003). The black crystal tuff overlying the 'E' Surface is often absent on the crests of the bedding undulations, revealing high fidelity fossil specimens. In contrast, the troughs of the

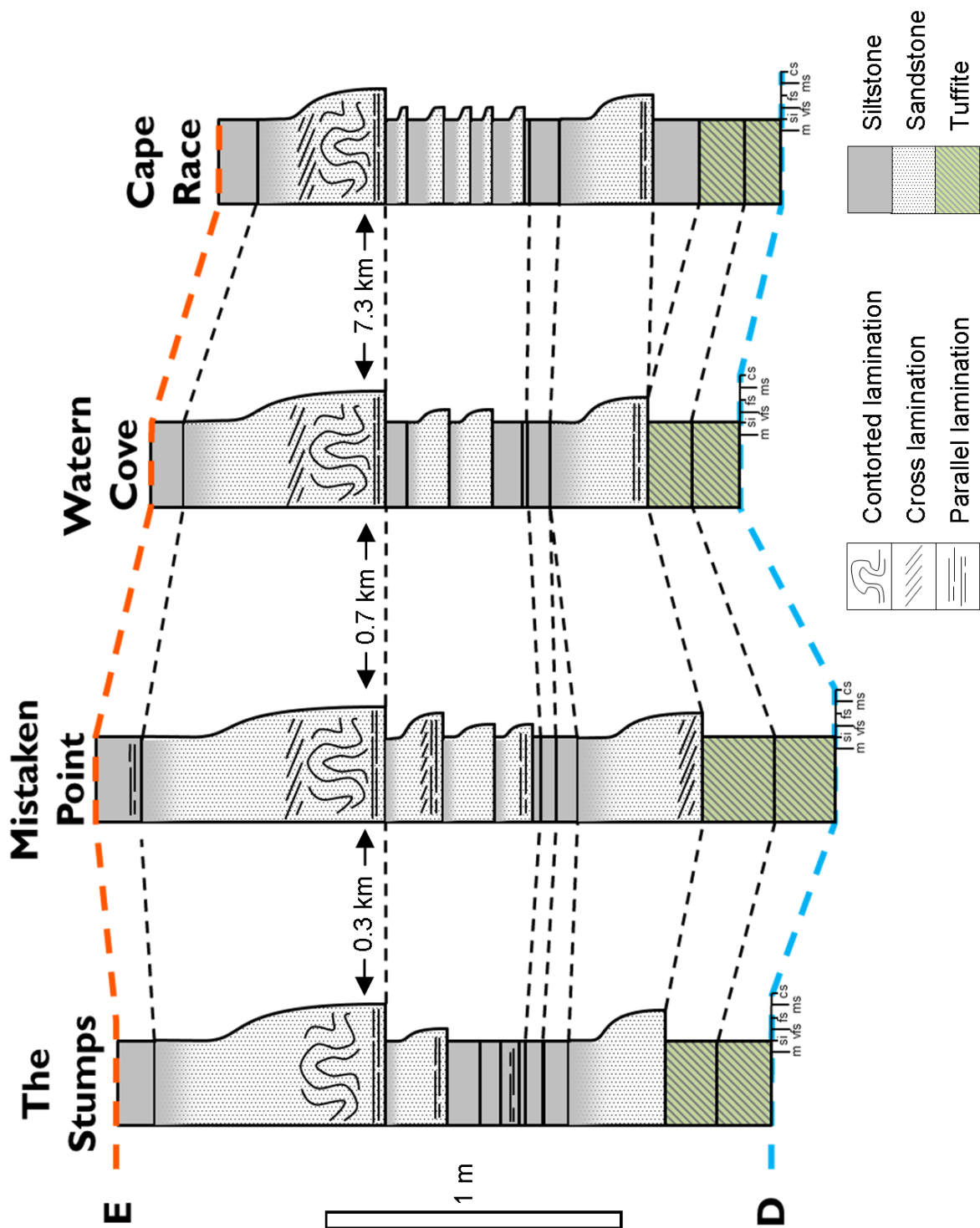


FIGURE 6.3. Detailed sedimentology of the 'D' and 'E' Surfaces, Mistaken Point Formation shown as a simplified graphical section from the 'D' to 'E' surfaces at each of the studied outcrops. The Mistaken Point Yale and Queens outcrops are combined due to their close proximity to each other, as are those at Watern Cove East and West. Scale bar is 1 m.

bedding undulations of the 'E' Surface remain largely covered by crystal tuff, locally prohibiting direct observation of any underlying fossils (Figure 6.2b). Some of the adhered crystal tuff remains at its original ~5 mm thickness, and minute amounts of the overlying grey-green tuffite can be observed on top. Where the crystal tuff remains on the 'E' Surface, the outer edges of these patches may be weakly adherent, and may be plucked off due to mechanical action to reveal a pristine fossil surface (Figure 6.2c).

### **Newly identified 'E' Surface outcrops**

The distinctive stratigraphic succession between the 'D' and 'E' surfaces outlined above has permitted recognition and correlation of those surfaces within the MPER and as far East as Cape Race (Figure 6.4). In particular, the black 5 mm thick chloritic crystal tuff that overlies the 'E' Surface is highly distinctive in having coarse-grained white and pink feldspar phenocrysts, permitting confident field recognition of the 'E' Surface horizon itself. The 'E' Surface has previously been documented at three localities (Clapham *et al.* 2003), but detailed mapping has revealed four additional localities (Figure 6.4), spanning a modern geographical extent of almost nine kilometres.

The three previously described outcrops of the 'E' Surface are:

- 1) Yale Outcrop – The most often studied, outcrop of the 'E' Surface, 104 m<sup>2</sup> in total areal extent, located on Mistaken Point (Figure 6.2a).
- 2) Queens Outcrop – This outcrop lies down-dip of the Yale surface, from which it is separated by a narrow gully, and is therefore closer to sea level. Most of the 'E' Surface here is only impacted by waves during storm conditions, except for the most southwestern portion located near a small gully, which experiences constant, intense, wave action. Most of the tuff overlying the Queens outcrop has been removed by weathering and abrasion.

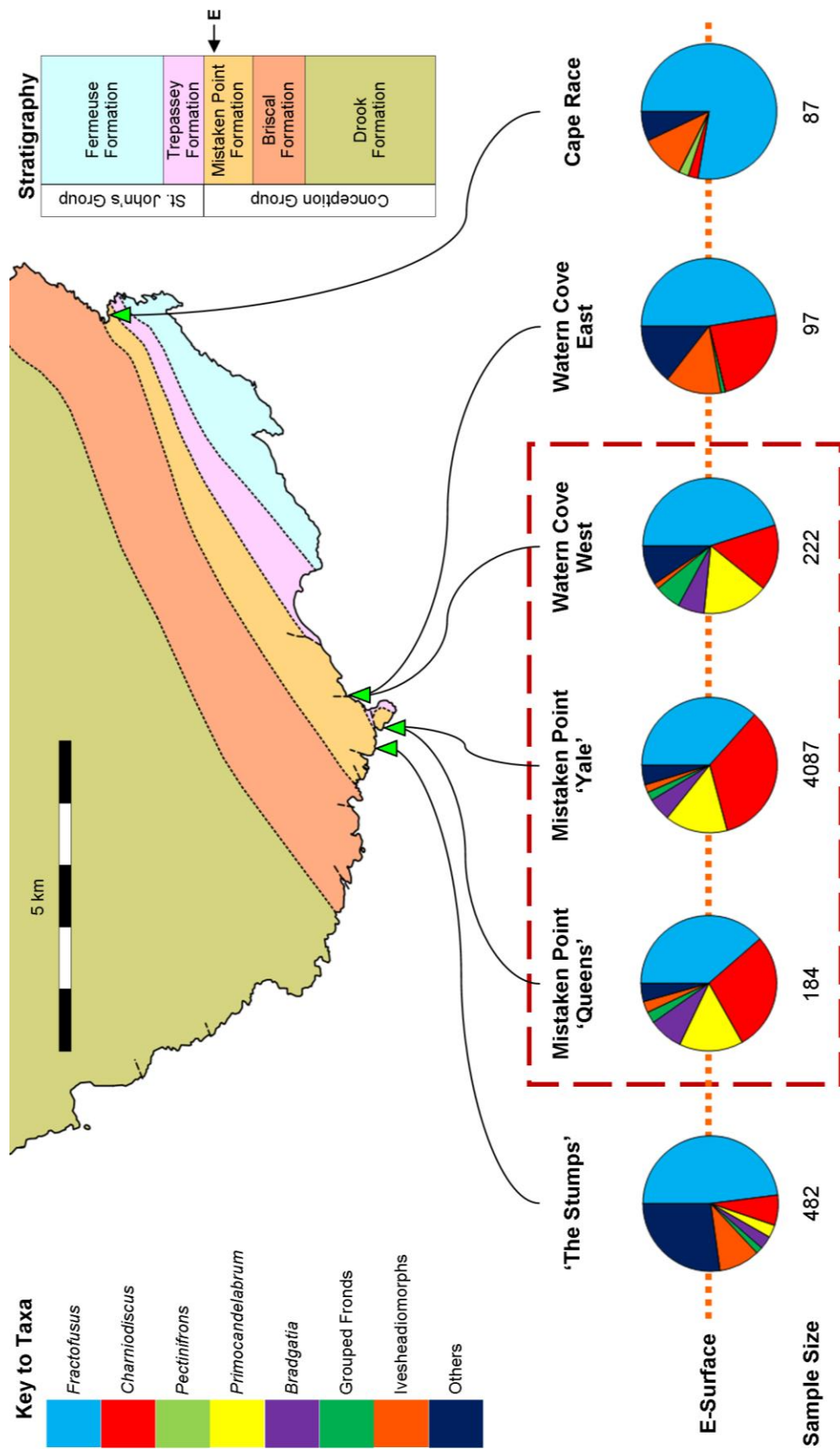


FIGURE 6.4. Comparison of observed fossil assemblages at different outcrops of the 'E' Surface within and around the Mistaken Point Ecological Reserve. Data collected by Clapham *et al.* (2003) are highlighted by the red box. Other data were collected by the authors. Geological map reflects new understanding of field relationships following recent mapping.

3) Watern Cove West – This steeply seaward-dipping outcrop is approximately 18 m<sup>2</sup> (Figure 6.5a), and lies 700 m east of Mistaken Point (see Clapham *et al.* 2003). The crystal tuff at this locality is un-eroded at higher levels, but at sea-level wave action and the presence of shingle has abraded the ‘E’ Surface to the extent that no fossils can be discerned (Figure 6.5b-d). The fine details of many fossils are obscured by the overlying tuff, such that only those taxa that have morphological features with significant positive topographic relief can be discerned in many places.

The four previously undescribed outcrops of the ‘E’ Surface recognized by correlation of fine-scale lithostratigraphy are:

1) Watern Cove East – This 29 m<sup>2</sup> ‘E’ Surface outcrop lies approximately 60 m East of Watern Cove West, and is offset from it by a N-S orientated normal fault with a throw of 1.5 m. The Watern Cove East outcrop is coastline-parallel (Figure 6.6a), and only experiences significant wave action at its western margin. Most of the ‘E’ Surface at this locality is still covered in crystal tuff, so much so that fossils are generally not exposed (Figure 6.6b).

2) Laurentian Gulch – An approximately 3 m<sup>2</sup>, highly cleaved and fractured outcrop of the ‘E’ Surface was found 150 m northwest of Mistaken Point, adjacent to a large fault in Laurentian Gulch. Only a few poorly preserved *Fractofusus* were observed at this locality, and it is of little use for palaeontological study.

3) The Stumps – This new locality is >150 m<sup>2</sup> in area, approximately 330 m northwest of the Yale Outcrop (Figure 6.4), and comprises three outcrops of the ‘D’ and ‘E’ surfaces, separated by minor faults with throws of approximately 2 m. The 36 m<sup>2</sup> of cleaved fossiliferous ‘E’ Surface on the seaward-most outcrop is very steeply dipping at the top. Portions of the outcrop furthest from the sea remain covered by the 5 mm thick layer of the

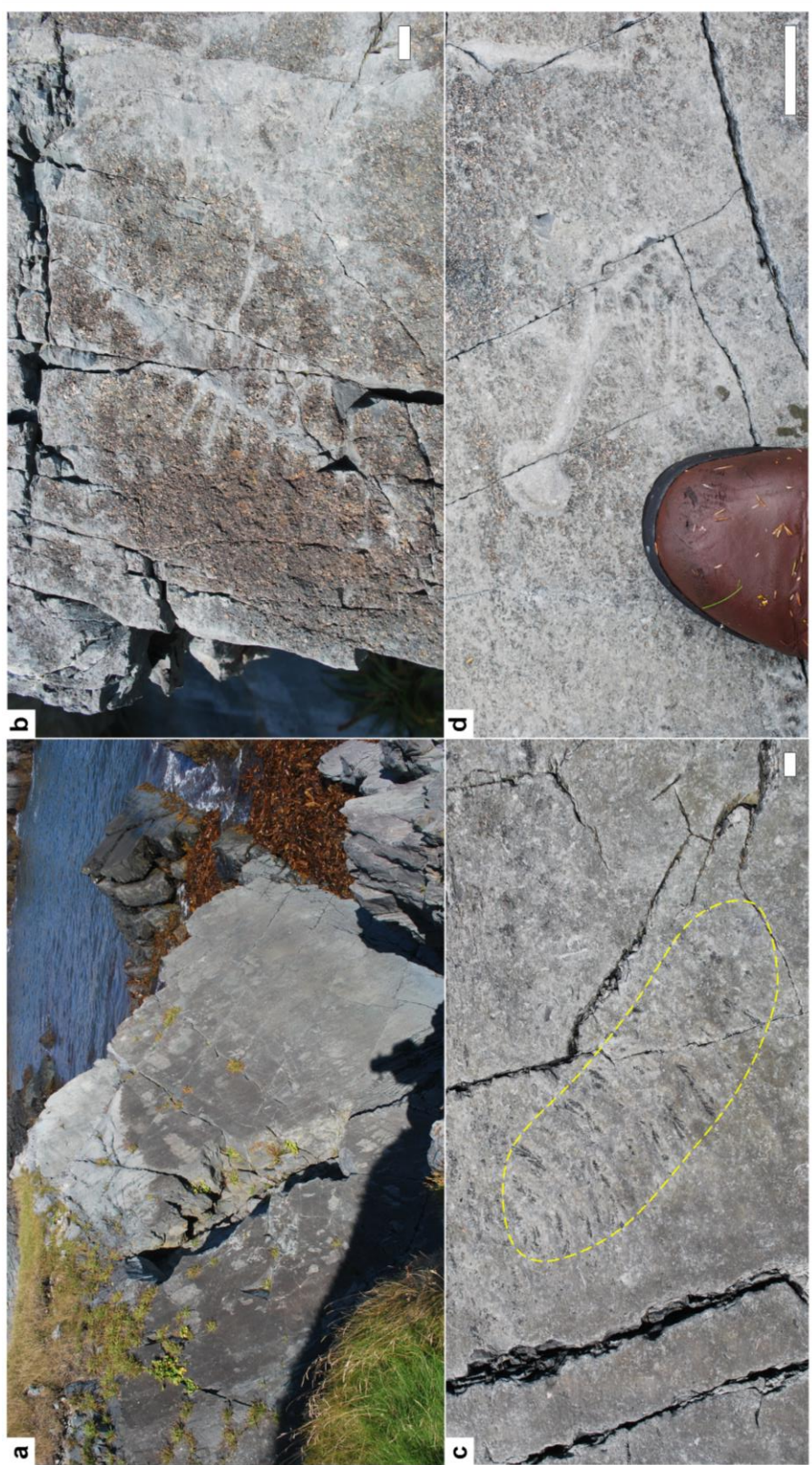


FIGURE 6.5. The 'E' Surface at Watn Cove West. A) Overview of the outcrop, looking sub-parallel to strike into Watn Cove. B) Example of *Fractofusus*, with prominent high epirelief features slightly eroded, while finer negative epirelief elements remain masked by the crystal tuff. Scale bar = 10 mm. C) Another example of *Fractofusus*, near the bottom of the surface. Only those elements preserved in negative epirelief are still visible. The outline of the specimen is highlighted by the dashed yellow line. Scale bar = 10 mm. D) Example of a heavily abraded *Charniodiscus* specimen. Scale bar = 50 mm.



FIGURE 6.6. The outcrop of the 'E' Surface at Watern Cove East, looking north-east. 'E' Surface marked E. Note geologist for scale.

crystal tuff typical of the 'E' Surface. Within the surf zone, the 'E' Surface is wave-polished, with variable thicknesses of tuff remaining, and fossil fidelity is generally poor. Strongly positive morphological features have been eroded, and those portions of fossils preserved in negative epirelief are generally tuff-filled (Figure 6.7). Some high quality preservation does exist between these end members.

4) Cape Race – This is the first documentation of the 'E' Surface beyond the Mistaken Point Ecological Reserve, approximately 8 km north-northeast of Mistaken Point (Figure 6.4). The beds here are very steeply dipping, and those in the surf zone are highly abraded. The 'D' and 'E' surfaces are recognisable as notches in the outcrop caused by preferential weathering and erosion of the tuffaceous horizons that overlie the fossiliferous surfaces (Figure 6.8a). The 6 m<sup>2</sup> outcrop of the 'E' Surface is rarely more than 1 m wide, and is laterally continuous for approximately 25 m. The steeply dipping bedding surface receives little direct sunlight, and is covered by algae, making photography and field observation of fossils particularly difficult (Figure 6.8b).

It is noted that the undulation of the surface at the Yale and Queens outcrops (Figure 6.2a–b) is barely evident 700 m away at Watern Cove (Figure 6.5a), and is absent at Cape Race (Figure 6.8a). This is consistent with the presence the undulations being a result of localized tectonic action rather than representing sedimentary features of the 'E' Surface.

### **Fossil Census Study**

Recognition of multiple outcrops of the 'D' and 'E' surfaces offers a unique opportunity to explore the degree of continuity of a fossil assemblage on a single fossilized seafloor over a large (several kilometre) lateral extent. To my knowledge, this is the first time an Ediacaran fossil-bearing surface has been recognized over such a distance, potentially allowing exploration of changes in community composition, sedimentation, and ecosystem



FIGURE 6.7. The outcrop of the 'E' Surface at The Stumps, showing an example of the surface close to high-tide mark. Note the *Charniodiscus* with holdfast disc and stem heavily abraded and its frond barely visible (white arrow), and a *Fractofusus* with high portions exposed through partial abrasion of the tuff, while finer-detail elements remain obscured by the remaining tuff (black arrow). Scale bar = 10 cm.

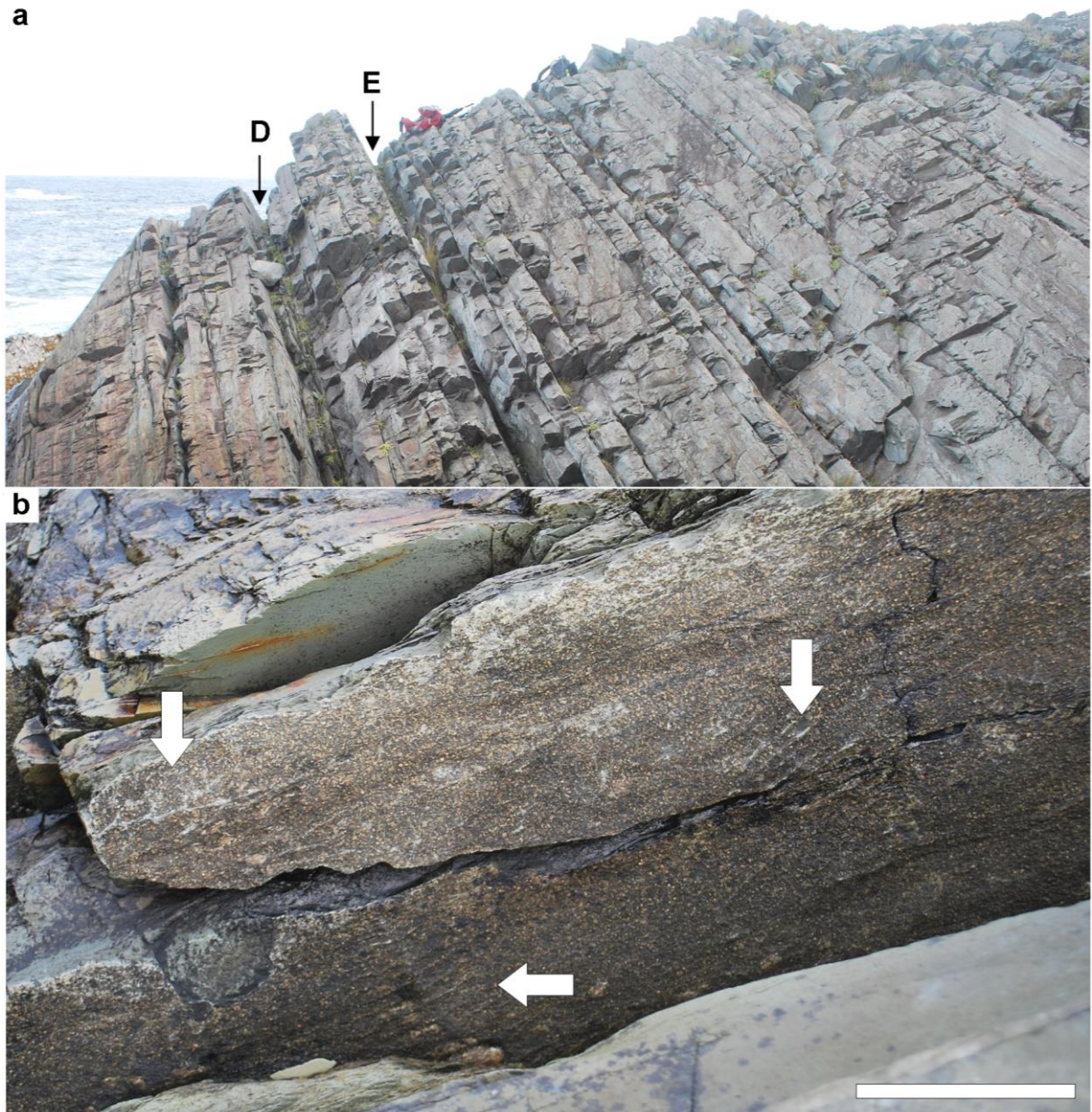


FIGURE 6.8. The outcrop of the 'E' Surface at Cape Race. A) Overview of the locality. 'E' Surface marked E. 'D' Surface marked D. Distance between the 'D' and 'E' surfaces is 1.85 m. B) Example of 'E' Surface at Cape Race. Note also *Fractofusus* specimens beginning to be exposed (white arrows), while finer-detail elements remain obscured by remaining tuff. Scale bar = 10 cm.

dynamics on a broad scale. Fossil census data from six outcrop localities of the ‘E’ Surface will now be compared, and the possible controls on the observed variability in community composition considered.

This study combines new data from The Stumps, Watern Cove East, and Cape Race localities with pre-existing species occurrence data from the Yale, Queens and Watern Cove West localities from a published dataset (Clapham *et al.*, 2003; Clapham 2011). The fossil assemblages were chosen to be assessed at generic level to minimize introduction of errors associated with species identification of poorly preserved specimens, and to maximize compatibility between this work and the pre-existing datasets. Because the previous work was undertaken before the formal description of many of the macrofossil taxa from the Conception Group (cf. Liu *et al.* 2015b), use of these datasets requires consideration of how to deal with early informal descriptors (Clapham *et al.* 2003), and their connection to modern formal generic diagnoses (Table 6.1).

<b>Clapham (2003) Nomenclature</b>	<b>Current Nomenclature</b>
“Dusters”	<i>Primocandelabrum</i> (Hofmann <i>et al.</i> 2008)
“Pectinate”	<i>Pectinifrons</i> (Bamforth <i>et al.</i> 2008)
“Spindle”	<i>Fractofusus misrai</i> and <i>F. andersoni</i> (Gehling & Narbonne 2007)
“Triangle”	<i>Thectardis</i> (Clapham <i>et al.</i> 2004)
“Network”	<i>Hapsidophyllas</i> (Bamforth & Narbonne 2009)
“Charniodiscus”	<i>Charniodiscus spinosus</i> and <i>C. procerus</i> (Laflamme <i>et al.</i> 2007)
“Ivesia”	Ivesheadiomorphs (Liu <i>et al.</i> 2011)
“ <i>Charnia</i> Type A”	<i>Charnia</i> , <i>Vinlandia</i> , some <i>Beothukis</i> = Grouped Fronds
“ <i>Charnia</i> Type B”	<i>Trepassia</i> , most <i>Beothukis</i> = Grouped Fronds
“Lobate Discs”	Others
“Spoon frond”	Others

TABLE 6.1. Correspondence between previous informal descriptive names (Clapham *et al.* 2003) and recent taxonomic diagnoses. The ivesheadiomorphs are considered to be the decayed remains of other organisms (Liu *et al.* 2011). Taxonomy of *Beothukis* detailed in Liu *et al.* (2016), while that of other Grouped Fronds is discussed in Brasier *et al.* (2012).

Most of the groupings used in the Clapham datasets are directly applicable to current taxonomic groups. However, consideration of some taxa remains problematic, particularly “*Charnia* Type A” and “*Charnia* Type B” of Clapham *et al.* (2003). “*Charnia* Type A” as identified in that study included specimens now assigned to *Charnia masoni* (Ford 1958), *Vinlandia antecedens* (Laflamme *et al.* 2007; Brasier *et al.* 2012), and *Beothukis mistakensis* (Brasier & Antcliffe 2009). “*Charnia* Type B” included *Trepassia* (previously *Charnia*) *wardae* (Narbonne *et al.* 2009), and *Beothukis* (formerly *Culmofrons*) *plumosa* (Laflamme *et al.* 2012; Liu *et al.* 2016). Additionally, some *Beothukis plumosa* were considered “*Charnia* Type A” rather than “*Charnia* Type B” (Clapham *et al.* 2003; Laflamme *et al.* 2012). Since these taxonomic revisions are difficult to disentangle in the original dataset, *Beothukis*, *Vinlandia*, *Trepassia*, and *Charnia* are, for the purposes of this comparative study, combined as “Grouped Fronds” (Table 6.1), allowing for the direct comparison of these new data with the data of Clapham *et al.* (2003). It is recognised that the artificial grouping “Grouped Fronds” is of limited relevance to taxon-specific palaeoecological studies, but it may prove informative when considering ecological parameters such as tiering at a community scale (cf. Clapham & Narbonne, 2002). The only remaining fossil not encompassed by formal genera or the “grouped fronds” is the “Spoon Frond” (Clapham *et al.* 2003). It is likely that this morphotype is a *Charniodiscus*, but since this taxon is a rare component (<0.6%) of the total community (Clapham 2011), it is not considered that this adversely affect these results.

These taxonomic discussions lead to us organize taxa into the following groupings:

*Fractofusus*, *Charniodiscus*, *Pectinifrons*, *Primocandelabrum*, *Bradgatia*, Grouped Fronds, Ivesheadiomorphs, and Others. Datasets for the Yale, Queens and Watern Cove West localities (Clapham *et al.* 2003) were collected from sub-sections of the total areal extent, as described in that publication. On Watern Cove East, Cape Race and the Stumps

census data was only recorded from accessible regions on the bedding planes (see Table 6.2). In all cases at new sites, each identified fossil was marked with a temporary plasticine marker to ensure it was not counted multiple times.

### Spatial variability in ‘E’ Surface fossil assemblages

The studied area, total number of specimens, and fossil densities for each of the studied surfaces are presented in Table 6.2. Overall fossil abundances and fossil densities (i.e. individual fossils per square metres) are found to be highly variable at the different sites.

Outcrop	Studied surface area (m <sup>2</sup> )	Specimens	Fossil Density (fossils/m <sup>2</sup> )
The Stumps	36	482	13.2
Mistaken Point Queens	3	184	56.5
Mistaken Point Yale	104	4087	39.0
Watern Cove West	7	222	31.9
Watern Cove East	29	97	3.3
Cape Race	6	87	14.5

TABLE 6.2. Summary of the studied surface area, fossil abundance and fossil density for all studied outcrops of the ‘E’ Surface.

Fossil census data for the ‘E’ Surface at the Queens, Yale, The Stumps, Watern Cove West, Watern Cove East, and Cape Race outcrops show that *Fractofusus* is the dominant taxon at all the localities, comprising between 36 and 75% of the measured populations (Figure 6.4). At the Yale outcrop *Charniodiscus* forms a significant portion of the biota but its relative abundance varies significantly from 2.3% to 34.2 % across the studied sites (Figure 6.4). *Primocandelabrum* is interestingly only found at the closely spaced Queens, Yale and Watern Cove West localities, and comprises between 0–15.8 % of the studied assemblages (Figure 6.4). Ivesheadiomorphs, inferred to be the decayed, microbially colonized and modified remnants of dead Ediacaran organisms, are considered by us to be necromass rather than part of the standing crop (Liu *et al.* 2011, 2015b). It is interesting to note that they form a significant component of the fossil assemblage at The Stumps,

Watern Cove East, and Cape Race, but are a relatively minor component of the biota on the Queens, Yale and Watern Cove West outcrops, constituting between 1.4 % and 13.4 % of the population. This phenomenon may reflect patchiness in the distribution of the pioneer colonizers of the 'E' Surface, but it requires explanation since there is no obvious reason why there should be spatially uneven rates of mortality (Figure 6.4). The Cape Race locality is the only outcrop of the 'E' Surface to contain examples of *Pectinifrons*, where it comprises 2.3% of the measured population.

### **Potential biases in census data from the 'E' Surface**

Differences are observed in the relative abundance of taxa from outcrop to outcrop (Table 6.2, Figure 6.4). This may partially reflect original variability within the fossil assemblage, for example variability in community composition related to depth, nutrient flux, regularity of disturbance, or distance offshore. However, before exploring these possibilities, potential non-biological explanations for this variability should first be considered to ensure that apparent patterns in the dataset are correctly interpreted.

The fossilization processes from biostratinomy through to lithification and diagenesis are familiar to palaeontologists, and are routinely included within taphonomy, and incorporated into quantitative palaeontological studies (Allison & Bottjer 2011). Some definitions of taphonomy consider tectonic, metamorphic, weathering, and erosional processes that may influence the fossil record (e.g. Lawrence 1968; Rolfe & Brett 1969; Valentine 1973; Behrensmeyer & Kidwell 1985), but this is far from the norm, and a diverse series of post-diagenetic processes are often overlooked by most palaeontologists. For clarity, the processes associated with metamorphism, tectonics, erosion, weathering and diagenesis are herein termed post-fossilization processes.

### *Observational and interpretational biases*

There is a noticeable difference between the proportion of the ‘E’ Surface population recognized as ivesheadiomorphs and *Primocandelabrum* between the older assemblage data (Clapham *et al.* 2003) and the data presented herein (Figure 6.4). This may result from a change in opinions regarding the nature of ivesheadiomorphs, since the recent suggestion that they reflect a heterogeneous grouping of partly decayed remains of a range of taxa (Liu *et al.* 2011) recognises a continuum between pristinely preserved fossils and the decayed remnants of the same taxa that would be recognized by all authors as ivesheadiomorphs. In the middle-ground between these end-members, biases of field practice might influence datasets collected at different times by different researchers. Human bias is less likely to explain the variability in the relative abundance of *Fractofusus*— a genus that is comparatively difficult to misdiagnose due to its highly distinctive zigzag midline, and a morphology that tapers at both ends (Gehling & Narbonne 2007). As such, some of the variability in the fossil assemblages cannot simply be due to different historical field practices.

While researchers may disagree on the taxonomic affinity of any given specimen, there is rarely disagreement that impressions on the ‘E’ Surface are indeed fossils. Yet there is considerable variation in measured fossil density, from 3.3 to 56.5 individuals per square metre across the studied area (Table 6.2). This variance could represent patchiness in the distribution of organisms on the Ediacaran seafloor, but possible abiogenic explanations require consideration.

### *Fossilization bias*

Although variation in sedimentology, particularly of the overlying bed, can be quite marked amongst different Ediacaran fossil-bearing horizons in Newfoundland (Liu 2016),

all studied outcrops of the 'E' Surface consistently overlie a mottled silty mudstone, and are overlain by a tuff that shows little lateral variation in mineralogy or grain-size on the scale of this study. The crystal tuff is inferred to have rapidly smothered the entire seafloor recorded by the various 'E' Surface outcrops (Seilacher 1992). The processes of sedimentation, decay and casting by a microbially-induced sulfidic 'death mask' (cf. Gehling 1999) are therefore considered to have been consistent across all outcrops of the 'E' Surface (though note the anomalous absence of a mineralized veneer on the 'E' Surface; Liu 2016). On the spatial scale of the collected data, any observed variation in preservational quality or assemblage composition is thus unlikely to reflect variability in biostratigraphy or taphonomy between the studied sites.

*Biases introduced by ambient conditions and bed aspect*

Ediacaran fossils in Newfoundland are usually impressions cast in low positive or negative epirelief, and are therefore best studied under low-angle lighting. Since the use of artificial lighting is often not practical in the field, ambient meteorological conditions can significantly impact the observation of fossils. The strike and dip of a bed, the time of day it is studied, and the calendar date combine to determine the angle at which sunlight strikes a fossil horizon, and affect how, and even if, fossils can be observed. The Laurentian Gulch outcrop, for example, never experiences favourable lighting due to its position in the cliff face and its small spatial extent, and as such it would be unlikely to reveal many fossils even if they were not also badly affected by mechanical fracturing. In contrast, other localities in the MPER experience good to optimal lighting conditions at different times throughout the day. For example, the Yale outcrop is best viewed in the late afternoon.

The tectonic processes responsible for determining the varying strikes and dips of beds observed today, combined with the time and date a bed is observed, thus influence the likelihood of discovery of new fossils and fossiliferous surfaces. Regulations governing field activities within the MPER forbid collection of fossils, so casting of specimens, under permit, is vital as a field technique to enable replicas of the surfaces to be studied under controlled lighting conditions in the laboratory (e.g. Liu *et al.* this volume). Although every effort was made to observe the studied outcrops under optimum lighting conditions, variation in weather conditions may feasibly have introduced an observation bias into the dataset, since the smallest and lowest relief specimens are less likely to be observed in poor lighting conditions.

#### *Erosion and weathering.*

Although most factors relating to observation, interpretation and original taphonomy and fossilization can be ruled out when attempting to determine the controls on observed variability between 'E' Surface fossil assemblages, before interpreting these patterns as reflecting original biology or ecology, modern weathering and erosion must be considered. There are, in general, four states in which 'E' Surface exposures can be found, which may be found in isolation or in combination at individual outcrop localities:

- 1) Covered by the full (approximately 5 mm) thickness of the crystal tuff of the over-bed. No fossils are exposed.
- 2) With little to no overlying tuff present on the surface, resulting in the exposure of all fossils present.
- 3) Exhibiting partial erosion of the crystal tuff, resulting in only high positive epirelief elements of fossils protruding through the remaining tuff. In such instances the original fossil assemblage can only be partially documented.

- 4) Where the surface has been worn smooth such that all tuff has been removed, and fossils are either of poor quality, or absent.

These four states can be explained by the action of two major mechanisms by which the crystal tuff is weathered and eroded from the 'E' Surface (Figure 6.9). First, prominent spalling processes completely remove discrete chips of the ~5 mm thick crystal tuff, which can leave a surface with no remaining tuffaceous material to obscure the fossils (Figure 6.9f, l-n). Spalling is dominant on outcrops with a low angle of dip close to the ocean, such as the Yale outcrop of the 'E' Surface, where it is evident particularly on the crests of tectonic undulations (e.g. Figure 6.2b). The exact mechanism by which the crystal tuff detaches from the fossil surface is unclear, but might include frost action and/or the pressure effects associated with salt-crystal growth (Wellman & Wilson 1965).

The second process is progressive abrasion of the crystal tuff, which is typically observed at outcrops where the surface is at or near sea level, such as the Watern Cove West surface (Figure 6.5, 6.9f-j). As this process of erosion acts upon the 'E' surface bedding plane, the most positive epirelief features of fossil specimens on the surface begin to be polished away, while the lowest relief – often most highly detailed – features remain covered in crystal tuff (Figure 6.5). Abrasion may be the product of erosion caused by the mechanical action of sediment-bearing waves and surface run-off, rock-falls and scree flows, as well as footwear. Abrasion due to wave action often results in surfaces with pristine coverings of complete tuff well-above sea level, but with a progressively more highly abraded surface towards sea level (Figure 6.5a). Abrasion is the major process that removes the overlying tuff from the 'E' Surface at The Stumps, Watern Cove East, and Cape Race

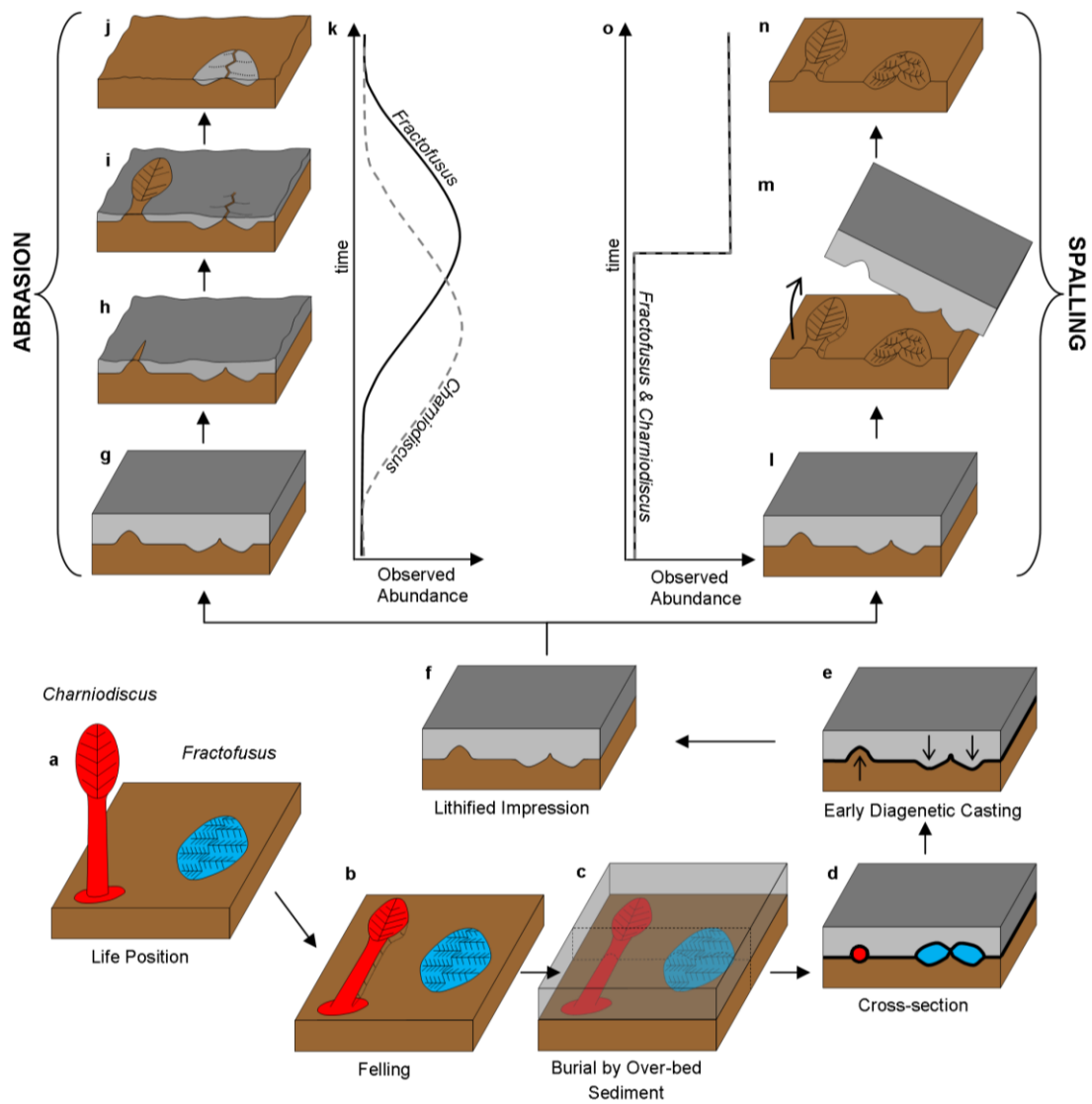


FIGURE 6.9. Block diagram showing the process of preserving a *Charniodiscus* (red) and a *Fractofusus* (blue) specimen, and the effects of both abrasion and spalling exposure Post-Fossilization Processes on the observed community. Fossil surface substrate in brown, overlying volcanogenic material in grey. A) Organisms in life position. B) Organisms toppled immediately prior to burial. C) Specimens buried by volcanogenic material, shown partly transparent here. D) Section through (A) showing the organisms pre-decomposition, and the formation of a mineralized veneer around all organic matter (cf. Liu 2016). E) Following decomposition, the underlying substrate moves upwards to meet the cast and preserve the upper surface of *Charniodiscus*, while the overlying ashy layer falls in to meet the cast and preserve the lower surface of *Fractofusus* (sensu Gehling, 1999). F) Final section through preserved specimens pre-exhumation. G-H) Beginning of abrasion of overlying ashy-layer, first partially exposing the positively preserved *Charniodiscus* stem while leaving *Fractofusus* concealed. I) Abrasion continues, and while abrading away the *Charniodiscus*, the central axis of the *Fractofusus* specimen is revealed. J) *Fractofusus* specimen, preserved largely in negative hyporelief, remains visible even when *Charniodiscus* has been abraded away. K) Graph showing the observed abundance of each taxa throughout the abrasion process. L-M) Spalling of the overlying ashy layer from the fossil surface. N) Example of fossil surface, exposed by spalling process. O) Graph showing the observed abundance of each taxa throughout the spalling process.

outcrops (Figures 6.6–6.8). Additional abrasion and erosion may result from the passage of feet on the Yale outcrop, and projects are underway to quantify the impact of such anthropogenic activity.

## **IMPLICATIONS OF POST-FOSSILIZATION PROCESSES FOR PALAEOECOLOGICAL STUDIES**

Since weathering and erosional processes differ in the degree to which they expose or erode fossils at different outcrops (and even on individual outcrops), they provide a first order bias on observed fossil assemblages (Figure 6.9). Where spalling processes are the dominant means by which the ‘E’ Surface is exposed, the bedding plane and its fossils are either fully concealed by tuff, or completely exposed (Figure 6.9o). On the Yale outcrop where the majority of the fossil surface is exposed, statistical analysis of the fossil population suggests that the presence of regions still covered by tuff does not greatly bias data relating to the abundance and distribution of the fossil assemblage (Mitchell *et al.* 2015). In contrast, where abrasion is active, comparatively small amounts of abrasion of the crystal tuff might be expected to result in a situation where high relief fossils (e.g. *Charniodiscus*) are over-represented within observed assemblages (Figure 6.9h, k). In contrast, increased abrasion (but not quite to the level of the under-bed) will increase the proportion of low-relief *Fractofusus* observed in the assemblage (Figure 6.9i, k).

Progressive abrasion down to and below the underlying bed is expected to result in positive epirelief fossils being completely removed, while fossils preserved in negative epirelief (e.g. *Fractofusus*) are predicted to become over-represented with respect to the original population (Figure 6.9j-k). The effects of abrasion are dominant on the ‘E’ Surface outcrops at The Stumps, Watern Cove West, Watern Cove East, and Cape Race (Figures 6.5–6.8). Fossil assemblages at those localities do indeed possess a larger proportion of *Fractofusus* than is seen at the (spalling dominated) Yale and Queens outcrops (Figure

6.4). Furthermore, these abrasion-dominated localities exhibit fossil assemblages with smaller proportions of taxa preserved in positive epirelief, such as *Charniodiscus*, than are observed at the Yale and Queens outcrops (Figures 6.4).

It is important to note that in the abrasion model proposed herein, there is only one point at which the proportion of taxa observed in positive and negative epirelief will be a broadly accurate representation of the 'E' Surface assemblage (Figures 6.9k). This is in contrast to the spalling model, which does not impart a significant temporal post-fossilisation bias to the composition of the 'E' Surface assemblage, so long as a significant portion of the bedding plane is exposed for study (Figures 6.9o). An additional bias is introduced when considering the size of Ediacaran organisms on surfaces prone to abrasion. The size of Ediacaran fossils commonly correlates with the maximum topographic height of their positive epirelief impressions. As such, localities dominated by abrasion processes may reveal individuals of different topographic height only following specific degrees of abrasion, such that certain components of the assemblage may not be recorded depending on how far abrasion has progressed. This effect may potentially impact studies examining the life cycle and reproduction of Ediacaran organisms (e.g. Mitchell *et al.* 2015), since fossil organisms of different size—that may relate to a different generation within the population—will be differentially represented through the abrasion process.

Fossil census data, specifically the proportions of various taxa comprising the observed population, have been used to argue for ecological succession within the MPER assemblages (Clapham *et al.* 2003). On the basis of data from multiple surfaces, it has been postulated that the pioneer colonizers of the seafloor surface would be dominated by reclining forms such as *Fractofusus*, and that as the community matured it would become progressively more tiered, with taxa such as *Charniodiscus* and *Primocandelabrum* comprising a larger percentage of the population (Clapham *et al.* 2003). If metrics such as

the *Fractofusus* to *Charniodiscus* ratio within a documented assemblage can be dependent upon the extent of post-fossilization processes such as weathering and erosion, as suggested herein, then such palaeoecological inferences based on assemblage data may be premature. It is advised that future work assessing the palaeoecology of Ediacaran benthic communities: a) considers the possible influence of spalling, abrasion, and other post-fossilisation processes on the collected datasets; b) wherever possible restricts comparisons between populations to surfaces that have undergone similar post-fossilization processes, in order to compare like with like, and; c) where possible, restricts studies to surfaces that have undergone extensive spalling-dominated weathering, which is most likely to reveal faithful representations of the original biotic community.

#### **EFFECTS OF SPALLING AND ABRASION ON FOSSIL MORPHOLOGY**

The manner in which fossils are exposed on a surface by post-fossilization processes may also have significant implications for the morphological characterization of Ediacaran taxa, since it should be anticipated that such effects could be evident at the scale of a single fossil. It is possible that the topography of individual fossils could enhance abrasion, for example by surface run-off, in localized areas. The observed variability in the quality of fossil specimens on a surface has previously been expressed as a measure of their Decay Index (Antcliffe *et al.* 2015) and ascribed to differing amounts of microbial decay prior to burial. However, at least some of the observed differences could be explained through differential post-fossilization processes acting upon individual specimens. The prospect of such small scale abrasion emphasizes the importance of studying multiple specimens from numerous bedding planes when discussing variation amongst individual taxa, and further work to investigate their impact on such studies is required.

## IMPLICATIONS FOR GEOCONSERVATION

While the spalling process is the dominant mechanism of crystal tuff removal on the Mistaken Point 'Yale' and 'Queens' outcrops, some examples of abrasion do exist. These have important impacts, particularly for the conservation of the Mistaken Point Yale outcrop of the E-Surface.

On September 23<sup>rd</sup> 2014, while the Yale outcrop of E-surface was being examined by the author it was struck by an abnormal wave that, having hit the base of the cliff, deposited water over an area of roughly  $\sim 25 \text{ m}^2$  at the most South-Western corner of the outcrop (Figure 6.10A). The sea water proceeded to run-off the crests of the 'tectonic ripples', and then along the strike of the ripple troughs to a point where the crest no longer constrained the flow, and the water ran down dip of the E-Surface. By this process the water was conducted down the surface, flows of various troughs combining, with the majority of the run-off being concentrated into a hollow  $\sim 10 \text{ m}$  down-dip from the access to the E-surface, and  $\sim 3 \text{ m}$  inland of the cliff edge (Figure 6.10 A,B). The hollow is believed to be associated with natural loss of material where cleavages have interacted to produce cracks from which rock has been removed. The hollow is of irregular shape, but no dimension is larger than  $50 \text{ cm}$  (Figure 6.10B).

When the incoming flows had filled the hollow, the water began to overflow from the most down-dip point. Compared to the flows within the troughs, a relatively high velocity current was seen to issue from the hollow. The area of surface on which this current flowed was notable for having fossils where the most prominent parts had been polished away.

The lack of polished fossil specimens on the rest of the Yale outcrop of the E-Surface, and by extension the absence of abrasion processes, is explained by closer consideration of

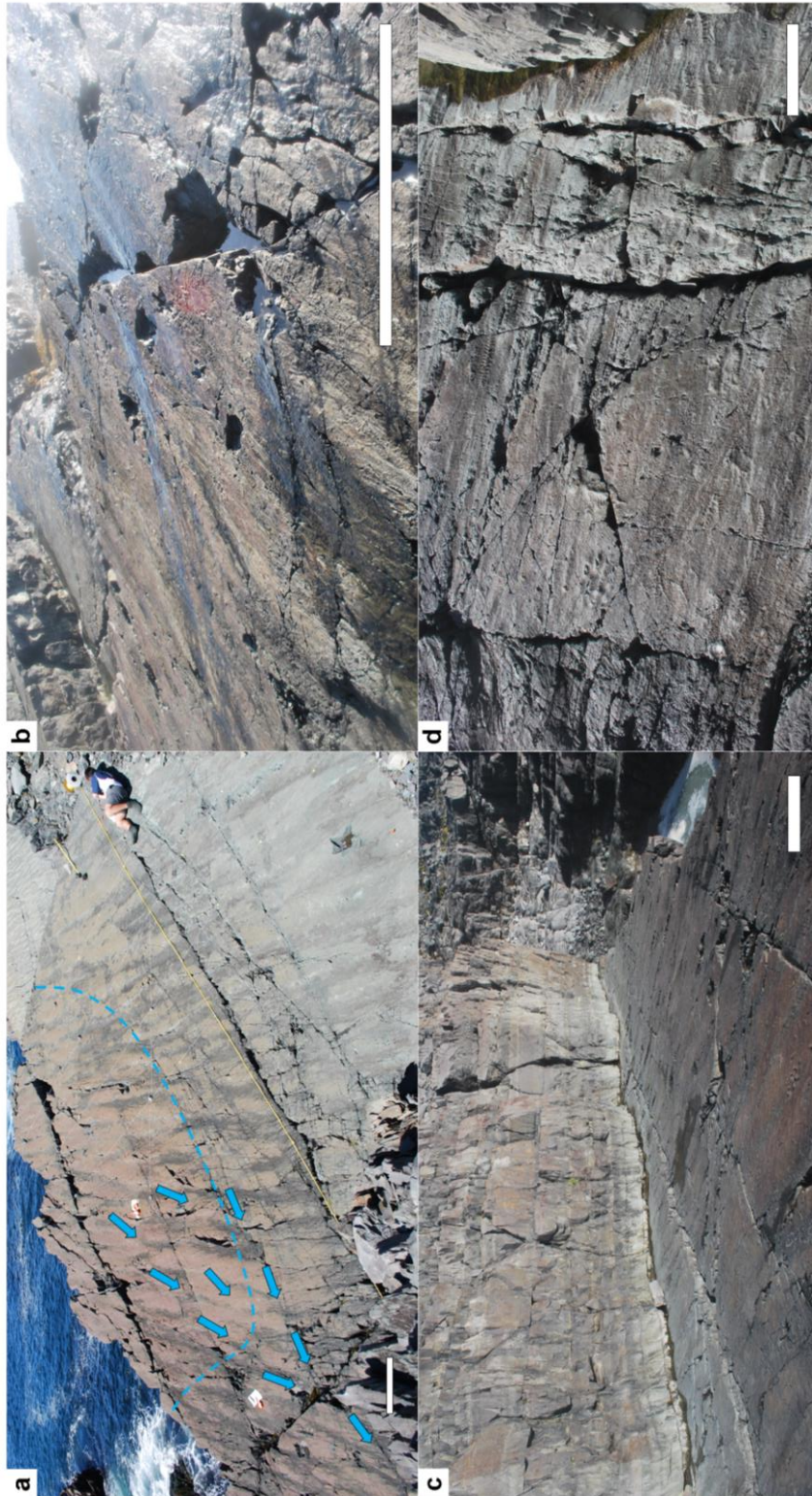


FIGURE 6.10. Mistaken Point 'Yale' E-surface outcrop. A) Photograph looking down upon the surface from 2008, onto which the impact of an anomalous wave from 23/9/2014 has been mapped (blue dashed line). Blue arrows show the various routes taken by flows of water following the splash. The scale bar is 1 m. B) Photograph taken directly after the wave-strike, show the flows mainly converging on a hollow (bottom left of A)), from which a relatively high velocity flow was seen to emanate. Scale bar 1 m. C) Small stream running down length of E-surface. Note large fracture sub-parallel to the flow. Scale bar 1 m. D) Fossils near the stream flow. Those on the opposite side of the fracture to the stream appear to be much less polished than those near the stream. Scale bar 10 cm.

erosion by abrasion. Abrasion is the mechanical erosion caused by the load of a flow impacting the surface over which the flow is traveling. The rate of erosion is dependent on the kinetic energy flux to the surface, and the susceptibility of the rock, and is roughly proportional to the velocity of the flowing water to the power of 5 (Hancock et al., 1998). Due to the effects of the boundary layer, where flow velocity approaches zero next to the rock face, the particle must detach itself from the flow, if it is to impact and erode the surface. Because of this, it is often the case that a velocity threshold will need to be exceeded before abrasion can begin.

In the case of the Mistaken Point 'Yale' E-surface, it is suggested that the water flowing off the crests does so relatively slowly, and most likely via planar flow – lacking the velocity to allow any minor particles carried in the flow to abrade the surface. However, as the water begins to accumulate, flow velocities would necessarily increase, and a change from planar to turbulent flow may occur. This regime is much more conducive to the abrasion of the surface, and explains why abrasion is seen in those areas where flows are confined, such as down-dip of hollows.

A similar area of abrasion is observed at the northeastern end of the Yale outcrop of the E-Surface. Looking down-dip from the topographically highest point on the E-surface, about one third of the way down a small stream runs onto the surface, and then along the base of small cliff (Figure 6.10C). The fossils over which the stream flows are abraded, in a manner comparable to those described from down-dip of the hollow. All fossils within 20-100 cm of the stream in a seaward direction, up to a large fracture that spans the entire length of the surface, are highly abraded (Figure 6.10D).

The current management plan for the Yale outcrop of the E-Surface is built on the assumption that the sea is eroding both the cliff on which the E-surface is found, and the

overlying cliff (along the base of which the stream runs) at the same rate. That is to say, it is assumed that fresh exposures of E-Surface are being uncovered at the same rate as the seaward edge of the E-Surface is being lost to the sea.

This assumption would be all that was necessary to assure the long term sustainability of the locality, were it not for the fact that the stream now abrades and polishes away fossils as quickly as they are revealed. While new surface may indeed be exposed, it is of little scientific or touristic value since the fossils are rapidly polished away. A possible explanation for why the entire surface has not been affected in this way, is that the stream may have only relatively recently begun to flow across the surface. If the stream is not diverted, the total area of fossil surface having fidelity of sufficient quality for scientific study and touristic use will gradually decrease, at the rate of cliff retreat.

The example of the abrasion down-dip of the hollow portends a potential unforeseen consequence of collection from fossil surfaces such as this. While the hollow mentioned in this study is not believed to have been created by collection of specimens, many man-made excavation of a similar size and shape do exist. The removal of specimens from these fossil assemblages hinders the progress of research by removing vital data from their wider context, and negatively impacts the attempts at palaeoecological studies that have recently showed great potential to elucidate the life histories of these enigmatic fossil organisms (Darroch et al., 2013; Mitchell et al., 2015). But more than this, it now appears that when specimens are removed from the outcrop it may lead to long-term damage of the surrounding fossils that remain on the surface due to locally increased abrasion induced by outflows from the newly created hollows.

## CONCLUSION

It is demonstrated that the most widely studied Ediacaran fossil horizon in Newfoundland, the Yale outcrop of the 'E' Surface at Mistaken Point, crops out at six other localities in and around the MPER over a distance of several kilometres. Fossil census data from six outcrops of this single horizon reveal a range of fossil abundances, with significant lateral variability in both the proportions of different taxa within the assemblage, and fossil density (Figure 6.4). Whereas biological communities may be expected to exhibit ecologically controlled patchiness in their benthic distributions (McIlroy 2007), the observed differences between the six localities are here attributed, at least in part, to differences in the tectonic, weathering, and erosion histories of the various outcrops.

The term 'post-fossilization processes' helps to clearly communicate the group of processes that act on a fossil assemblage after those processes that are normally grouped together under the study of taphonomy (cf. Wilson 1988). This study emphasizes the need for palaeontologists to consider and document potential biases introduced by tectonics, metamorphism, weathering, erosion, and discovery when analysing and presenting Ediacaran palaeoecological data, and even when considering the presence or absence of perceived characters in individual specimens. It is hoped that by bringing post-fossilization processes to the attention of the wider community, their influence can be identified and accounted for, leading to more accurate interpretation of Ediacaran palaeobiology.

While the removal of specimens is now much more controlled following the creation of the Mistaken Point Ecological Reserve, strategies should be further developed to protect against on-going damage caused by historical attempts at sampling. This may include remedial work on sites of historic collection, and also new recommendations for collection

strategies, e.g. that collection only be permitted on the edge of surfaces where down-dip flows cannot develop.

## ACKNOWLEDGEMENTS

This research was supported by the Natural Environment Research Council (grant number NE/J5000045/1). Alex Liu and Tom Hearing are thanked for their help and assistance in gathering the data. The Parks and Natural Areas Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, provided permits to conduct research within the Mistaken Point Ecological Reserve. Access for research to fossil localities within the Mistaken Point Ecological Reserve is by permit only. Readers are advised that the fossils around Cape Race are protected by the Paleontological Resource Regulations 67/11, under the Historic Resources Act, 1990.

## REFERENCES

- Allison, P.A. & Bottjer, D.J. 2011. Taphonomy: bias and process through time. *In*: Allison, P.A. & Bottjer D.J. (eds) *Taphonomy*. Dordrecht, Springer, Netherlands, 1-17.
- Anderson, M.M. & Misra, S.B. 1968. Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland. *Nature*, **220**, 680-681.
- Antcliffe, J.B., Hancy, A.D. & Brasier, M.D. 2015. A new ecological model for the ~565Ma Ediacaran biota of Mistaken Point, Newfoundland. *Precambrian Research*, **268**, 227-242.
- Bamforth, E.L. & Narbonne, G.M. 2009. New Ediacaran rangeomorphs from Mistaken Point, Newfoundland, Canada. *Journal of Paleontology*, **83**, 897–913.
- Bamforth, E.L., Narbonne, G.M. & 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.
- Behrensmeier, A.K. & Kidwell, S.M. 1985. Taphonomy's contributions to paleobiology. *Paleobiology*, **11**, 105–119.
- Benus, A.P. 1988. Sedimentological context of a deep-water Ediacaran fauna (Mistaken Point, Avalon Zone, eastern Newfoundland). *In*: Landing, E., Narbonne, G.M. & Myrow, P.M. (eds) *Trace Fossils, Small Shelly Fossils and the Precambrian*

- Cambrian Boundary*. New York State Museum and Geological Survey Bulletin, **463**, 8–9.
- Brasier, M.D. & Antcliffe, J.B. 2009. Evolutionary relationships within the Avalonian Ediacara biota: new insights from laser analysis. *Journal of the Geological Society*, **166**, 363–384.
- Brasier, M.D., Antcliffe, J.B. & Liu, A.G. 2012. The architecture of Ediacaran fronds. *Palaeontology*, **55**, 1105–1124.
- Clapham, M.E. 2011. Ordination methods and the evaluation of Ediacaran communities. In: Laflamme, M., Schiffbauer, J. D. & Dornbos, S. Q. (eds) *Quantifying the Evolution of Early Life*. Springer Netherlands, Topics in Geobiology, **36**, 3–21.
- Clapham, M. E. & Narbonne, G. M. 2002. Ediacaran epifaunal tiering. *Geology*, **30**, 627–630.
- Clapham, M.E., Narbonne, G.M. & Gehling, J.G. 2003. Paleocology of the oldest known animal communities: Ediacaran assemblages at Mistaken Point, Newfoundland. *Paleobiology*, **29**, 527–544.
- Clapham, M.E., Narbonne, G.M., Gehling, J.G., Greentree, C. & Anderson, M.M. 2004. *Thectardis avalonensis*: a new Ediacaran fossil from the Mistaken Point biota, Newfoundland. *Journal of Paleontology*, **78**, 1031–1036.
- Darroch, S.A.F., Laflamme, M., Schiffbauer, J.D. & Briggs, D.E.G. 2012. Experimental formation of a microbial death mask. *PALAIOS*, **27**, 293–303.
- Darroch, S.A.F., Laflamme, M. & Clapham, M.E. 2013. Population structure of the oldest known macroscopic communities from Mistaken Point, Newfoundland. *Paleobiology*, **39**, 591–608.
- Darroch, S.A., Sperling, E.A., Boag, T.H., Racicot, R.A., Mason, S.J., Morgan, A.S., Tweedt, S., Myrow, P., Johnston, D.T., Erwin, D.H. & Laflamme, M. 2015. Biotic replacement and mass extinction of the Ediacara biota. *Proceedings of the Royal Society B*, **282**, 20151103.
- Fedonkin, M.A., Gehling, J.G., Grey, K., Narbonne, G.M. & Vickers-Rich, P. 2007. *The Rise of Animals: Evolution and Diversification of the Kingdom Animalia*. John Hopkins University Press, Baltimore, 326 pp.
- Ford, T.D. 1958. Precambrian fossils from Charnwood Forest. *Proceedings of the Yorkshire Geological Society*, **31**, 40–57.
- Flude, L.I. & Narbonne, G.M. 2008. Taphonomy and ontogeny of a multibranching Ediacaran fossil: *Bradgatia* from the Avalon Peninsula of Newfoundland. *Canadian Journal of Earth Sciences*, **45**, 1095–1109.
- Gehling, J.G. 1999. Microbial mats in Terminal Proterozoic siliciclastics: Ediacaran death masks. *PALAIOS*, **14**, 40–57.

- Gehling, J.G. & Narbonne, G.M. 2007. Spindle-shaped Ediacara fossils from the Mistaken Point assemblage, Avalon Zone, Newfoundland. *Canadian Journal of Earth Sciences*, **44**, 367–387.
- Hancock, G.S., Anderson, R.S., and Whipple, K.X., 1998, Beyond Power: Bedrock River Incision Process and Form, *in* Tinkler, K.J. and Wohl, E.E. eds., *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, American Geophysical Union, p. 35–60.
- Hofmann, H.J., O'Brien, S.J. & King, A.E. 2008. Ediacaran biota on the Bonavista Peninsula, Newfoundland, Canada. *Journal of Paleontology*, **82**, 1–36.
- Laflamme, M., Narbonne, G.M. & Anderson, M.M. 2004. Morphometric analysis of the Ediacaran frond *Charniodiscus* from the Mistaken Point Formation, Newfoundland. *Journal of Paleontology*, **78**, 827–837.
- Laflamme, M., Narbonne, G.M., Greentree, C. & Anderson, M.M. 2007. Morphology and taphonomy of an Ediacaran frond: *Charnia* from the Avalon Peninsula of Newfoundland. *In*: Vickers Rich, P. & Komarower, P. (eds) *The Rise and Fall of the Ediacaran Biota*. Geological Society, London, *Special Publications*, **286**, 237–257.
- Laflamme, M., Schiffbauer, J.D., Narbonne, G.M. & Briggs, D.E.G. 2011. Microbial biofilms and the preservation of the Ediacara biota. *Lethaia*, **44**, 203–213.
- Laflamme, M., Flude, L.I. & 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.
- Lawrence, D.R. 1968. Taphonomy and information losses in fossil communities. *Geological Society of America Bulletin*, **79**, 1315–1330.
- Liu A.G. 2016. Framboidal pyrite shroud confirms the 'death mask' model for moldic preservation of Ediacaran soft-bodied organisms. *PALAIOS* in press
- Liu A.G., McIlroy D., Brasier M.D. 2010. First evidence for locomotion in the Ediacara biota from the 565Ma Mistaken Point Formation, Newfoundland. *Geology*, **38**, 123–126.
- Liu, A.G., McIlroy, D., Antcliffe, J.B. & Brasier, M.D. 2011. Effaced preservation in the Ediacara biota and its implications for the early macrofossil record. *Palaeontology*, **54**, 607–630.
- Liu A.G., Matthews J.J., Menon L.R., McIlroy D. & 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: Biological Sciences*, **281**, 20141202.
- Liu A.G., Matthews J.J., Menon L.R., McIlroy D. & Brasier M.D. 2015a. The arrangement of possible muscle fibres in the Ediacaran taxon *Haootia quadriformis*. *Proceedings of the Royal Society B: Biological Sciences*, **281**, 20142949.

- Liu, A.G., Kenchington, C.G. & Mitchell, E.G. 2015b. Remarkable insights into the paleoecology of the Avalonian Ediacaran macrobiota. *Gondwana Research*, **27**, 1355–1380.
- Liu, A.G., Matthews, J.J. & 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.
- McIlroy, D. 2007. Lateral variability in shallow marine ichnofabrics: implications for the ichnofabric analysis method. *Journal of the Geological Society, London*, **164**, 359–369.
- Menon, L.R., McIlroy, D. & Brasier, M.D. 2013. Evidence for Cnidaria-like behavior in a ca. 560Ma Ediacaran *Aspidella*. *Geology*, **41**, 895–898.
- Mitchell, E.G., Kenchington, C.G., Liu, A.G., Matthews, J.J. & Butterfield, N.J. 2015. Reconstructing the reproductive mode of an Ediacaran macro-organism. *Nature*, **524**, 343–346.
- Narbonne, G.M. 2004. Modular construction in the Ediacaran biota. *Science*, **305**, 1141–1144.
- Narbonne, G.M. 2005. The Ediacaran biota: Neoproterozoic origin of animals and their ecosystems. *Annual Review of Earth and Planetary Sciences*, **33**, 421–442.
- Narbonne, G.M., Laflamme, M., Greentree, C. & Trusler, P. 2009. Reconstructing a lost world: Ediacaran rangeomorphs from Spaniard’s Bay, Newfoundland. *Journal of Paleontology*, **83**, 503–523.
- Narbonne, G.M., Xiao, S. & Shields, G.A. 2012. The Ediacaran Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G. (eds) *The Geologic Time Scale*. Elsevier, Amsterdam, 413–435.
- Rolfe, W.D.I. & Brett, D.W. 1969. Fossilization processes. In: Eglinton, G. & Murphy, M. T. J. (eds) *Organic Geochemistry*. Springer Berlin Heidelberg, 213–244.
- Seilacher, A. 1992. Vendobionta and Psammocorallia - lost constructions of Precambrian evolution. *Journal of the Geological Society*, **149**, 607–613.
- Valentine, J.W. 1973. *Evolutionary Paleocology of the Marine Biosphere*. Prentice-Hall, 511 p.
- Van Kranendonk, M.J., Gehling, J.G. & Shields, G.A. 2008. Precambrian. In: Ogg, J.G., Ogg, G. & Gradstein, F.M. (eds) *The Concise Geologic Time Scale*. Cambridge University Press, Cambridge, 23–36.
- Wellman, H.W. & Wilson, A.T. 1965. Salt weathering, a neglected geological erosive agent in coastal and arid environments. *Nature*, **205**, 1097–1098.
- Wilby, P.R., Kenchington, C.G. & Wilby, R.L. 2015. Role of low intensity environmental disturbance in structuring the earliest (Ediacaran) macrobenthic tiered communities. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **434**, 14–27.

- Williams, H. & King, A.F. 1979. *Trepassey Map Area, Newfoundland*. Geological Survey of Canada, Energy, Mines, and Resources Canada, 24 p.
- Wilson, M.V.H. 1988. Taphonomic processes: information loss and information gain. *Geoscience Canada*, **15**, 131-148.
- Wood, D.A., Dalrymple, R.W., Narbonne, G.M., Gehling, J.G. & 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.

# Chapter 7: Fieldwork and Fossil Protection: A Review of the Avalonian Ediacaran Experience

---

## **ABSTRACT**

The increase in Ediacaran research over the past 50 years has been accompanied by an equal growth in interest from the general public; precipitating a necessary development of both geoconservation legislation and management frameworks. Various geoconservation laws, both in England and Newfoundland, are reviewed, focussing on access to localities, removal of material, and export of specimens. Examples of fossil theft and damage are provided as benchmarks against which to assess various approaches. Problems concerning ambiguity and contradiction in legislation are highlighted, as well as the overall complexity of both jurisdictions' structures. The current issues are discussed, including the importance of community involvement, and recommendations for the future proposed.

## **INTRODUCTION**

Geoconservation, or Earth Heritage Conservation as it has also been characterised, is primarily concerned with the safeguarding of those examples of the Earth's physical resources that are regarded worthy of protection. Rationale for conserving a geological feature can be wide ranging, including importance to cultural heritage, geological education and understanding, or the overall geomorphology and aesthetics of an area.

The terminology of reserves and resources, used within the hydrocarbon production and mining industries, is not used within geoconservation. As the value of geodiversity can rarely be quantified in terms of economic value, the question of what is, and is not a 'reserve' becomes highly subjective. In the field of geoconservation, the geological

features and landforms being discussed are termed the resources. This terminology is also used in conservation law, e.g. The Historic Resources Act, 1990.

It is important to recognise the difference between preservation and conservation when applied to geological resources. Preservation is the work to maintain a feature in the same state for the future; to freeze it in time. In contrast, conservation is the effort to manage something so as to retain its quality over time. While preservation would seek to mothball a cliff exposure and prevent any further erosion, conservation would manage that erosion to ensure that exposure of a particular feature was maintained. A conservation approach can only be used where the outcrop is considered to be a renewable resource. Finite geological resources often require a preservation-based approach.

The conservation of geological resources has, for some time, been recognised as a matter of importance. However, appreciation of the issue still lags behind that of the conservation of modern wildlife and habitats. Natural outcrops and landforms, as well as exposures created artificially are pivotal to our understanding of earth history, and are the foundation for geological research.

Outcrops are also vital in the education and training of future generations of geologists, providing opportunity to view exemplar sections that demonstrate key concepts within the science. It should also be said that geological landforms add to the aesthetic and wider environmental character of a landscape, and therefore enhance the cultural heritage of an area.

The evolution of the scientific method also requires a certain level of geoconservation for the process to be practicably achieved. Stratigraphic protocols require type sections to act as reference samples of specified units (Salvador, 1994), and palaeontological descriptions require a holotype, which, while often collected and placed in a museum, sometimes

remain on the outcrop. Without conservation, which balances the needs of access for scientific research and education with the long-term sustainability of a locality, key examples of geological history could be lost, with untold consequences to future scientific understanding.

This chapter will seek to review and analyse the different approaches to geoconservation taken in England and Newfoundland, especially with regard to how these approaches affect researchers. It is important to note that it is England that will be considered, and not the entire United Kingdom. While much legislation is similar across England, Wales, Scotland, and Northern Ireland, conservation policy is a devolved area, and so different legislative frameworks have developed in the Nations.

## **FOSSIL PROTECTION FRAMEWORKS**

Ediacaran strata have long been intensely studied, recognising their significance as the transitions from the microbial-dominated Proterozoic, to the metazoan environments of the Phanerozoic. With fossiliferous outcrops being relatively sparse, those that do exist are understandably a focus for geoconservation efforts, as well as research.

The Ediacaran fossils of Mistaken Point, Newfoundland (Figure 7.1), were first identified in 1967, and immediately recognised as being significant and complex macroscopic Precambrian organisms (Anderson and Misra, 1968). Similar fossils were also described from the Charnian outcrops (Figure 7.2) of the English East Midlands (Ford, 1958), and structures thought to represent trace fossils (though now thought to be associated with microbial mats) were described from the Long Mynd, Shropshire, England (Figure 7.3), in the mid-19<sup>th</sup> century (Salter, 1856). More recently, Ediacaran specimens have been described from the Catalina Dome (Figure 7.4), Bonavista Peninsula, Newfoundland (Hofmann et al., 2008).



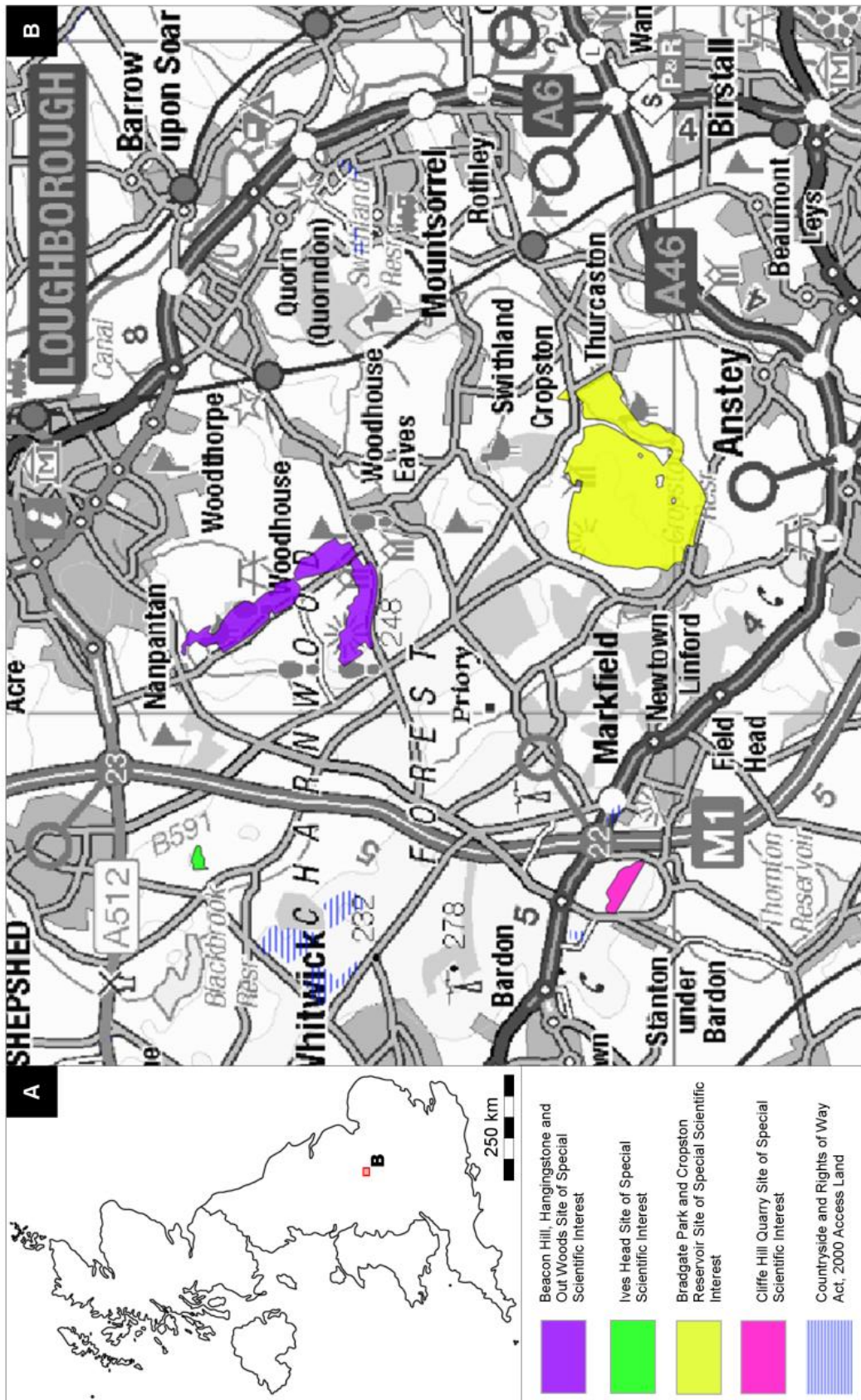


FIGURE 7.2. Locality map for the Charnwood Forest area. A: Map of United Kingdom, with the Charnwood Forest area highlighted. B: Map of the Charnwood Forest Area, showing the areal extent of different conservation designations. Grid lines at 10 km spacings.

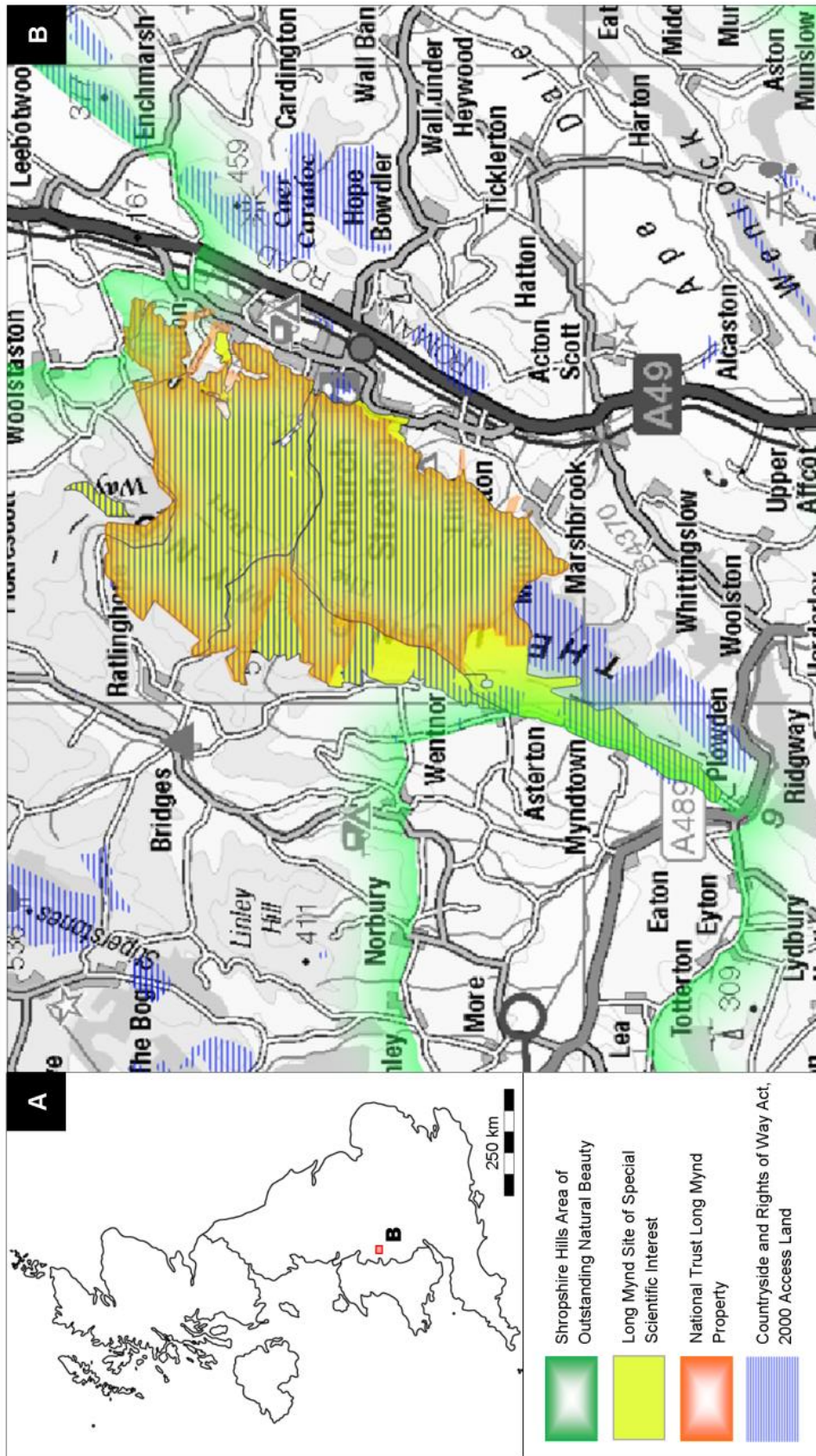


FIGURE 7.3. Locality map for the Long Mynd area. A: Map of United Kingdom, with the Long Mynd area highlighted. B: Map of the Long Mynd Area, showing the areal extent of different conservation designations. Grid lines at 10 km spacings.

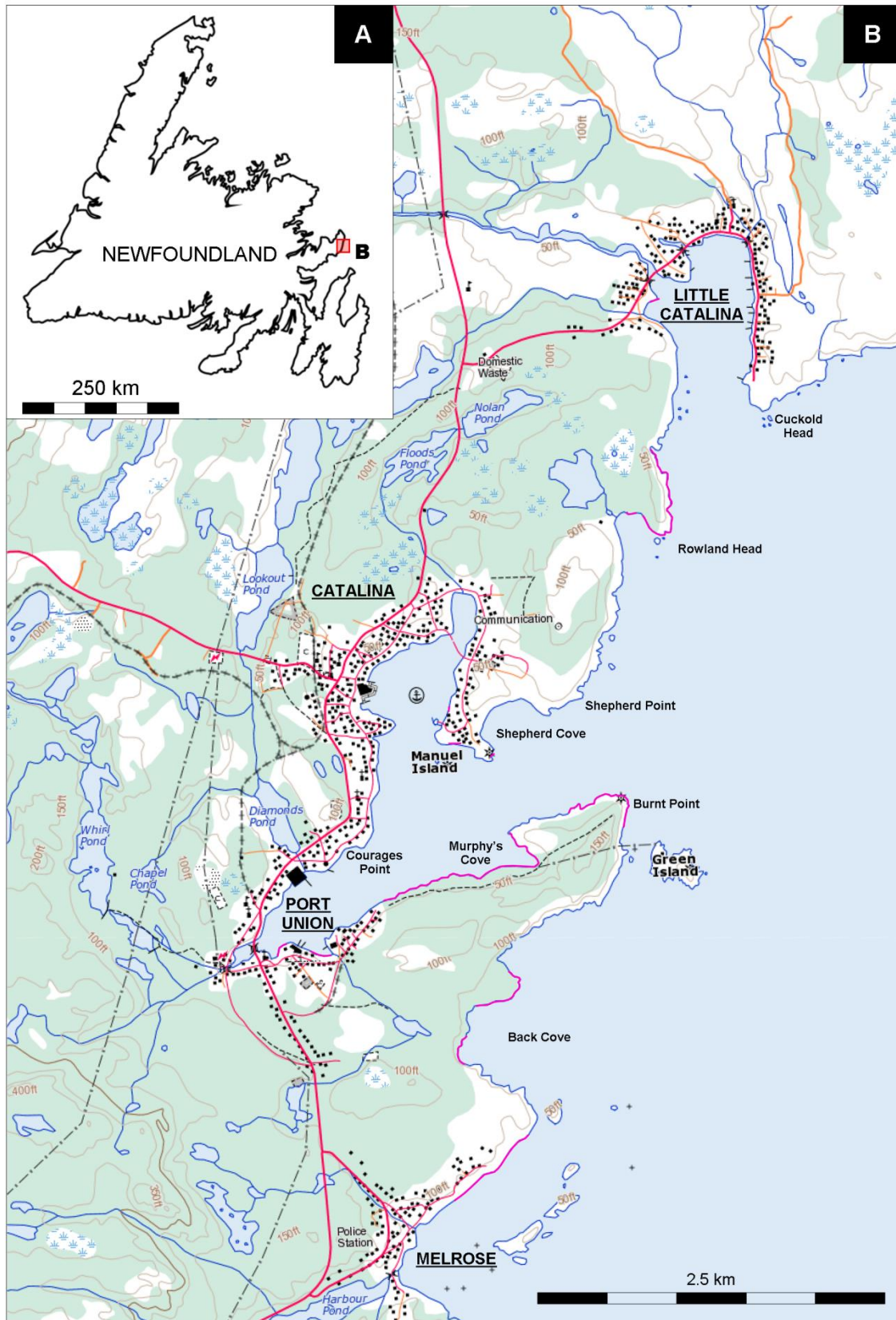


FIGURE 7.4. Locality map of the Trinity Bay North township area, formed of the settlements of Melrose, Port Union, Catalina, and Little Catalina. Those stretches of coastline designated Significant Palaeontological Sites are highlighted in pink.

These four sections are linked by having been deposited on the palaeo-continent of Avalonia, in tectonically active basins associated with island arc volcanism (Myrow, 1995). While these areas share a common geological history, tectonics has left them divided among a number of national and local jurisdictions, with unique frameworks for geoconservation.

## **Newfoundland**

Mistaken Point and the Catalina Dome are situated within the Canadian province of Newfoundland and Labrador, and are governed by legislation enacted, on a principle level, by the provincial House of Assembly. The Mistaken Point Ecological Reserve Order was brought into effect on the 31<sup>st</sup> of July 1987, establishing the Mistaken Point Ecological Reserve (MPER) as an 8.5 km long stretch of coastline for the protection of fossils, the encouragement of scientific research, and the enhancement of education. The Order was made under the authority of the Wilderness and Ecological Reserves Act, 1980 (WER Act), with specific provisions under the Order being prescribed in the Fossil Ecological Reserve Regulations (FER Regulations).

Following the discovery of new fossil localities to the west of the then Reserve boundaries (Narbonne and Gehling, 2003), an emergency extension was added with effect from 24<sup>th</sup> January 2003. This extension became a permanent part of the MPER, creating the modern boundaries seen today, on 17<sup>th</sup> March 2009. Management of lands covered by the WER Act is administered by the Parks and Natural Areas Division of the Department of Environment and Conservation.

While protecting the rights of locals to traditional activities such as berry picking, the WER Act and FER Regulations prevent access to the fossil localities, except where a permit is provided (e.g. for educational tours and scientific research) or where

accompanied by MPER staff (e.g. guided tours). The WER Act also prohibits the use of motorised vehicles, and the removal of any specimens (fossiliferous, or otherwise) without permit. Application for scientific study permits involve little bureaucratic burden, and common stipulations include the filling of post-fieldwork reports, and the presence of MPER staff when sampling. Permit applications are often processed within a week of application.

The track that all drivers must use to access the Mistaken Point trail head is flanked by a number of signs reminding visitors of the regulations regarding access to the fossil sites. This is in addition to signage at the trail head itself, at the boundary of the Reserve, and at intervals along the boundary of the 'Fossil Protection Zone' for which permits are required to enter.

However, not all the land area commonly considered as being within the MPER (and therefore under the jurisdiction of the WER Act and FER Regulations) is legally within MPER's boundaries. Several relatively small areas are instead designated as Crown Lands Reserves, under the Lands Act 1991. This allows for more flexibility in land use than would be allowed under the WER Act, and permits the development of trails that increase safety and reduce wider ecological impact. Those Crown Lands Reserves in the Mistaken Point area, while overseen by the Lands Branch of the Department of Municipal and Intergovernmental Affairs, are still managed by the Parks and Natural Areas Division of the Department of Environment and Conservation (Government of Newfoundland and Labrador, 2015).

Fossils within the Crown Land Reserves are protected separately via the Historic Resources Act, 1990 (HR Act). The Palaeontological Resource Regulations, 2011 (PR Regulations), were created under the authority of the HR Act, and both protect certain

prescribed lands as Significant Palaeontological Sites, and also specific taxa as Significant Fossils, wherever they may be found within the Province. Administration under the HR Act is performed by the Provincial Archaeologist in the Department of Business, Tourism, Culture and Rural Development.

Permits under the PR Regulations require a senior researcher to submit detailed proposals which are then peer-reviewed. Researchers must state all the 'significant palaeontological sites' in which they wish to study. Applications under the regulations usually take several months to be processed. Permits that are granted require reports to be submitted following the research, and that due care for the appearance of the outcrop is taken into consideration while sampling. However, many areas covered by the PR Regulations are not staffed or regularly monitored, and so compliance with the governance in these areas is not known.

The HR Act and PR Regulations are the method of protection used for the Catalina Dome outcrops on the Bonavista Peninsula, around the township of Trinity Bay North. Being relatively more built-up than the south-east coast of the Avalon Peninsula, designation as an Ecological Reserve would not be practicable due to the likely land-rights issues that would arise. Trailheads leading to Significant Palaeontological Sites now have large signs making clear that interference with the fossils is punishable by a large fine and/or imprisonment (Figure 7.5a). Illegal removal, destruction, or interference with fossil specimens protected by the HR Act and PR Regulations may lead to a fine of up to \$50,000 CAD per day, or imprisonment, or both.

The movement of fossil specimens in and out of Canada is controlled by the federal Cultural Property Export and Import Act 1975, and the Control Lists created thereunder.

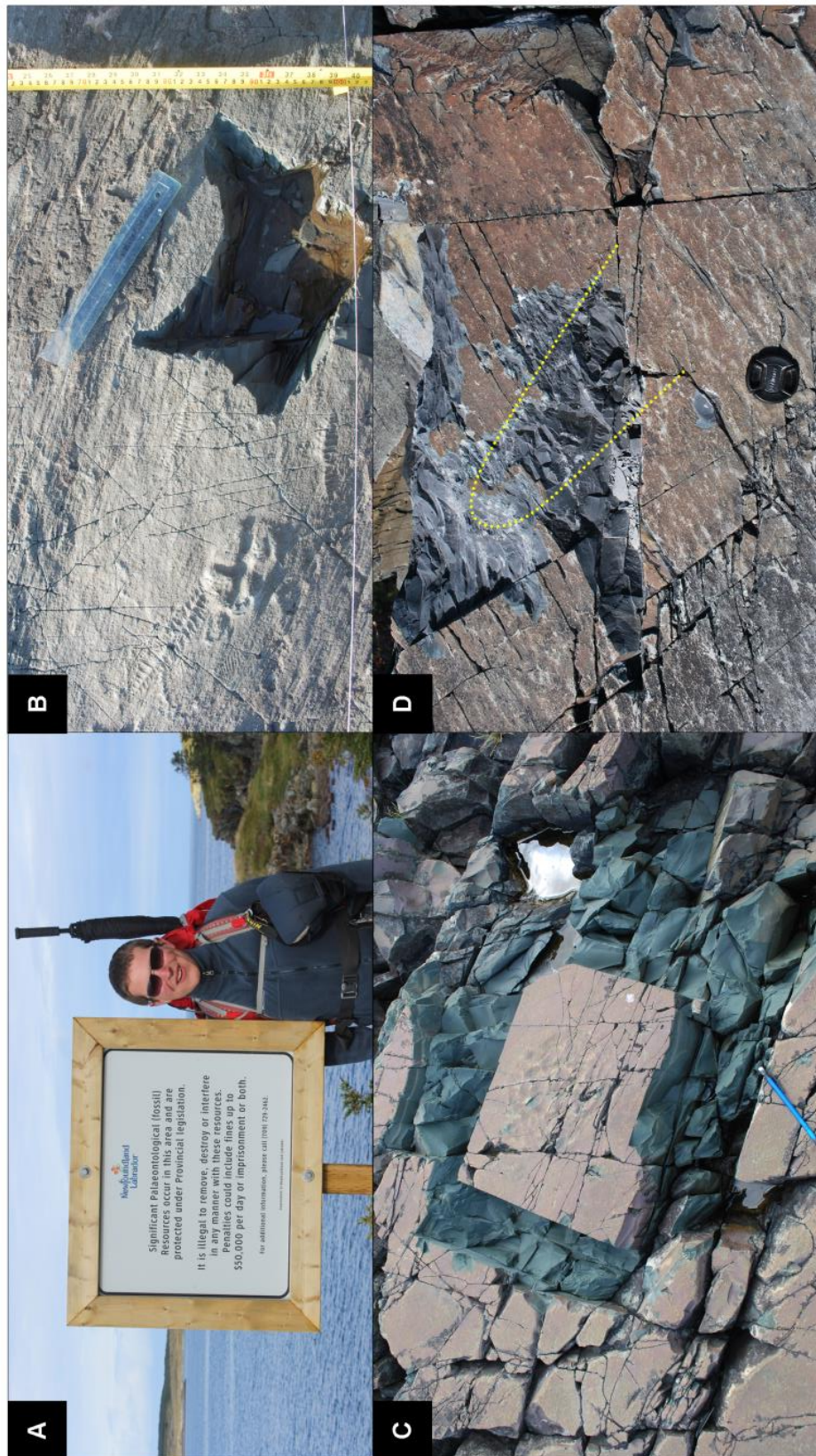


FIGURE 7.5. A) The author standing with geconservation signage at the Catalina Dome. B) An example of fossil extraction from the Mistaken Point E-surface. Note 30 cm ruler for scale. C) Damage left by a failed attempt to remove and ivesheadiomorph, now in MPER. Note pencil for scale. D) Destroyed specimen of *Charnia grandis* from the Catalina Dome. Original outline of specimen in dotted yellow line. Note lense cap for scale.

## **ENGLAND**

In England, there are two major outcrops of Ediacaran siliciclastic sequences; Charnwood Forest in Leicestershire, and the Long Mynd, Shropshire.

The Long Mynd, a heath and moorland plateau, is owned by the National Trust – a conservation charity covering England, Wales, and Northern Ireland. Protection is afforded to the ~2000 hectare site via byelaws, which are created by the National Trust under the provision of Section 24 of the National Trust Act, 1971.

The byelaws prevent, amongst other things, the unauthorised removal of gravel, sands, clay, or any other substance from Trust property and the defacing of rock surfaces. Failure to comply with the byelaws can lead to a fine of up to £20, plus an extra £2 for each day the offence continues.

The Long Mynd is also designated as a Site of Special Scientific Interest (SSSI) under Section 28 (amended) of the Wildlife and Countryside Act, 1981 (WC Act). SSSI's are the primary method of geoconservation within England, with the non-departmental public body Natural England being responsible for designation and management. Land under SSSI status is still possessed by its pre-designation landowner, but restriction to activities are put in place, especially regarding planning consent for development. SSSIs are not patrolled on a regular basis, unless other designations cause this to happen (e.g. National Trust property).

The original WC Act made prosecution against third parties who damaged or destroyed SSSIs very difficult, as it was necessary to prove that the person in question had knowledge they were within an SSSI. A new offence was created by Section 55 of the Natural Environment and Rural Communities Act, 2006 (NERC Act); that of intentionally

or recklessly damaging or destroying the natural conservation or geological features of an SSSI. Critically, this offence does not require prosecutors to prove there was knowledge of being within a designated area. Convicted individuals can be fined a sum up to level 4 on the Standard Scale (£2500 at time of writing).

The Long Mynd is also within the Shropshire Hills Area of Outstanding Natural Beauty (AONB). This designation offers protection from development, but no extra regulation with regard to access or removal of specimens. The power to designate and oversee AONBs is performed by Natural England.

Much of the Long Mynd is also open access land where there is a so-called 'right to roam'. Due to this status, Natural England is able restrict access for 'the purpose of conserving flora, fauna or geological or physiographical features' under Section 26 of the Countryside and Rights of Way Act, 2000 (CROW Act). The CROW Act also made amendments to previous legislation regarding SSSIs and AONBs. While the opportunity to restrict access for the purpose of geoconservation exists, it is thought this power has never been used.

The other major fossiliferous Ediacaran locality in England is that of the outcrops of the Charnian Supergroup in the English East Midlands. Bradgate Park, location of the Memorial Crags fossiliferous outcrop, is designated as part of the Bradgate Park and Cropston Reservoir SSSI, with its Precambrian palaeontology, as well as various modern biotic features, being specified as features for conservation. Likewise, outcrops containing Ediacaran fossils have been noted and prescribed for conservation within the nearby Beacon Hill, Hangingstone, and Out Woods SSSI.

Discoidal fossils are known from the Cliffe Hill Quarry SSSI, and ivesheadiomorph impressions have been described from the Ives Head SSSI.

Permission to sample at Long Mynd require permission from the landowner, the National Trust, so that an exemption from the byelaws can be given. In addition to this, the management plan for each SSSI includes a list of '*operations likely to damage the special interest*'. Amongst other things, the SSSIs discussed here included controls on the '*extraction of minerals, including peat, topsoil, subsoil and stone*' and the '*removal of geological specimens, including rock samples, minerals and fossils*'. Permission to perform these operations requires the consent of Natural England.

### **FOSSIL DAMAGE AND THEFT**

The Avalonian Ediacaran localities have been targets for rock-sample collection for some time. Potential fossil-bearing specimens were collected from Long Mynd by the eminent English geologist, John William Salter (1856; 1857). Samples from the Mistaken Point Formation in the St. John's area were collected as early as 1868 as part of the first survey of Newfoundland (Murray, 1881), and cubic pyrite crystals were collected from the fossiliferous deposits on the Bonavista Peninsula as early as 1689 (Fisher and Thornton, 1689). Following the discovery of rangeomorph impressions in 1967, but prior to MPER being designated, a number of fossil specimens were collected for museum collections (Figure 7.5b), particularly the Royal Ontario Museum. The amount collected, and the damage done was only governed by the competence and conduct of the researchers involved as no regulation existed.

During September 1998, an attempt was made to remove an ivesheadiomorph specimen from a locality between Pigeon Cove and Drook Point. This locality now lies within the reserve, following the Emergency Extension to MPER in 2003. The excavation was prevented by several members of the local community in Portugal Cove South, and the sample, surrounded by diamond saw cuts, remains in the outcrop to this day (Figure 7.5c).

More recently, MPER staff, as part of their regular patrols of the MPER discovered damage to the 'Pizza Bed', Pigeon Cove. This relatively small locality is the basis for a number of key studies, including the concept of ivesheadiomorphs as the decayed remains of frondose Ediacaran organisms (Liu et al., 2011), and the discovery of a collection of juvenile rangeomorphs showing the oldest example of secondary community succession (Liu et al., 2012). A large amount of contractor's expanding foam has been sprayed on the surface, particularly around the largest ivesheadiomorph. It is presumed this was either a bungled attempt to cast the specimen, or a deliberate act of vandalism.

The Burnt Point Significant Palaeontological Site, in the Trinity Bay North area of the Bonavista Peninsula, Newfoundland, was host to one of the few examples of the fossil *Charnia grandis* anywhere in the world (Hofmann et al., 2008). On August 28<sup>th</sup> 2012 it was discovered by the author that the specimen had been destroyed, presumably in a botched attempt to steal the specimen. No cutting equipment had been used, and therefore the bid to remove the impression had proved futile due to the rock breaking along cleavage, leaving the fossil in many hundreds of pieces and beyond repair (Figure 7.5d). The Royal Canadian Mounted Police, and the Department for Tourism, Culture and Recreation (as it was then) were informed immediately, but due to lack of information no prosecutions were possible.

Monitoring of a number of key horizons on the Long Mynd shows repeated sizable removals of material, too large to be associated with research-based collection. Indeed searches on eBay reveal multiple Longmyndian specimens for sale at prices up to and over £90 (Archive.org, 2016).

Protection of fossil specimens in the field is often complicated by a lack of clarity of what fossils legally are. The absence of a specific definition in UK legislation has led to the

matter being decided in case law. It has previously been contended that fossils are to be regarded as minerals for the purposes of the law (Norman, 1994), however the issue may be somewhat more complicated. In the case of *Attorney General v. Tomline* 1877, which focused mainly on the right of possession of an area of land, the coprolites within that plot were deemed to be minerals. Lord Justice Mellish, in the case of *Hext v. Gill* 1872 stated that the term minerals;

*“...includes every substance which can be got from underneath the earth for the purpose of profit, unless there is something in the context or in the nature of the transaction to induce the Court to give it a more limited meaning.”*

However, caution is advised by Ball (1919), noting that a definition of mineral will be dependent upon the issues of each case. So while ambiguity still potentially exists, it would appear that fossils are to be considered as part of the mineral rights associated with an area of land. *In situ* fossils are therefore the property of whoever owns the mineral rights, and therefore cannot be collected without permission of the landowner. *Ex situ* fossils are a more complicated matter, as it is unclear whether a loose specimen can be considered abandoned, and therefore not subject to Section 1 of the Theft Act, 1968 (Taylor and Harte, 1988).

Ownership of specimens, both *in situ* and *ex situ* is also of importance, as damage to another's property without lawful excuse is a criminal act under the Criminal Damage Act, 1971. While this legislation does not support the active management of palaeontological resources, it does allow another avenue to pursue those who have damaged fossils.

Conviction can lead to a period of imprisonment or a fine.

The matter of fossil export from the UK is also complicated, and one that came to light following the discovery of *Westlothiana*, a Carboniferous stem-amniote (Smithson and Rolfe, 1990). When a German museum attempted to buy the specimen for £180,000, an

export licence was applied for under the Export of Goods (Control) Order, 1987, as the fossil was valued at more than the benchmark £20,000, and more than 50 years old.

However, the Department of Trade and Industry ruled that as fossils are not ‘manufactured’, they are not subject to the Order. This therefore leaves a situation where the only legislation controlling the export of fossils is at the European Union level (Liston, 2014), meaning there is little to prevent intra-EU exports.

## **DISCUSSION**

Both Newfoundland and England have employed a patchwork approach to conservation of their key geological resources (Figure 7.6). While this has the benefit of flexibility, and the ability to fit suitable designations to the property in question, it also leads to a potentially overly complicated system, both in term of management and accessibility.

The English system has been one mainly built around the control of development within the area around a site of conservation. As SSSI or AONB status does not affect the ownership of the land in question, control of access to the property is mainly left to the landowner. The exception to this, while not affecting Ediacaran fossiliferous sections in England, is the designation as a National Nature Reserve, which are usually directly managed by Natural England, with access conditions sometimes being imposed.

The bias in the English system towards development and the actions of landowners is self-evident from the language used in the CROW Act, where the language of ‘*owner or occupier*’ is used to describe those persons who may apply for permission to carry out an otherwise prohibited operations within an SSSI. If this is refused, they may also appeal to the Secretary of State. This drafting disregards the reality that many of those who may legitimately seek a permit to remove samples, e.g. researchers, are highly unlikely to be the landowner. While it is common courtesy to seek the landowner’s permission, it seems

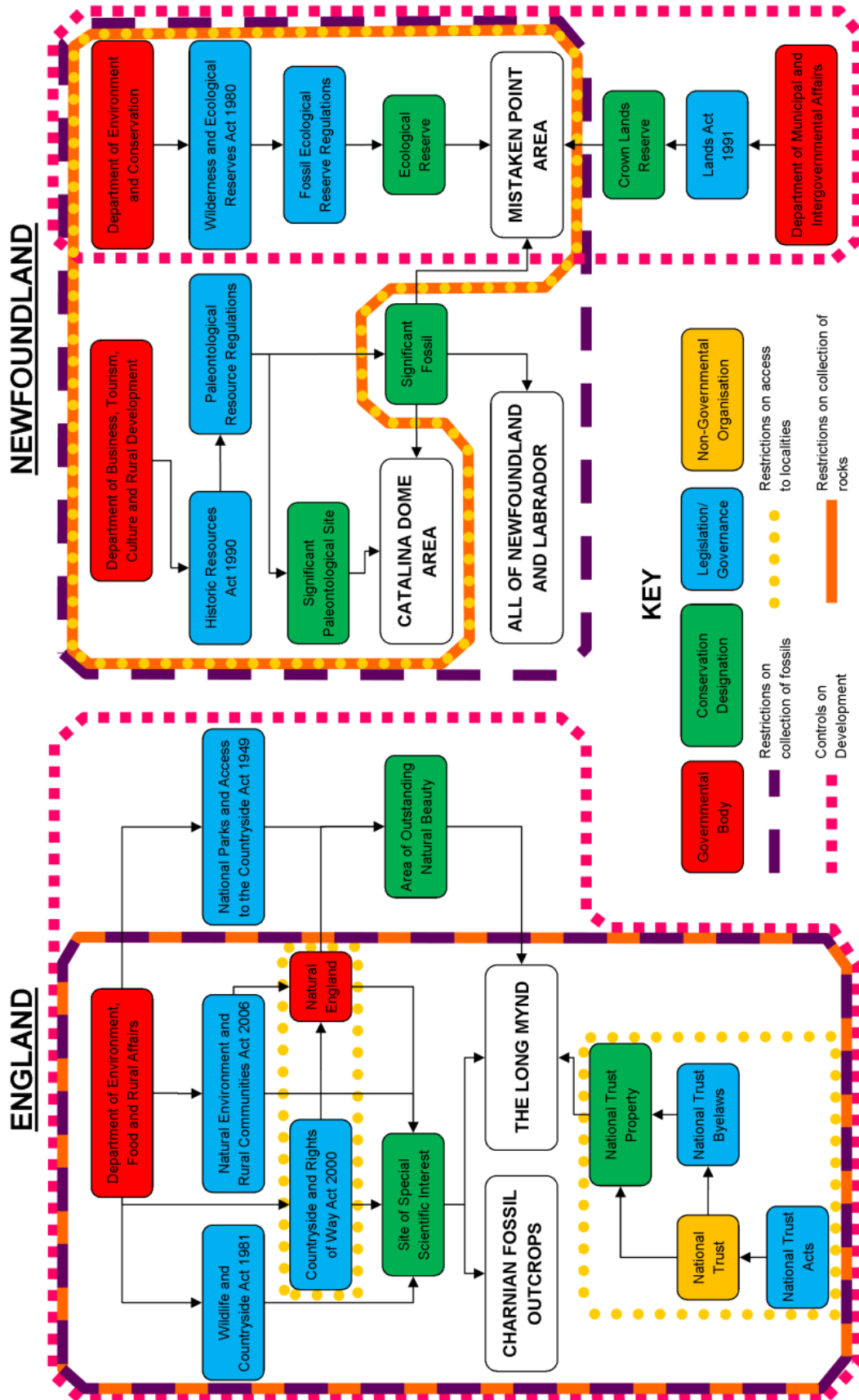


FIGURE 7.6. Diagram showing a simplified representation of the legislative framework governing the conservation of Ediacaran fossil localities in England and Newfoundland.

excessively bureaucratic to also require the landowner to obtain the permit, rather than the researcher themselves.

It is worthy of note that while not affecting the sites listed here, key geological localities in England may also be protected or managed, either directly or indirectly, through a myriad of other designation statuses, including Country Parks, Limestone Pavement Orders, Local Nature Reserves, Marine Conservation Zones, Marine Nature Reserves, National Parks, Geological Conservation Review Sites, Heritage Coasts, Regionally Important Geological and Geomorphological Sites, and Woodland Parks.

Newfoundland's approach is markedly different, focussing less on development of the landscape, and more on access and protection of the outcrops themselves. An unfortunate complication has been brought in by the inclusion of fossil protection within the HR Act. This has led to applications to work in Significant Fossil Sites being formally adjudicated upon by the Provincial Archaeologist (and not the Provincial Palaeontologist), rather than those in the Department of Environment and Conservation who have built up expertise in Ediacaran geology through their work at Mistaken Point.

The designation as an Ecological Reserve has also provided a number of unwanted complications. It can be argued that the Reserve model leans closer to preservation than conservation. Indeed, Section 5(e) of the WER Act states that an ecological reserve may be set aside so as to "*preserve rare botanical, zoological, geological or geographical characteristics*".

The decision to use a preservation-based approach is based on the assessment that the unique fossil surfaces are a finite resource when measured on a generational scale. However, this has led to the unwanted application of the principle of preservation to the entire Reserve, even in areas well away from fossil localities. Issues have arisen following

the proposal to develop trackways within the Reserve. Paths can both improve safety and decrease the environmental impact of foot traffic on the area at-large, but the preservation-based approach across the entire Reserve has prevented pathway development. Instead, areas planned for minor trail and explanation board development have had to be excised from the Reserve, and designated as Crown Lands Reserves. This complex process has led to the Department of Municipal and Intergovernmental Affairs

and the Department of Business, Tourism, Culture and Rural Development also now being involved in the management of the area.

Fossil protection and management in MPER is therefore administered by three different departments of the provincial government, and a patchwork of legal governance covering both land areas, and specific taxa. However, this melange of legislation has left several gaps. As the Crown Lands Reserves in the Mistaken Point area are not designated as Significant Palaeontological Sites under the HR Act and PR Regulations, only the fossils themselves, and specifically only those prescribed as Significant Fossils in the PR Regulations are protected. Therefore, within these areas, the removal of non-fossil-bearing samples and the use of casting mediums is allowable without permit. It is worthy of note that these Crown Lands Reserves are relatively small; the Watern Cove example is just 0.05 hectares (0.016% of the 296 hectares of MPER) (Government of Newfoundland and Labrador, 2015).

Fossil theft is a key concern at all the Avalonian Ediacaran localities. In general, the preferred method of prevention has been to keep the precise locations of key outcrops unpublished. While this has the disadvantage of making it harder for new researchers to access and view previously studied sites, it has on the whole been justified.

Within the Mistaken Point Ecological Reserve the ~100 fossil-bearing bedding planes are spread across 17 km of protected coastline, meaning that locating the horizons without the support of MPER staff or the scientific community is relatively hard. However, looking at the localities designated in the Trinity Bay North area of Newfoundland under the HR Act, 14 individual Significant Palaeontological Sites have been created, some less than 100 m in length. Because of this, *in situ* fossil specimens are being potentially compromised by publication, in law, of their precise location. This issue is exacerbated as sites under the HR Act are not staffed or routinely patrolled in the same way as MPER.

Further issues arise from the implementation of HR Act, particular confusion caused by the drafting of the PR Regulations. Regulation 6 (2) states that “*The fossils described in Schedule B are designated as significant fossils*”. Schedule B reads as follows;

*Schedule B*  
*Significant fossils*

1. *All pre -Quaternary vertebrate fossils, being all vertebrate fossils found in consolidated rock.*
2. *All fossils from rocks of Ediacaran age or older, excluding microfossils and the common form of Aspidella.*
3. *In particular:*
  - Aspidella terranovica Billings 1872*
  - Avalofractus abaculus Narbonne et al. 2009*
  - Beothukis mistakensis Brasier & Antcliffe 2009*
  - Blackbrookia sp. Hofmann et al. 2008*
  - Bradgatia linfordensis Boynton and Ford 1995*
  - Buthotrephis Crimes & Anderson 1985*
  - Charnia antecedens Laflamme et al. 2007*
  - Charnia grandis Glaessner & Wade 1966*
  - Charnia masoni Ford 1958*
  - Charniodiscus arboreus Glaessner 1959*
  - Charniodiscus procerus Laflamme et al. 2004*
  - Charniodiscus spinosus Laflamme et al. 2004*
  - Fractofusus andersoni Gehling & Narbonne 2007*
  - Fractofusus misrai Gehling & Narbonne 2007*
  - Hadrynichorde catalinensis Hofmann et al. 2008*
  - Hadryniscalia avalonica Hofmann et al. 2008*
  - Hiemalora stellaris Fedonkin 1980*
  - Ivesheadia lobata Boynton & Ford 1995*
  - Parviscopa bonavistensis Hofmann et al. 2008*
  - Pectinifrons abyssalis Bamforth et al. 2008*

*Primocandelabrum hiemalorum* Hofmann et al. 2008

*Thectardis avalonensis* Clapham et al. 2004

*Trepassia wardae* Narbonne et al. 2009

*pro Charnia wardi* Narbonne and Gehling 2003

*Triforillonia costellae* Gehling et al. 2000

4. Also including:

(a) *incertae sedis* and dubiofossils;

(b) undescribed plant remains, for example, carbonaceous megafossils including *Vendotaenia*); and

(c) stromatolites of probable pre-Ediacaran age on the Burin Peninsula.

The effect of this Schedule is to both protect (section 3) and not protect (section 2)

*Aspidella* – a conundrum that legislators are yet to resolve. The schedule affords protection to all Ediacaran fossils (section 2), and then details a number of particular Ediacaran taxa (section 3). Section 4(a), however, reads as if the PR Regulations also grant protection to all structures of unknown taxonomic and biological affinity. How classification as a dubiofossil or *incertae sedis* would be adjudicated upon within the judicial system remains unclear.

## CONCLUSIONS

Newfoundland and Labrador, Canada, and England, United Kingdom have employed radically different legislative frameworks to support their geoconservation efforts. This has often led to multiple designations conceived in isolation from one another, being applied to a region; increasing confusion and the bureaucratic burden to both government and stakeholders. While those in Newfoundland focus on controlling access and interaction with key localities and taxa, the English model centres around oversight of development and regulations on the actions of landowners.

Legislation alone cannot ensure the long term protection of geologically significant sites.

As the destruction of one of only two known *Charnia grandis* specimens, and sale of Long Mynd samples online shows, the law alone is of little use once a rare and finite resource

has been removed. While total security can never be guaranteed, access controls that are monitored and preferably staffed appear to be essential to ensuring the continued preservation of the most scientifically significant localities.

Fossil localities are as significant to local communities by means of adding to the cultural heritage and economy, as they are to researchers and the development of knowledge.

Indeed, with researchers often being transient annual visitors, and many sites having no permanent staff or monitoring, local communities are often the best guardians of these global significant localities – as has been shown around the Mistaken Point Ecological Reserve.

It is therefore essential that geoconservation frameworks, both legislative and with regard to management are designed in close consultation with both the scientific community and local residents and stakeholders. Furthermore legislation should, where possible, attempt to anonymise the exact locations of key horizons, as has been done at MPER.

How the law on geoconservation would be applied, both in Canada and the UK, remains an unknown due to the paucity of prosecutions. It is therefore essential that legislation is accessible in terms of language and is also actively advertised so all stakeholders are aware of it; neither researchers nor member of the public are commonly well versed in the intricacies of the law, and so these important regulations should be as clear as possible.

The long term sustainability of both Ediacaran research and the tourist-based economies of certain communities are reliant on the correct balance being struck between free access and complete closure, and the subtle difference between conservation and preservation. Future legislative advancements should seek to simplify the current framework and ensure that designations recognise the needs and concerns of all partners, while ensuring the long term sustainability of these fossil resources.

## ACKNOWLEDGEMENTS

Thanks are extended to the Parks and Natural Areas Division, Department of Environment and Conservation for providing research permits for the Mistaken Point Ecological Reserve, and to the Department of Business, Tourism, Culture and Rural Development for providing research permits for the Trinity Bay North area. Thanks are extended to the National Trust and Natural England for their support in accessing the English sections. The research was funded by a Natural Environment Research Council (NERC) doctoral studentship to JJM while at the University of Oxford.

## REFERENCES

- Anderson, M.M., and Misra, S.B., 1968, Fossils found in the Pre-Cambrian Conception Group of South-eastern Newfoundland: *Nature*, v. 220, no. 5168, p. 680–681, doi: 10.1038/220680a0.
- Archive.org, 2016,  
<https://web.archive.org/web/20160429112055/http://www.ebay.co.uk/itm/BELTA-NELLIFORMIS-BRONZAE-MEDUSOIDS-EDIACARAN-635-myo-FOSSIL-SM100-/111930188841?hash=item1a0f8f2429:g:I3QAAOSwoudW367j>:
- Ball, W.V., 1919, Petroleum and the Law of Mines and Minerals: *Law Quarterly Review*, v. 35, p. 307.
- Fisher, W., and Thornton, J., 1689, *The English Pilot. The Fourth Book, describing The Sea-Coasts ... from the River Amazons to Newfoundland, with all the West India Navigation, etc.* pp. 50.: London.
- Ford, T.E., 1958, Precambrian fossils from Charnwood Forest: *Proceedings of the Yorkshire Geological Society*, v. 31, p. 211–217.
- Government of Newfoundland and Labrador, 2015, Mistaken Point: Nomination for Inscription, UNESCO World Heritage List:
- Hofmann, H.J., O'Brien, S.J., and King, A.E., 2008, Ediacaran biota on Bonavista Peninsula, Newfoundland, Canada: *Journal of Paleontology*, v. 82, no. 1, p. 1–36, doi: 10.1666/06-087.1.
- Liston, J., 2014, Fossil protection legislation: Chinese issues, global problems: *Biological Journal of the Linnean Society*, v. 113, no. 3, p. 694–706, doi: 10.1111/bij.12293.

- 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*, v. 54, no. 3, p. 607–630, doi: 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*, v. 169, no. 4, p. 395–403, doi: 10.1144/0016-76492011-094.
- Murray, A., 1881, Reports of Progress on the Geological Survey of Newfoundland 1864-1881:
- Myrow, P.M., 1995, Neoproterozoic Rocks of the Newfoundland Avalon Zone: *Precambrian Research*, v. 73, no. 1–4, p. 123–136.
- Narbonne, G.M., and Gehling, J.G., 2003, Life after snowball: The oldest complex Ediacaran fossils: *Geology*, v. 31, no. 1, p. 27–30, doi: 10.1130/0091-7613(2003)031<0027:LASTOC>2.0.CO;2.
- Norman, D.B., 1994, Fossil collecting: international issues, perspectives and a prospectus: *Geological and Landscape Conservation Geological Society*, London, p. 63–68.
- Salter, J.W., 1857, On Annelide-burrows and Surface-markings from the Cambrian Rocks of the Longmynd. No. 2: *Quarterly Journal of The Geological Society*, v. 13, no. 1–2, p. 199–206, doi: 10.1144/GSL.JGS.1857.013.01-02.29.
- Salter, J.W., 1856, On Fossil Remains in the Cambrian Rocks of the Longmynd and North Wales: *Quarterly Journal of The Geological Society*, v. 12, no. 1–2, p. 246–251, doi: 10.1144/GSL.JGS.1856.012.01-02.31.
- Salvador, A., 1994, *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*: Geological Society of America.
- Smithson, T.R., and Rolfe, W.D.I., 1990, *Westlothiana* gen. nov.: naming the earliest known reptile: *Scottish Journal of Geology*, v. 26, no. 2, p. 137–138, doi: 10.1144/sjg26020137.
- Taylor, M.A., and Harte, J.D.C., 1988, Palaeontological site conservation and the law in Britain: *Special Papers in Palaeontology*, v. 40, p. 21–39.

# Chapter 8: Conclusions

---

Extensive field mapping of coastal outcrops has generated a more accurate geological map of the Mistaken Point Ecological Reserve (MPER), Avalon Peninsula, and improved understanding of the lithostratigraphic relationships within the succession. The rocks of MPER represent a shallowing upwards siliciclastic succession deposited in a backarc basin. The Drook and lower Briscal formations record sedimentation associated with the initial rifting and development of the basin. At c.567 Ma the basin transitioned to backarc spreading and strong island arc volcanism, as shown by the increased sedimentation rate and tuffite horizons of the upper Briscal and Mistaken Point formations. The Trepassey and Fermeuse formations record the stage of basin maturity, with seafloor spreading beginning to cease and sediments prograding into the basin; a progression that occurred at c.564 Ma.

The late Ediacaran siliciclastic successions of Newfoundland contain some of the first evidence for complex multicellular organisms in the geological record. The use of high-precision  $^{206}\text{Pb}/^{238}\text{U}$  (zircon) ID-TIMS geochronology to multiple levels within the MPER, has permitted the construction of a more robust and better resolved chronostratigraphy for this noteworthy fossiliferous succession.

The late Ediacaran deposits of the Catalina Dome, Bonavista Peninsula, Newfoundland have historically been lithologically correlated with the broadly time-equivalent rocks of MPER. The lithostratigraphic units have also been considered to be isochronous over the intervening 200 kilometres. Following extensive field mapping, a new lithostratigraphy for the Catalina dome was erected, accompanied by two chronostratigraphic reference points. The new lithostratigraphy and chronostratigraphic data presented for the Catalina Dome

are inconsistent with the previous assumption that the stratigraphic units of the Avalon Peninsula can be directly applied to the stratigraphy of the Catalina Dome.

The newly established Trinity Bay North Group of the Catalina Dome represents a broadly coarsening upwards succession from siliceous basin plain deposits of the Shepherd Point Formation through to the slope sandstones of the Port Union Formation. This is capped by the slumped slope mudstones of the Little Catalina Formation. The Trinity Bay North Group is inferred to have been deposited within an island arc setting.

The use of high-precision  $^{206}\text{Pb}/^{238}\text{U}$  (zircon) ID-TIMS geochronology at two levels within the Catalina Dome succession has permitted the construction of the first chronostratigraphic framework for this important fossiliferous succession. Previous dates, based on the assumption that chronostratigraphic correlation can be inferred from lithostratigraphic correlation with the rocks of MPER, have underestimated the age of these fossil-bearing rocks by up to 5 Myr.

The lithologic and chronologic decorrelation of the Catalina Dome and MPER successions prompts the necessary re-evaluation of other late Ediacaran successions in Newfoundland, which may have been prematurely characterised as belonging to the Conception, St. John's, and Signal Hill Groups.

In both the Catalina and MPER successions the rangeomorphs *Vinlandia* and *Trepassia* are the first complex forms to appear, closely followed by a radiation of taxa around 575 Ma. This rapid expansion in taxonomic diversity at the base of the fossil-bearing units within MPER and the Catalina Dome supports the 'Ediacaran Explosion' hypothesis.

The presence of trace fossils in the rocks of MPER, and the muscle-bearing stauromedusan-like *Haootia* in Catalina Dome successions, both at ~565 Ma, marks a

coeval first occurrence of these metazoan related structures. High-precision dates from both successions supply the first reliable chronostratigraphic constraints for these major biotic innovations, providing an important benchmark for molecular clock and other evolutionary calculations reliant on fossil reference points. The creation of a regional biostratigraphy for Newfoundland would be premature at this time. Initial attempts at biostratigraphic correlation between the successions of Newfoundland and England are prevented by the paucity of fossiliferous horizons in the Charnwood Forest outcrops.

The Ediacaran successions of Avalonia in Newfoundland and the United Kingdom are poorly constrained, chronostratigraphically, between 545 Ma and 565 Ma. This time interval includes the widespread disappearance of rangeomorphs from the fossil record. Lack of chronostratigraphic benchmarks during this interval precludes the accurate integration of Avalonian palaeontological data, with that from the White Sea and Nama assemblages. This time interval is also associated globally with the Shuram anomaly – the largest known carbon isotope excursion in the geological record (Grotzinger et al., 2011). Further investigation is required to better constrain these youngest Ediacaran Avalonian deposits, and to accurately correlate them with other Ediacaran successions worldwide.

Critical analysis of the depositional environments in which the Ediacaran biota are preserved in MPER and the Catalina Dome show there is no evidence to support previous claims of non-marine and sub-aerial facies. Both sections show no sign of sedimentary structures commonly associated with shallow marine or sub-aerially exposed deposits. Geochemical proxies, previously used to infer the presence of palaeosols, are shown to be not applicable to the Ediacaran of Newfoundland, and have been used outside the parameters of their original methodology. The MPER and Catalina Dome siliciclastic

successions are interpreted as deep marine deposits, with the strong likelihood that fossils preserved within could therefore not have been phototrophic.

Detailed examination of tuffite deposits within the MPER succession suggests that they were deposited by ashy turbidites, as opposed to the previous water-settled fallout ash hypothesis. This new depositional mechanism challenges the current taphonomic model by implying frondose organisms were felled by the ashy-turbidite that buried them, rather than living in a pseudo-procumbent life position due to contour currents. The new depositional mechanism for tuffites also necessitates added caution when contextualising geochronological dates yielded therefrom.

Careful examination of weathering and erosion of the tuffites within MPER reveals how these modern processes can alter the exposure and observation of fossil assemblages. The term 'post-fossilisation processes' is used to clearly communicate these principles, and the need for palaeontologists to incorporate the impact of tectonics, metamorphism, weathering, erosion, and discovery biases when analysing and presenting data on fossil populations. Post-fossilisation processes help explain the differences in observed fossil assemblages between different outcrops of the same fossiliferous horizon, and challenges palaeoecological interpretations that are based on observed difference in fossil census data, such as community succession models.

The study of post-fossilisation processes also informs geoconservation strategies for Ediacaran fossiliferous localities, which are significant tourist attractions as well as scientific resources. The historic removal of specimens has the potential to cause on-going damage to the wider surfaces from which they were excised, and mitigation strategies should be put in place to prevent this.

Newfoundland and Labrador, Canada, and England, United Kingdom have employed radically different legislative frameworks to support their geoconservation efforts, and the protection of Ediacaran fossil-bearing localities. Those in Newfoundland focus on controlling access and interaction with key localities and taxa; the English model centres around oversight of development and regulations on the actions of landowners.

Legislation alone cannot ensure the long term protection of geologically significant sites, as shown by the destruction of one of only two known *Charnia grandis* specimens, and sale of Long Mynd samples online. Access controls that are monitored and preferably staffed appear to be essential in ensuring the continued preservation of the most scientifically significant localities.

Fossil localities add to the cultural heritage and economic diversity of local communities, and as such locals are often the best guardians of these sites. Geoconservation frameworks succeed when designed in consultation with local residents and stakeholders, and the scientific community, as shown at MPER.

The application of the laws on geoconservation are yet to be tested, both in Newfoundland and England, creating uncertainty over interpretation. It is therefore essential that legislation is clear and accessible in terms of language, and is also actively advertised so all stakeholders are aware of it.

The long term sustainability of both Ediacaran research and the tourist-based economies of certain communities are reliant on the correct balance being struck between free access and complete closure, and the subtle difference between conservation and preservation. Future legislative advancements should seek to simplify the current frameworks and ensure that designations recognise the needs and concerns of all partners, while ensuring the long term sustainability of these fossil resources.