

# **The ichnology of the Winterhouse Formation**

By

©Robyn Rebecca Reynolds, B.Sc. (Hons)

A thesis submitted to the

School of Graduate Studies

in partial fulfilment of the requirements for the degree of

**Master of Science**

**Department of Earth Sciences**

Memorial University of Newfoundland

**October, 2015**

St. John's

Newfoundland

## Abstract

The Upper Ordovician Winterhouse Formation of Western Newfoundland contains a, hitherto undescribed, well-preserved and diverse assemblage of trace fossils. This study provides the first systematic ichnological review of the area. 20 ichnotaxa are documented herein from the mudstone and sandstone storm deposits of the formation. A detailed morphologic three-dimensional reconstruction and analysis of a complex *Parahaentzschelinia*-like burrow system that is prolific throughout the formation is also undertaken. This analysis allows for a reconsideration of the trace-maker's ethology and paleobiology, and highlights a need for a systematic ichnotaxonomic review of *Parahaentzschelinia*. Additional reconstructions of natural mineral-filled fractures associated with *Parahaentzschelinia*-like burrows in the cemented silt-rich fine-grained sandstones illustrate that the burrows create planes of weakness within the cemented sandstone, along which natural fractures preferentially propagate. This suggests that these trace fossils create mechanical heterogeneities that can steer fracture development, and can potentially have a dramatic effect on reservoir characteristics in bioturbated reservoirs where induced fracturing techniques may be employed.

## Acknowledgements

Firstly I would like to thank my supervisor, Dr. Duncan McIlroy, for providing me with this opportunity, and for your support and mentorship throughout the past three years. In addition to everything I have learned from you about ichnology and sedimentology, your approach to research and your method of supervising/teaching has made me a stronger, more independent, and confident scientist. Your hard work, dedication, and genuine passion for science has been an inspiration.

Thank you to my supervisory committee member Dr. Richard Callow for your support and insight throughout the duration of this project. Thank you to Dr. Stephen Hubbard and Dr. Renata Netto for helpful review and suggestions.

Funding for this project was provided by a National Sciences and Engineering Research Council of Canada (NSERC) grant to Dr. Duncan McIlroy. I also gratefully acknowledge Memorial University School of Graduate Studies for financial support in the form of a fellowship and scholarships, as well as Chevron Canada Ltd. for supporting me with the Chevron Canada Ltd. Rising Star Award for the past two years.

Thank you to everyone in the MUN Ichnology Research Group – I couldn't have asked for a better group of people to work with. Thank you so much Edgars Rudzitis for your help with sample prep and lab work, and for always going above and beyond in anything you helped me with. Katie, Tiffany, Jill, Eli, Sam – it has been so comforting and inspiring to have such a down to earth group of motivated, intelligent, strong, and cool women to go through this program with.

Thank you to my family and friends for continuing to support and encourage me through grad school, even though it has meant I've taken more than my fair share of rain cheques and missed far too many family dinners and social engagements with you all throughout the past few years.

To my awesome brother John and my amazing mom Colleen, I can't thank you enough for your support and love. Mom, you continue to be my number one role model and number one fan at the same time. Your belief in me, and your insistence that I can do anything I put my mind to, continues to motivate me and propel me forward. I would not be the person I am today without you.

And finally, to my incredible best friend, partner in crime, soulmate, and husband, Chris... words cannot express how grateful I am for you, and for our amazing relationship. You have been by my side (literally, right there just a few feet away... be it in the office, the field, or at home...) through thick and thin, and your unconditional and unfaltering support, motivation, and love has made this journey so much better. I am so excited to move forward and continue to take on the world together.

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- Fig. 4.1: A) Geologic map of the Port au Port Peninsula of Newfoundland, including the Winterhouse Formation as part of the Long Point Group (arrowed). Inset is an outline of a map of the island of Newfoundland, showing the (boxed) location of the Port au Port Peninsula (after Cooper *et al.*, 2001); B) Stratigraphic column of the foreland basin succession of the Port au Port Peninsula containing the Long Point Group. The green box highlights the Winterhouse Formation (after Quinn *et al.*, 1999).
- Fig. 4.2: A) Top down image of the sample that was modelled for this study showing aff. *Parahaentzschelinia* burrows connected in chains, as well as the two fracture systems that were identified in the sample. Blue and red arrows indicate the two different fracture systems (the fracture models are false



coloured accordingly); B) Model viewed bedding parallel from above, showing the two fracture systems (in red and blue) and the burrow network (sand colour). These images were produced using the rendering settings “Maximum Projection” which combines the models based on their image levels, and displays them such that overlapping portions are highlighted. Where the red-coloured fracture system and the burrows overlap is clearly visible in the highlighted portions, illustrating that these fractures are contained within the burrow network, and run along the burrow tunnels; C) Fracture models only, viewed bedding parallel from above. These images were produced using the rendering settings “Scatter HQ” which displays the exterior of the selection; D) Side view of models of the planar fracture system (blue) and burrows; E) Opposite side view of the two fracture systems; D and E clearly demonstrate the orientation of the planar fracture system (blue) is inclined at an angle c  $40^{\circ}$  from bedding parallel.

Fig. 4.3: A-B) Grind images of the sample showing the planar fracture system (arrowed) preferentially deflecting toward the burrows (A) and then propagating through them and continuing on (B); C) The model (viewed bedding parallel from above) shows that the fractures (blue) run in a generally straight orientation through the sample, but where the burrows are present they preferentially deflect toward the burrow networks and propagate through them (highlighted in D)

Fig. 4.4: A-C) Models of sub-vertical fracture system (red) and burrows (brown), rendered using “Maximum Projection” settings, which highlighted overlap portions of the models. This clearly illustrates that this fracture system is directly related to the burrow network. The fractures are contained within the burrow network, and run along the burrow tunnels, with the burrows clearly being the loci of crack propagation. Where multiple burrows are connected in chains, the fractures extend along the connecting tunnels, creating a larger interconnected fracture network; A) Viewed bedding parallel from above; B) Viewed obliquely from above; C) Viewed obliquely from below; D) Dry grind image showing that these fractures frequently terminate in a Y-shaped bifurcation with an angle of c.  $60^{\circ}$  (arrowed); E-F) Wet grind image illustrating that some places the two fracture systems connect to form a larger network (arrowed in E).

# CHAPTER 1

## Introduction and overview

# **Chapter 1 – Introduction and overview**

## **1. Introduction**

This thesis-based Master's degree comprises three linked studies, all of which are unified by their focus on the ichnology of the calcareous silt-rich sandstones and mudstones of the Late Ordovician Winterhouse Formation of Western Newfoundland. The three studies make up three main chapters that are each prepared for publication and are submitted herein in manuscript format.

### **1.1 Chapter 2 - Systematic ichnology of the Ordovician Winterhouse Formation of Long Point, Port au Port, Newfoundland, Canada**

The manuscript presented in Chapter 2 is based on a study focused on the entire ichnological assemblage of the Winterhouse Formation. The Winterhouse Formation contains a hitherto undescribed well-preserved and diverse assemblage of Ordovician trace fossils. This study provides the first systematic documentation of the ichnological assemblage in the Winterhouse Formation. This systematic ichnological study can be used to enhance our understanding of the paleoecology of the Winterhouse Formation, and can be used for comparison in other ichnological studies, particularly those focussed on the Ordovician Anticosti Basin and other eastern Laurentian basins that are elsewhere prospective for hydrocarbons (Hannigan and

Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011).

## **1.2 Chapter 3 - Detailed three-dimensional morphological analysis of *Parahaentzschelinia*-like burrow systems**

Chapter 3 focuses on a detailed three-dimensional analysis of a complex burrow system that is prolific in the Winterhouse Formation. The main sub-vertical component of the discussed burrow system is comparable to *Parahaentzschelinia* (Chamberlain, 1971). The morphology of the burrow system described herein is however much more complex and variable than descriptions of the type material of *Parahaentzschelinia* (cf. Chamberlain, 1971). These complex morphologies are herein studied and described in detail using the high-resolution serial grinding and three-dimensional reconstruction techniques described by Bednarz *et al.* (2015). The aims of this study are to: 1) document and describe the various morphological components of complex *Parahaentzschelinia*-like burrow systems from the Winterhouse Formation; and 2) compare these burrows to similar modern and fossil burrows to allow a reconsideration of the trace-maker's ethology and paleobiology.

### **1.3 Chapter 4 - The relationship between *Parahaentzschelinia*-like burrows and natural fracture propagation patterns in the Winterhouse Formation**

Chapter 4 describes a pilot study that builds upon the hypothesis that trace fossils have the potential to directly affect the fracture susceptibility of bioturbated reservoir facies (Bednarz and McIlroy, 2012). Using the three-dimensional modelling techniques of Bednarz *et al.* (2015) this study aims to document the three-dimensional relationship between the natural fracture patterns and the distribution of aff. *Parahaentzschelinia* burrows in the cemented fine-grained silty sandstones of the Winterhouse Formation.

## **2. Literature review**

### **2.1 The Winterhouse Formation**

The island of Newfoundland was formed as part of the Appalachian orogen and was largely formed during the rifting, widening, and subsequent closure of the Iapetus Ocean during the early Paleozoic (Williams *et al.*, 1996). The island has been divided into four distinct tectono-stratigraphic zones; from west to east these zones are the Humber Zone, the Dunnage Zone, the Gander Zone, and the Avalon Zone (Fig. 1.1; e.g. Williams, 1979, 2004; Williams *et al.*, 1988, 1996; Coleman-Sadd *et al.*, 1992). The Winterhouse Formation is a part of the Humber Zone (Williams *et al.*, 1996). The sedimentary rocks of this region have been interpreted as being deposited on the Laurentian margin of the Iapetus Ocean as shelf and slope deposits (Williams *et al.*,

1996). During the Middle-Late Ordovician, sediment was deposited along the eastern margin of Laurentia in disconnected tectonically active foreland basins (Lavoie, 1994; Dietrich *et al.*, 2011). These deposits make up the Western Newfoundland Basin; they include the Table Head Group, the Goose Tickle Group, and the Long Point Group (Dietrich *et al.*, 2011).

The Upper Ordovician Winterhouse Formation was deposited as part of the Long Point Group in the Western Newfoundland Basin (Waldron *et al.*, 1993; Quinn *et al.*, 1999). The Long Point Group is exclusively exposed in outcrop on the Port au Port Peninsula in Western Newfoundland (Fig. 1.2), though there is likely to be extensive sub-crop below the Gulf of St. Lawrence (Sinclair, 1993; Quinn *et al.*, 1999). The Long Point Group is generally considered to represent a foreland basin fill deposited between the Taconic and Acadian orogenies (e.g. Waldron *et al.*, 1993). However some authors have suggested that the basin was tectonically active during the Late Ordovician (Stockmal *et al.*, 1995; Quinn *et al.*, 1999). This group comprises three formations: the Middle Ordovician shallow marine fossiliferous limestones of the Lourdes Formation, which gradationally underlies the mixed siliciclastic/carbonate succession making up the Winterhouse Formation, and finally the marginal marine and deltaic red sandstones of the Misty Point Formation, conformably overlying the Winterhouse Formation (Fig. 1.2; Quinn *et al.*, 1999; Dietrich *et al.*, 2011).

The Winterhouse Formation is over 800 metres thick, with the lower 320 metres being well exposed on the Port au Port Peninsula, while the upper approximately 540 metres do not outcrop (Quinn *et al.*, 1999). The exposed section generally consists of

coarsening upward parasequences and is composed of trace fossil-rich interbedded carbonaceous silty mudstones and sandstones with limestone breccias and slump deposits at some intervals (Quinn *et al.*, 1999). The lithology of the silt-rich carbonate-cemented fine-grained sandstones of the Winterhouse Formation is analogous to unconventional tight gas reservoir facies. Owing to the complex tectonic history of the area, the formation is faulted and the silt-rich sandstone facies contains abundant natural fractures. The succession shows net progradation and is thought to represent shallow marine storm-dominated shelf-deposits (Quinn *et al.*, 1999). The Winterhouse Formation contains a rich ichnological assemblage which has been hitherto undescribed.

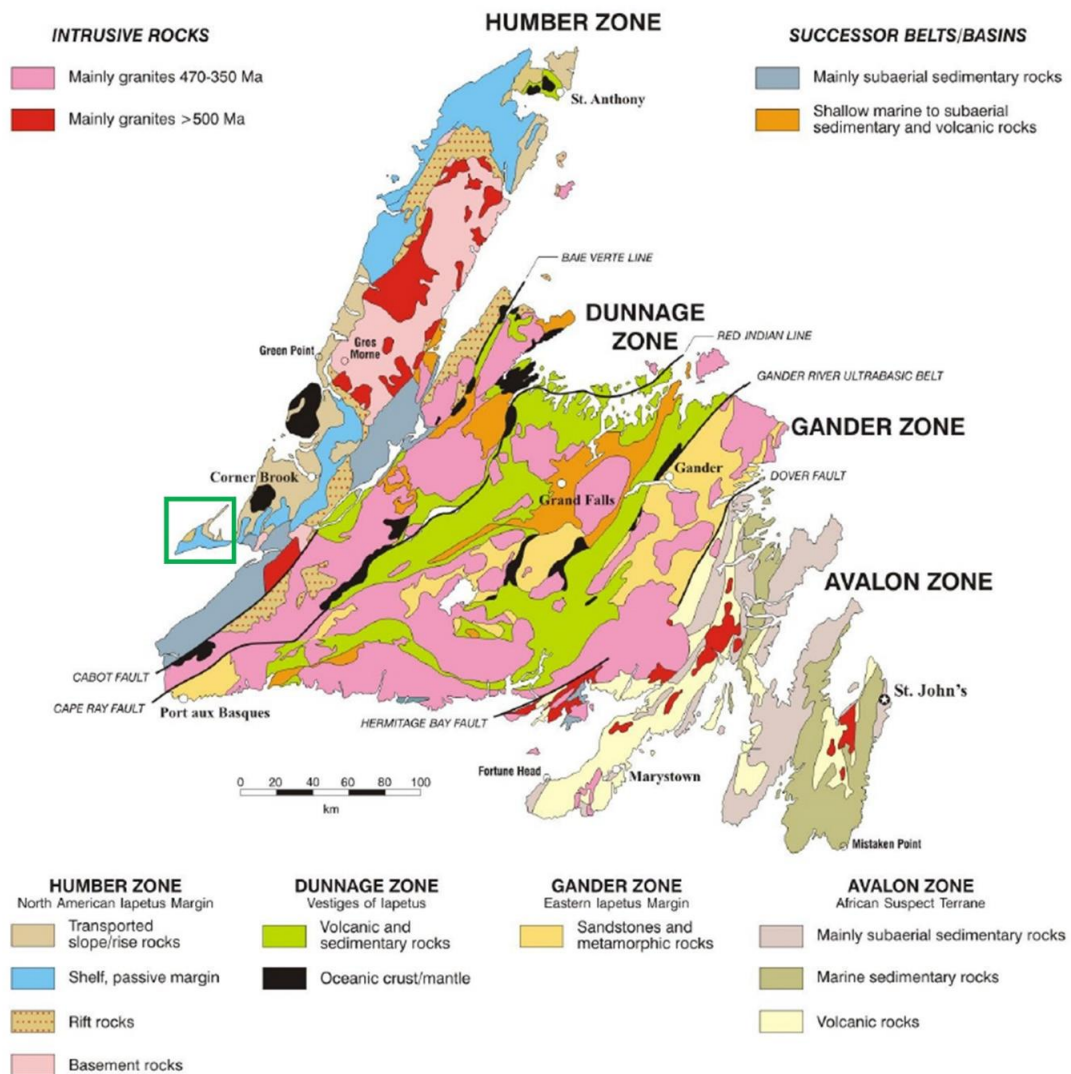


Fig. 1.1. A map of the island of Newfoundland showing the divisions of the four distinct tectono-stratigraphic zones; from west to east these zones are the Humber Zone, the Dunnage Zone, the Gander Zone, and the Avalon Zone. Green box shows location of the Port au Port Peninsula, which is in the Humber Zone (From Williams, 2004).



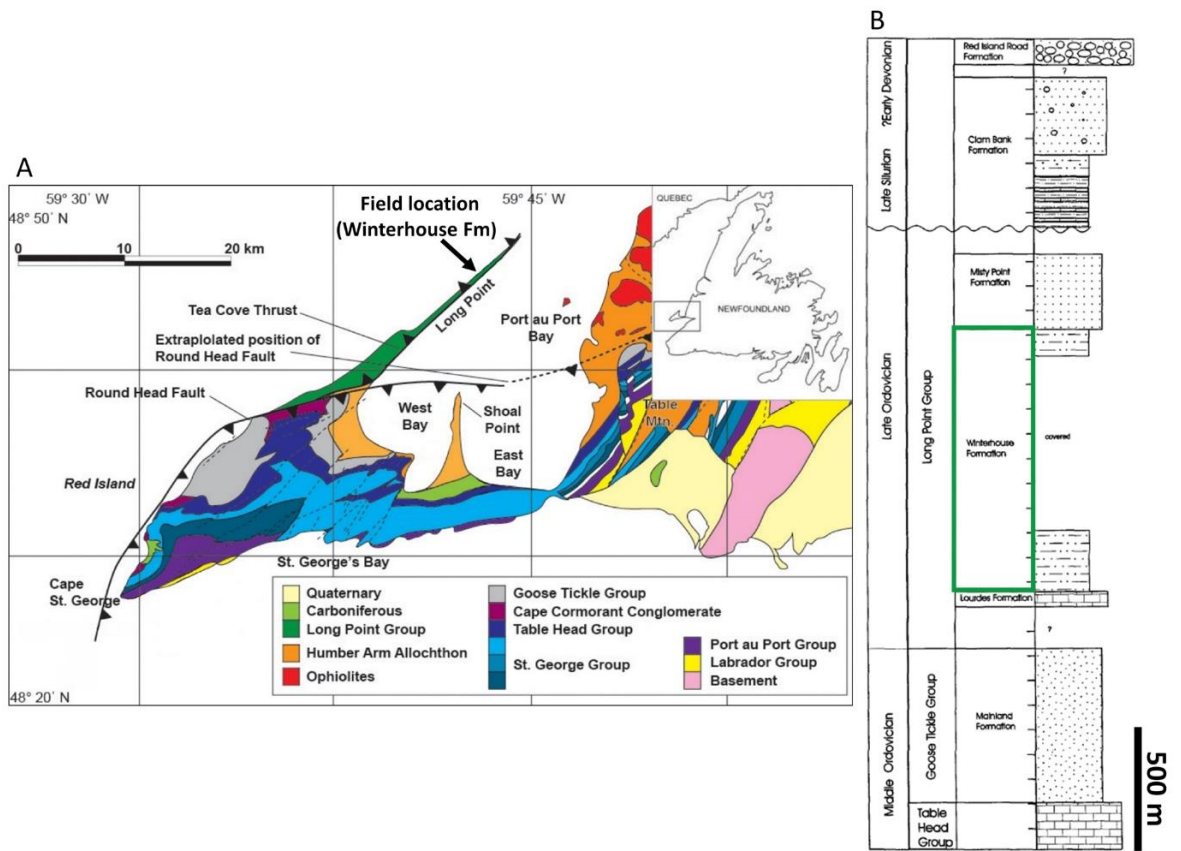


Fig. 1.2. A) Geologic map of the Port au Port Peninsula of Newfoundland, including the Winterhouse Formation as part of the Long Point Group (arrowed). Inset is an outline of a map of the island of Newfoundland, showing the (boxed) location of the Port au Port Peninsula (after Cooper *et al.*, 2001); B) Stratigraphic column of the foreland basin succession of the Port au Port Peninsula containing the Long Point Group. The green box highlights the Winterhouse Formation (after Quinn *et al.*, 1999).

## 2.2 *Parahaentzschelinia*

*Parahaentzschelinia* is described as a burrow system made up of conical bundles of numerous tubes radiating vertically and obliquely from one master shaft, commonly preserved on bedding plane surfaces as a rosette-shaped group of numerous small circular cross-sections, with a central conical depression due to erosion (Chamberlain, 1971; Dam, 1990; Uchman, 1995). Two ichnospecies of *Parahaentzschelinia* have been described: 1) the type species, *P. ardelia* Chamberlain, 1971 and; 2) *P. surlyki* Dam, 1990.

The type material of *Parahaentzschelinia* was described from thin bedded sandstones of the Pennsylvanian Atoka Formation in Oklahoma (Chamberlain, 1971). The type ichnospecies, *P. ardelia*, was described as conical bundles of small, irregular, tubes that are passively filled with mud or sand and radiate vertically and obliquely upward from a fixed point within the sediment (Fig. 1.3; Chamberlain, 1971). Bedding plane cross-sections were described as conical depressions 15-60 mm across, with individual tubes being 1.5 mm wide, and a “narrow lateral (?) gallery” was suggested at the base of the conical structure (Chamberlain, 1971). Type material was collected and figured (cf. Chamberlain, 1971); however a formal diagnosis was not provided.

The second ichnospecies, *Parahaentzschelinia surlyki*, was described from the shallow marine Lower Jurassic Neill Klintor Formation in Greenland (Dam, 1990). *Parahaentzschelinia surlyki* differs from *P. ardelia* in the following ways: 1) its much larger size, with tunnel diameters ranging from 4-20 mm and bedding surface cross-

sections up to 120 mm in diameter; 2) its thick ornamented concentric mud linings up to 8 mm thick; 3) and a main vertical shaft up to 15 mm in diameter and 15 cm in length, as opposed to the lateral gallery suggested for *P. ardelia* (Fig. 1.4; Dam, 1990). In the Neill Klintor Formation, *P. surlyki* was found to be numerous in fine-grained hummocky cross-stratified sandstones, and the long central shaft was suggested to be an escape burrow, while the thick wall was considered to be related to substrate cohesion (Dam, 1990).

The first formal diagnosis of *Parahaentschelinia* at the ichnogenic level was provided by Uchman (1995). Although a formal diagnosis had not been given for *P. ardelia*, an emended diagnosis for the ichnospecies was proposed based on material described from Late Carboniferous storm deposits in Poland (Gluszek, 1998). The proposed ichnospecific diagnosis included branched, horizontal tunnels with meniscate backfill (Gluszek, 1998). Gluszek's material was exclusively cross-sections on horizontal bedding planes, and consisted of rosette-shaped groups of cross-sections of vertical tubes with concentric filling of the same material as the host rock, as well as short horizontal branched burrows with meniscate filling, comparable to *Macaronichnus segregatis* (Gluszek, 1998). The rosette-shaped groupings on bedding planes were reported up to 9 cm in diameter, with an average diameter of 3 cm, while individual vertical burrow cross-sections were relatively consistent from 3 to 5 mm, and horizontal tunnels were up to 35 mm in length (Gluszek, 1998).

*Parahaentschelinia* has generally been interpreted as a dwelling and feeding burrow produced by a small deposit-feeding organism that repeatedly extended itself up and outward from a fixed point within the sediment in search of food

(Chamberlain, 1971; Dam, 1990; Gluszek, 1998). Most authors have considered the trace-maker to be a small worm (Chamberlain, 1971; Gluszek, 1998), while others have suggested that the structure is similar to burrows constructed by siphonate bivalves (Fürsich et al., 2006).

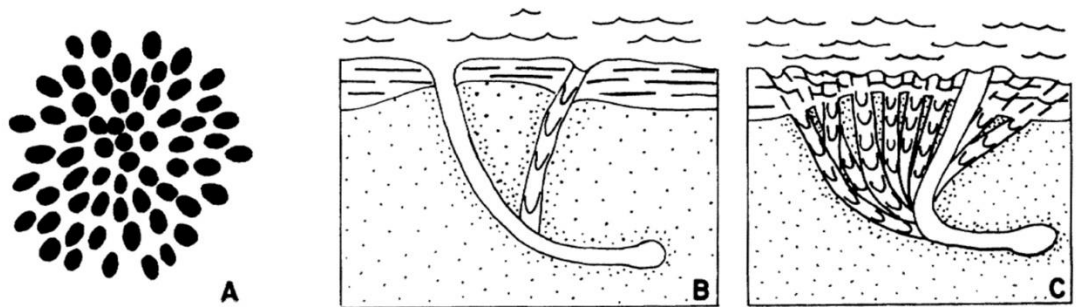


Fig. 1.3. Idealized sketch of *Parahaentzschelinia ardelia* based on material from the type locality of the Pennsylvanian Atoka Formation in Oklahoma, USA. A) Plan pattern; B) Cross section of initial development of burrowing; C) Complete perforation of sediment, showing conical bundles of small, irregular, tubes that are passively filled with mud from overlying sediment, and radiate vertically and obliquely upward from a fixed point within the sediment, possibly the “narrow lateral (?) gallery” (Chamberlain, 1971).

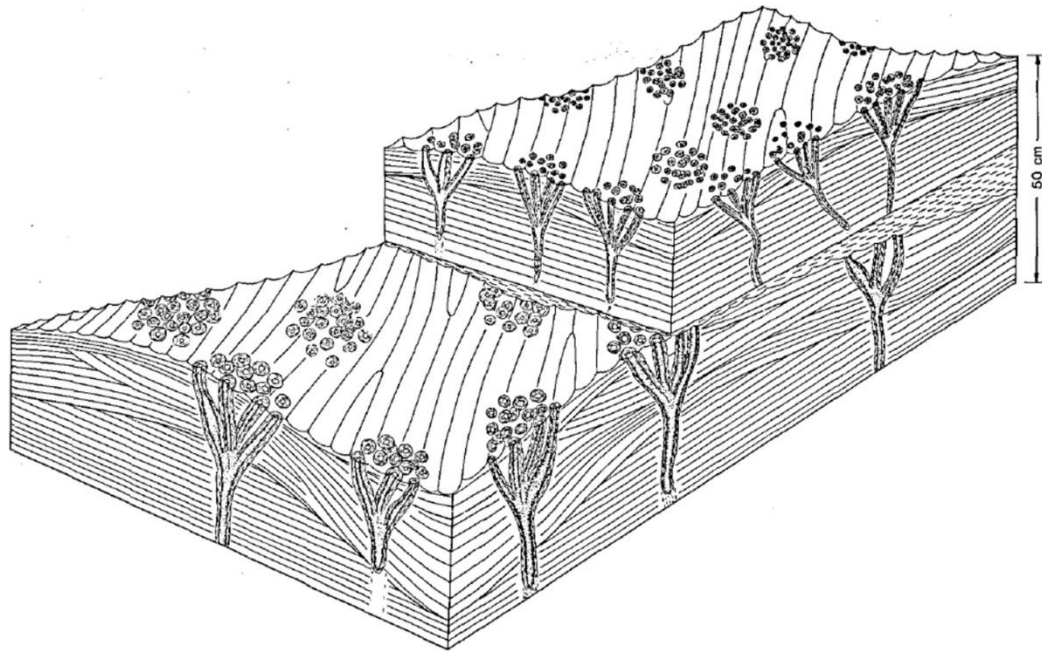


Fig. 1.4. Idealized sketch of *Parahaentzschelinia surlyki* based on specimens in hummocky cross-stratified sandstones of the shallow marine Lower Jurassic Neill Klintor Formation in Greenland. The central vertical shaft was interpreted as an escape burrow, while the numerous smaller tubes were interpreted as being developed as the trace maker repeatedly extended itself up and outward from a central point within the sediment in search for food. (From Dam, 1990).

### **2.3 Unconventional hydrocarbon plays and the potential impact of bioturbation on fracture susceptibility**

Unconventional hydrocarbon plays such as tight gas and shale gas plays are currently a key source of global energy. These plays are much more poorly understood than conventional reservoirs, and are typically composed of heterogeneous clay-rich mudstone or cemented “tight” fine-grained sandstone beds with ineffective micro-porosity and very little conventional permeability (Curtis, 2002; Holditch, 2006).

Shale gas plays are self-contained petroleum systems in which the source, reservoir, and seal are co-located (Martini *et al.*, 1998; Curtis, 2002). These plays are typically comprised of heterogeneous, low-permeability, organic carbon-rich mudstones, commonly containing high hydrophilic clay mineral content and varying amounts of silt-grade material (e.g. Curtis, 2002; Lemiski *et al.*, 2011). These systems contain large volumes of natural biogenic or thermogenic gas, which is typically: 1) present as free gas within unconnected microscopic inter-granular pore spaces or natural fractures; 2) adsorbed onto kerogen and clay-particle surfaces; or 3) dissolved in kerogen and bitumen (Schettler and Parmely, 1990; Curtis, 2002; Lemiski *et al.*, 2011). Sediments of this nature contain ineffective micro-porosity and matrix permeabilities in the nanodarcy range.

Tight gas plays differ from shale gas plays in that they are composed of a higher percentage of silt and sand-sized framework grains, and the source and reservoir rocks are not co-located. Tight gas sandstones act only as reservoir rocks, holding gas which

has migrated from nearby source rocks, with which they are commonly interbedded. Tight gas reservoirs are unconventional in the sense that they contain ineffective micro-porosity and therefore have very little conventional permeability (Holditch, 2006). The hydrocarbons contained within these reservoir facies are essentially stuck within pore spaces due to high capillary pressure conditions resulting from low porosity and permeability, and narrow pore throats.

The common aspect of developing unconventional plays is that they are difficult to exploit, as low permeabilities mean that fluid migration pathways are very short (Holditch, 2003, 2006). Unconventional plays cannot produce economic volumes of hydrocarbons at economic flow rates without assistance from reservoir stimulation treatments or special recovery processes and technologies that enhance the permeability of reservoir rocks (Holditch, 2003, 2006). In shale hydrocarbon and tight gas plays, hydraulic fracturing is typically used to create open fracture networks as conduits through which hydrocarbons can flow to the wellbore from otherwise impermeable media (Curtis, 2002; Holditch, 2003, 2006; Jenkins and Boyer, 2008). Permeability can be improved either by accessing pre-existing natural fracture systems or by inducing new fractures (Curtis, 2002). Current unconventional reservoir exploitation processes are highly dependent on the susceptibility of the reservoir rock to form fracture networks that are connected to the wellbore (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013).

Predicting the rheologic properties and fracture susceptibility of unconventional shale hydrocarbon and tight gas reservoir facies is a significant challenge that requires

more attention (cf. Bednarz and McIlroy 2012). Successful exploitation of such unconventional reservoirs relies upon the recognition of stratigraphic intervals that may be artificially fractured (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013). The recognition and assessment of pre-existing natural fractures, zones of enhanced brittleness in otherwise ductile shales, and planes of weakness, along which induced fractures may propagate, is critical in this process (e.g., Bowker *et al.*, 2007; Cipolla *et al.*, 2009, 2010; Bednarz and McIlroy, 2012; Bustin and Bustin, 2012). Producing realistic models of the mechanical properties of unconventional reservoirs is challenging and requires consideration of all lithologic anisotropies (e.g. sedimentary fabrics and ichnofabrics).

Bioturbation can result in the redistribution and sorting of grains, thereby producing anisotropies that can have a dramatic effect on a range of reservoir properties (cf. Pemberton and Gingras, 2005; Spila *et al.*, 2007; Tonkin *et al.*, 2010; Lemiski *et al.*, 2011; Bednarz and McIlroy, 2012; Gingras *et al.*, 2012, 2013). Enhanced fluid flow in some tight sandstones, siltstones, and mudstones is considered to be possible because of high porosities associated with trace fossils such as *Phycosiphon*, *Zoophycos*, and *Chondrites* (Pemberton and Gingras, 2005, Spila *et al.*, 2007; Lemiski *et al.*, 2011; Bednarz and McIlroy, 2012; Gingras *et al.* 2012, 2013; La Croix *et al.*, 2013). It has also been proposed that the fracture susceptibility of unconventional reservoirs is affected by burrow spacing and connectivity (Bednarz and McIlroy, 2012). It has been proposed that silt-rich *Phycosiphon*-like burrows in



shales increase fracture susceptibility by creating brittle quartz frameworks that may act as loci for fracture propagation in otherwise ductile mudstones (Bednarz and McIlroy, 2012).

### **3. Scientific importance and expected outcome**

The outcome of this research is relevant to a range of studies involving bioturbated sandstone facies, particularly studies focused on the Ordovician Anticosti Basin and other eastern Laurentian basins that are prospective for hydrocarbons (Hannigan and Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011).

#### **3.1 Chapter 2 - Systematic ichnology of the Ordovician Winterhouse**

##### **Formation of Long Point, Port au Port, Newfoundland, Canada**

The calcareous silt-rich sandstones and mudstones of the Late Ordovician Winterhouse Formation of Western Newfoundland contain a hitherto undescribed well-preserved and diverse assemblage of trace fossils. Systematic ichnological studies are important for cataloguing trace fossil assemblages and can be used to enhance the understanding of the paleoecology of an area, as well as for comparison in other ichnological studies. This systematic ichnological study of the Winterhouse Formation is particularly useful for comparison with studies focussed on the Ordovician of the Anticosti Basin and other eastern Laurentian basins (Hannigan and

Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011).

### **3.2 Chapter 3 - Detailed three-dimensional morphological analysis of *Parahaentschelinia*-like burrow systems**

The lack of documentation of the range of morphological disparity within the type series is found to be a shortcoming of the description of *Parahaentschelinia* that is probably true for many taxa (see also Miller, 2011).

This study highlights the importance of thoroughly documenting the complexity and range of burrow morphologies in a type series, rather than just a single idiomorphic specimen, when creating diagnoses and descriptions. Complex morphologies of trace fossils generally reflect a range of behaviours in the trace-making organism(s) (Hansel, 1984; Dawkins, 1989; Miller and Aalto, 1998). Understanding complex burrow morphologies, including the range of morphological disparity, is important for interpreting trace-maker behaviour (cf. Miller, 1998; Miller and Aalto, 1998; Bednarz and McIlroy 2009; Miller, 2011). Incomplete morphological understanding causes problems when inferring trace-maker ethology, leading to oversimplified paleobiological and paleoenvironmental interpretations. The critical analysis of the morphological complexity of the *Parahaentschelinia*-like burrow systems described herein allow for comparison with similar modern and fossil burrows in order to more realistically reconsider the trace-maker's ethology and paleobiology.

Idealizing morphological descriptions of type material and omitting a discussion of the variability of morphologies in the diagnoses of type specimens also has the potential to create ichnotaxonomic conundrums (cf. Miller, 2011). Considering the strong similarity between *Parahaentschelinia* and the sub-vertical burrow components described herein, it is likely that the material could be ascribed to that taxon, but it is recommended that the type locality of *Parahaentschelinia* be re-sampled and analysed in the light of this study. If the variety of morphologies described herein are indeed found in the type locality then an emended ichnogenic diagnosis would be required.

### **3.3 Chapter 4 - The relationship between *Parahaentschelinia*-like burrows and natural fracture propagation patterns in the Winterhouse Formation**

Since the permeability of unconventional reservoir rocks must be enhanced by special recovery techniques in order to stimulate economic production, the identification of stratigraphic intervals through which fractures may preferentially propagate is therefore critical for effective reservoir stimulation by hydraulic fracturing. Subtle lithologic and ichnological heterogeneities may dramatically affect reservoir properties, including rheologic properties and fracture susceptibility. There is currently a need to develop a better understanding of the factors that influence fracture susceptibility in unconventional hydrocarbon reservoirs. Predicting the rheologic properties and fracture susceptibility of unconventional shale hydrocarbon and tight gas reservoir facies is a significant challenge that has received little attention to date (Bednarz and McIlroy 2012).

Trace fossils are an overlooked source of mechanical heterogeneity that can potentially have a dramatic effect on natural and artificial fracture development in reservoir facies. To date no studies have directly studied the relationship between trace fossils and fracture susceptibility in tight sandstones. In this regard, there is a need for improved three-dimensional morphological understanding of ichnofabric-forming trace fossils (cf. Leaman and McIlroy, 2015) and their relationship to the rheological properties of both brittle and ductile sedimentary facies (Bednarz and McIlroy, 2012). This study presents a three-dimensional model illustrating the relationship between a vertical burrow (aff. *Parahaentschelina*) that occurs in meandering chains, and associated natural mineral-filled fractures in cemented silt-rich fine-grained sandstones of the Winterhouse Formation in Western Newfoundland. The Winterhouse Formation is considered analogous to unconventional tight gas reservoir facies in the region. The natural fractures in the bioturbated sandstones of the Winterhouse Formation allow this investigation of fracture susceptibility in relation to trace fossil distribution.

Maximizing the surface area of fluid flow pathways that are connected to the wellbore, by creating and/or accessing complex interconnected fracture networks in otherwise impermeable reservoir facies, is a critical factor in productivity (e.g., Cipolla *et al.*, 2009, 2010; Wang and Reed, 2009; Fan *et al.*, 2010; Khan *et al.*, 2011, 2012; Bust *et al.*, 2013). Complex, interconnected three-dimensional trace fossil networks within “tight” sandstone reservoir facies can potentially create complex, interconnected planes of weakness along which fractures may preferentially propagate, thereby significantly increasing the surface area of fracture networks.

Understanding the structure and distribution of burrows in potential reservoir facies is essential for accurate calculations of reservoir properties and for geomechanical modelling. The complete nature and extent of the relationship between burrows and fracture propagation patterns cannot be fully appreciated and understood from two-dimensional cross sections in outcrop, core or hand sample. This study demonstrates how the serial grinding and three-dimensional modelling methodologies described by Bednarz *et al.* (2015) can be employed in studies investigating the relationship between fracture systems and trace fossils.

The methodology used in this study will provide a framework for a better morphological understanding of the relationship between burrows and natural fracture propagation patterns. This work is a proof of concept study aiming to lead to larger scale more complete future studies integrating rock mechanics, structural geology, petroleum geology, and ichnology. An understanding of the effect of trace fossils on natural fracture susceptibility is significant for realistic reservoir characterization in bioturbated reservoirs where induced fracturing techniques may be employed.

#### **4. Material and methodology**

Material for this study was collected both from float and in-situ from the Winterhouse Formation on the Port au Port Peninsula in Western Newfoundland (Fig. 1.2). These samples are augmented by hundreds of high-resolution field photographs.

All samples used to produce three-dimensional models were processed using the precision serial grinding and photography methods described by Bednarz *et al.*

(2015). For this process, each sample was encased in a plaster block to create a consistent frame of reference, and sequentially ground in consistent precise increments using a diamond carbide grinding tool operated by a computer guided milling machine at Memorial University of Newfoundland. Separate samples were ground in the bedding-parallel direction and perpendicular to bedding. Grinding increments for this study were 0.1 mm, enabling the high-resolution reconstruction of sub-millimetre-scale structures. Photos were taken after each sequential cut under consistent lighting conditions. Each sample was photographed both dry and wet with oil, as some features were more easily studied while wet while others were only visible while dry. The photos were then digitally aligned and processed in Adobe Photoshop™.

The high-resolution three-dimensional morphological models of *Parahaentzschelinia*-like burrows and the natural fracture systems were produced from two samples using the modelling methodology described by Bednarz *et al.* (2015). Each burrow and fracture system was tracked separately and manually selected with a tablet pen from sequential images. The burrows and fractures were then isolated from each photo and imported into the three-dimensional modelling software VG Studio Max™, producing high-resolution models of the burrows that can be manipulated and sectioned in any plane.

Full block models comparable to a standard CT image array were also produced by importing the aligned block photographs into the modelling software, as opposed to extracting the burrows from each photograph. This enabled the capability to clip

through each of the full samples in any orientation, and the observation of near burrow sedimentary structures on any plane cut through a model of the sample.

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## CHAPTER 2

Systematic ichnology of the Ordovician Winterhouse Formation of  
Long Point, Port au Port, Newfoundland, Canada

**Systematic ichnology of the Ordovician Winterhouse  
Formation of Long Point, Port au Port, Newfoundland,  
Canada**

Robyn Reynolds, Duncan McIlroy

Memorial University of Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive,  
St. John's, Newfoundland, A1B 3X5, Canada

**KEYWORDS**

Systematic ichnology; ichnotaxonomy; ichnology; Ordovician; Winterhouse  
Formation; Newfoundland, Canada

Corresponding author: Robyn Reynolds, Memorial University of  
Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive, St.  
John's, Newfoundland, A1B 3X5, Canada, Robyn.reynolds@mun.ca; 709  
864 6762; 709 864-7437 (fax)

## 1. Abstract

Twenty ichnotaxa are documented from the mudstone and sandstone storm deposits of the Upper Ordovician Winterhouse Formation, which is exclusively exposed on the Port au Port Peninsula of Western Newfoundland. This is the first systematic ichnological documentation of the Winterhouse Formation, which contains a well-preserved and diverse assemblage of trace fossils. 19 ichnospecies are assigned to 15 ichnogenera, and one additional unknown burrow system is described. The ichnotaxa documented in this study are: *Chondrites targionii*, *Chondrites recurvus*, *Cruziana goldfussi*, *Cruziana* isp., *Dictyodora zimmermanni*, *Halopoa imbricata*, *Monomorphichnus lineatus*, *Paleodictyon gomezi*, ?*Parahaentzschelinia* isp., *Phymatoderma granulata*, *Phymatoderma* aff. *granulata*, *Phymatoderma melvillensis*, *Rhizocorallium commune*, *Rusophycus* isp., *Skolichnus hoernessi*, *Squamodictyon petaloideum*, *Taenidium* isp., *Teichichnus rectus*, *Trichichnus linearis*, and an unknown open gallery system. The ichnofossil assemblage reflects a diverse array of interpreted trace-maker behaviours, including dwelling, locomotion, and a variety of different feeding strategies.

## **2. Introduction**

### **2.1 Purpose**

The calcareous silty sandstones and mudstones of the Late Ordovician Winterhouse Formation of Western Newfoundland contain a, hitherto undescribed, well-preserved and diverse assemblage of trace fossils. This systematic ichnological study can be used to enhance our understanding of the paleoecology of the Winterhouse Formation, and can be used for comparison in other ichnological studies, particularly those focused on the Ordovician Anticosti Basin and other eastern Laurentian basins that are elsewhere prospective for hydrocarbons (Hannigan and Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011).

### **2.2 Geological and paleoenvironmental setting**

The Upper Ordovician Winterhouse Formation was deposited as part of the Long Point Group in the Western Newfoundland Basin (Fig. 2.1; Waldron *et al.*, 1993; Quinn *et al.*, 1999). The only onshore exposure of the Long Point Group is on the Port au Port Peninsula in Western Newfoundland, but these deposits are thought to be extensive offshore below the Gulf of St. Lawrence (Sinclair, 1993). The lower 320 m of the Winterhouse Formation is exposed in outcrop on the Port au Port Peninsula, and another approximately 540 m interval is thought to be covered above this (Quinn *et al.*, 1999).

The Winterhouse Formation is a mixed siliciclastic/carbonate succession that shows net progradation and is thought to represent shallow marine storm-dominated

shelf-deposits (Quinn *et al.*, 1999). The exposed section consists of upward-coarsening parasequences of inter-bedded carbonaceous silt-rich mudstones and silt-rich fine-grained sandstones with abundant trace fossils capped by marine flooding surfaces (Fig. 2.2 A), with minor limestone breccias and slump deposits. Bioturbation is common in the inter-bedded decimetre-scale mudstone beds and centimetre-scale sandstone beds of the lower Winterhouse Formation. Ripple cross-laminated sandstone beds are normally graded, have erosive bases with tool marks, and both sinuous crested wave ripples and interference ripples on their upper surfaces (Fig. 2.2). This association of sedimentary structures is considered herein to be indicative of storm deposits including tempestites deposited from hypopycnal flows (cf. Aigner and Reineck, 1982). Hummocky cross-stratification is present in many of the approx. 10 cm thick sandstone beds that characterize the upper portion of parasequences, and indicate shallowing of the parasequences to above storm wave base. Tabular cross-bedded sandstones show a net mean increase in thickness (>50cm thick) and abundance toward the top of the exposed section. Bioturbation is less common in the thickly bedded tabular cross-bedded sandstones than in the mud-rich lower portion of the Winterhouse Formation.



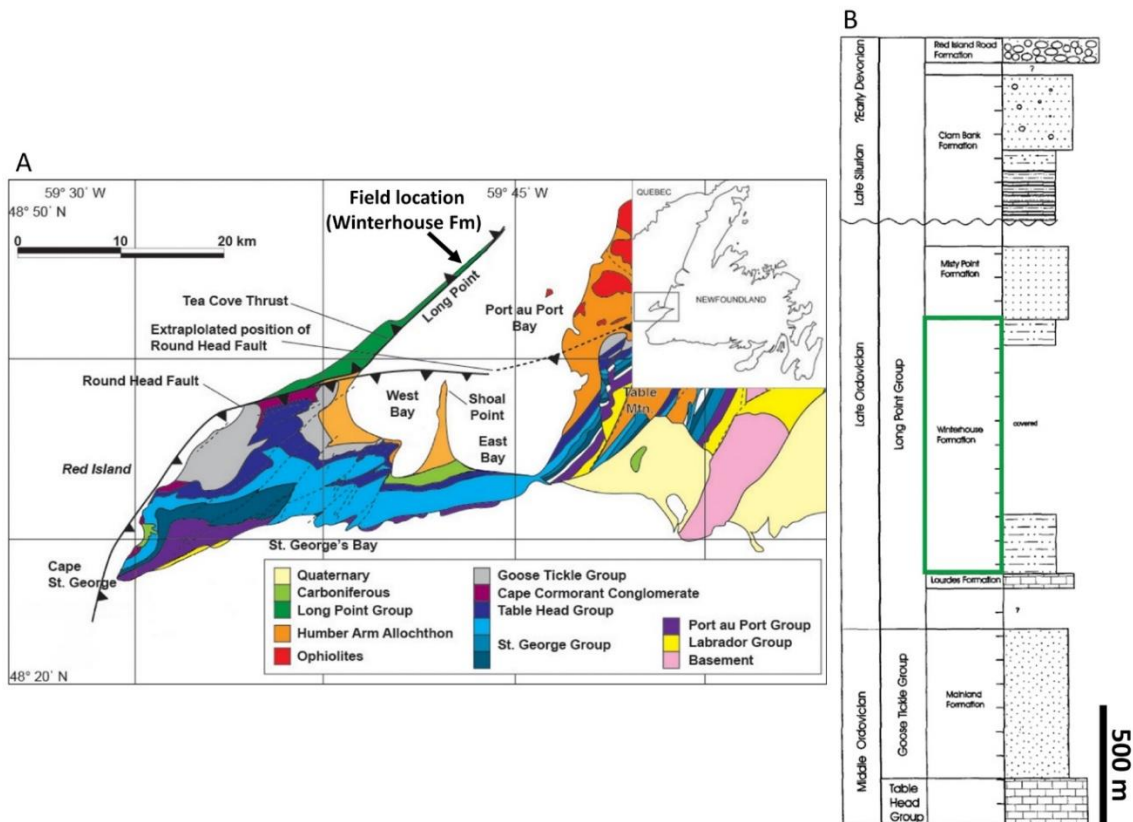


Fig. 2.1. A) Geologic map of the Port au Port Peninsula of Newfoundland, including the Winterhouse Formation as part of the Long Point Group (arrowed). Inset is an outline of a map of the island of Newfoundland, showing the (boxed) location of the Port au Port Peninsula (after Cooper *et al.*, 2001); B) Stratigraphic column of the foreland basin succession of the Port au Port Peninsula containing the Long Point Group. The green box highlights the Winterhouse Formation (after Quinn *et al.*, 1999).

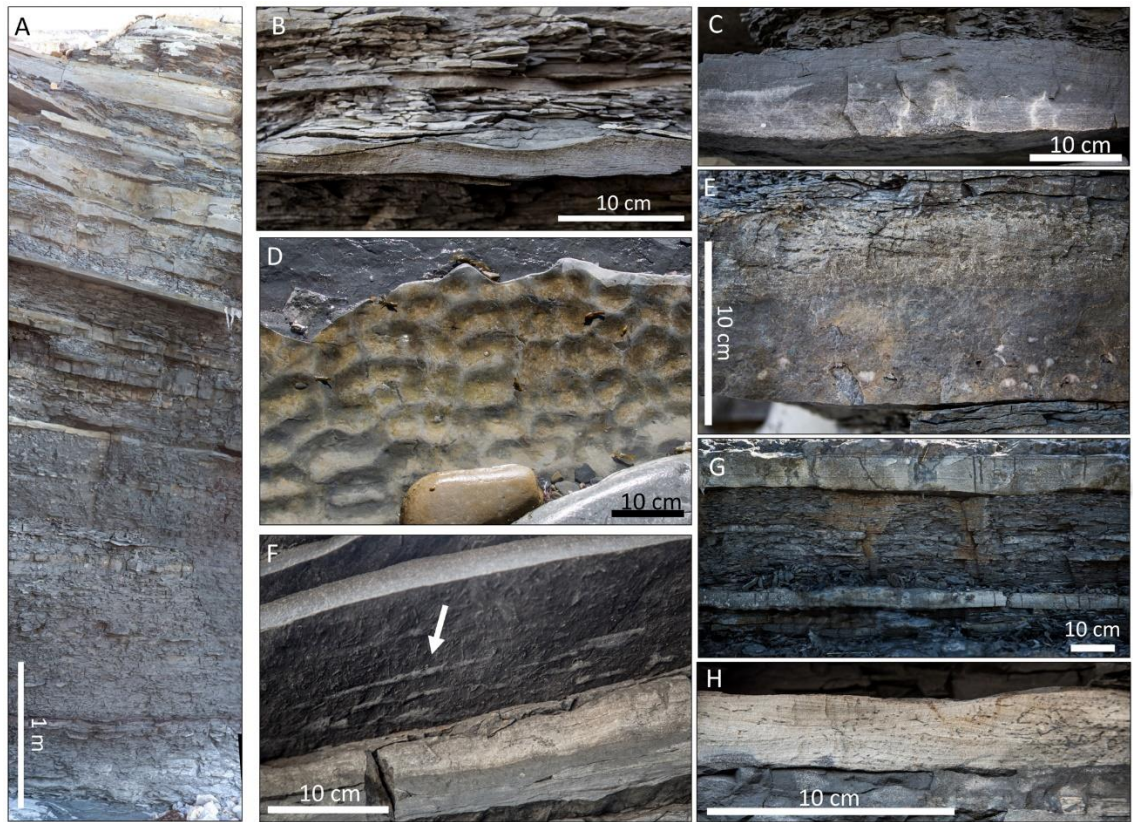


Fig. 2.2. Sedimentology of the Winterhouse Formation exposed in Long Point: A) Upward coarsening decimetre-scale carbonate-rich silty mudstone beds inter-bedded with centimetre-scale silty fine-grained sandstone event beds; B) Normally graded, ripple cross-laminated sandstone bed with erosive base sand wave and interference ripples on upper surfaces; C) Hummocky cross-stratified sandstone; D) Upper surface of sandstone bed with wave-generated interference ripples; E) Hummocky cross-stratified sandstone bed with shell debris at base; F) Base of sandstone bed containing tool marks (arrowed); G) Interbedded decimetre-scale mudstone beds and centimeter-scale sandstone event beds, penetrated by *Trichichnus* and aff. *Parahaentzschelinia* burrows penetrating; H) Centimeter-scale ripple-cross-laminated sandstone beds containing *Chondrites*.

### 3. Systematic ichnology

Ichnogenus *Chondrites* von Sternberg, 1833

**Type Ichnospecies:** *Chondrites targionii* Brongniart, 1828

**Ichnogeneric Diagnosis:** Regularly branching tunnel systems consisting of a small number of master shafts open to the surface that ramify at depth to form a dendritic network (From Uchman, 1999; after Osgood, 1970 and Fürsich, 1974b).

**Remarks:** This ichnogenus was in a state of disarray, having over 150 *Chondrites* ichnospecies until review by Fu (1991). Using mode of branching as the only ichnotaxobase, the over 150 ichnospecies were synonymized, leaving only 4 valid ichnospecies: *C. targionii* Brongniart, 1823, *C. intricatus* Brongniart, 1828, *C. patulus* Fischer-Ooster, 1858, and *C. recurvus* Brongniart, 1823 (Fu, 1991). The ratio of burrow width to burrow system radius was proposed as an additional useful ichnotaxobase, as it better describes overall morphology (Uchman, 1999). It was argued that specimens with similar branching mode but considerably different morphometric parameters should be differentiated at the ichnospecific level (Uchman, 1999). Following this, two additional ichnospecies were distinguished, *C. stellaris* Uchman, 1999, and *C. caespitosus* Fischer-Ooster, 1958 (Uchman, 1999). Most recently the ichnospecies *C. affinis* von Sternberg,

1833, which had otherwise been synonymized with *C. targionii*, was re-established on the basis of its ratio of burrow width to burrow system radius (Uchman *et al.*, 2012).

*Chondrites* has been described from the Cambrian to the Holocene (e.g. Werner and Wetzel, 1981; Crimes, 1987) and has been interpreted to represent the systematic probing activity of an unknown infaunal deposit-feeding organism, possibly using a retractable proboscis (e.g. Osgood, 1970; Uchman, 1999). It has also been suggested that surface deposit feeders create the tubular structures that are subsequently packed with faecal pellets in subsurface burrows (Kotake, 1991). However, most modern consensus points towards a chemosymbiotic function (Seilacher, 1990; Fu 1991). *Chondrites* is considered to be a deep tier trace fossil that may represent dysoxic paleoenvironmental conditions (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986, 1989, 1991; Seilacher, 1990; Fu, 1991). It has been suggested that the trace maker was capable of tolerating dysaerobic conditions via a connection to the overlying water column (Bromley and Ekdale, 1984; Ekdale and Mason, 1988).

*Chondrites targionii* (Brongniart, 1828)

Fig. 2.3 A-C

**Ichnospecific Diagnosis:** *Chondrites* characterized by well expressed primary successive branchings, which are commonly slightly curved. The angle of branching is usually sharp. Most of the tunnels are a few millimetres wide (From Uchman, 1999)

**Description:** Straight to slightly curved tunnels are 1-3 mm wide. Tunnel diameters are relatively consistent within a single specimen and are filled with finer grained material than the host sediment. Primary successive branching is well expressed, commonly displaying second and third order branching. Angle of branching is typically around 45°. Branches can be over 10 cm in length, with whole burrow systems reaching up to 20 cm in diameter. Specimens were observed in float and in situ, and occur on both the base of fine-grained sandstone event beds and on exposed upper bedding plane surfaces.

**Remarks:** *Chondrites targionii* and *C. affinis* were initially synonymized due to their similarly acute angle of branching and slightly curved branches (Fu, 1991; Uchman, 1999). Examination of the type material of *C. affinis*, along with comparable but better preserved material from the Late Cretaceous-Eocene Saraceno Formation of the Southern Apennines, Italy, demonstrated that the morphometric parameters of these two ichnospecies are different (Uchman *et al.*, 2012). The majority of specimens of *C.*

*targionii* have tunnels ranging from 1.5-2.5 mm wide, while tunnels of *C. affinis* are typically 4-5.5 mm wide, thus the ratio of burrow width to burrow system radius is generally smaller in *C. affinis* (Uchman *et al.*, 2012). *Chondrites targionii* tunnels have also been reported to be as narrow as 0.5 mm wide (Brongniart, 1828), thus overlapping with the generally smaller ichnospecies *C. intricatus* (Brongniart, 1828), however *C. intricatus* is differentiated by its straight or almost straight branches (see Fu, 1991; Uchman, 1999; Uchman *et al.*, 2012).

*Chondrites recurvus* (Brongniart, 1823)

Fig. 2.3 D, E

**Diagnosis:** *Chondrites* in which branches arise only on one side of the master branch and which are all bent in one direction in a lyre-shape in two, bilaterally opposed directions. There are commonly one or two orders of branching, rarely a third (From Uchman, 1999; after Fu, 1991)

**Description:** The master branch of the specimens herein exhibits the diagnostic lyre shape (Fig. 2.3 D). Second and third order branches are slightly to strongly curved, and arise predominantly from the convex side of branches. Tunnel widths range from 1-5 mm. Tunnels are unlined and filled with finer-grained material than the host rock. Burrow systems are in excess of 10 cm in total diameter.



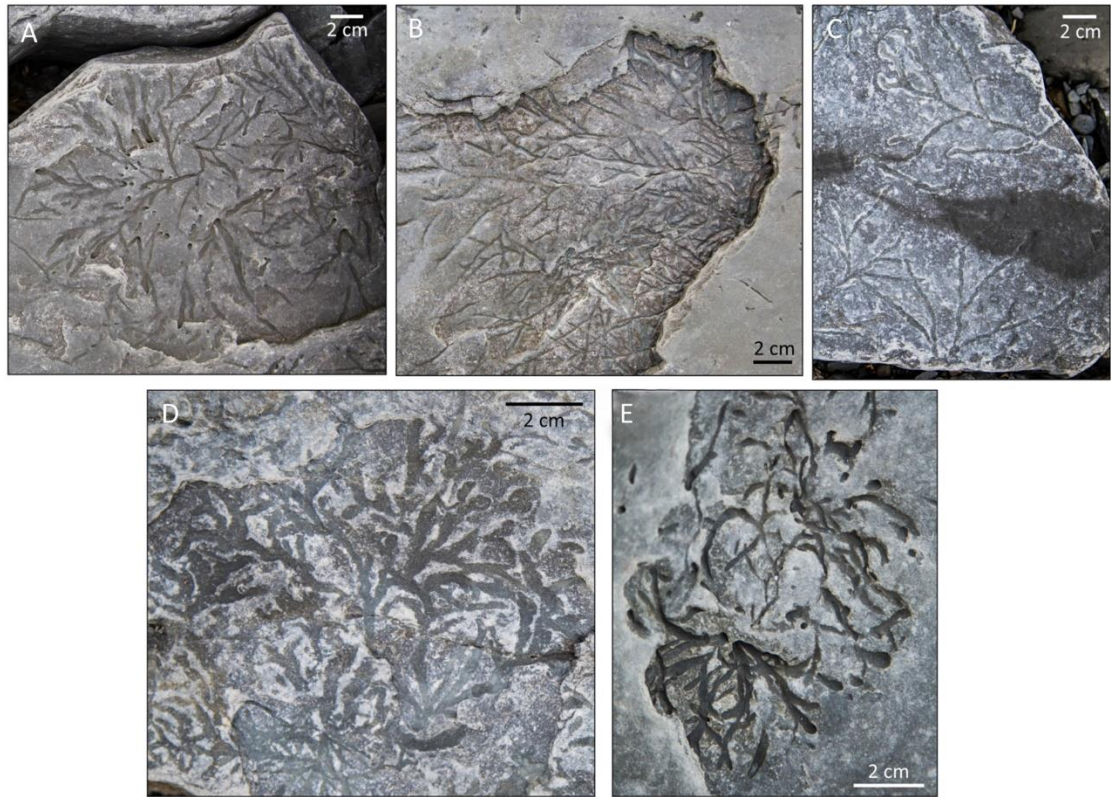


Fig. 2.3. *Chondrites* preserved in silty fine-grained sandstones. A-C) *Chondrites targionii*; D-E) *Chondrites recurvus*

Ichnogenus *Cruziana* d'Orbigny, 1842

**Type Ichnospecies:** *Cruziana rugosa* d'Orbigny, 1842 (Miller 1889).

**Ichnogeneric Diagnosis:** Elongate, bandlike, bilobate or—rarely—unilobate furrows or burrows covered by herringbone-shaped or transverse ridges, with or without two outer smooth or longitudinally striellate zones outside the V-markings, with or without lateral ridges and/or wisp-like markings if preserved on bedding soles (From Fillion and Pickerill, 1990; after Häntzschel 1975; Pickerill *et al.* 1984).

*Cruziana* cf. *goldfussi* (Rouault, 1850)

Fig. 2.4 A

**Ichnospecific Diagnosis:** *Cruziana* with well-developed inner lobes but lacking outer lobes. Scratch marks are fine and regular, do not criss-cross, make an acute V-angle and may become parallel to the median line a median-posterior direction. Outer margins typically consist of two lateral ridges (From Fillion and Pickerill, 1990; after Rouault, 1850; Crimes and Marcos 1976; Durand 1985).



**Description:** Bilobate trace with lateral ridges and a pronounced median furrow preserved in convex hyporelief on the base of a fine grained sandstone bed. Lobes are weakly convex, and 4-6 mm in width, with lateral grooves approximately 1 mm in width. Overall trace width is up to 1.5 cm, with a length of 5 cm. The lobes are highly weathered, but faint scratch marks preserved are orientated almost parallel to median furrow (Fig. 2.4 A).

**Remarks:**

The described specimen is heavily weathered, but most closely resembles *Cruziana goldfussi*. *Cruziana goldfussi* is part of the ‘*Cruziana rugosa* Group’ (Seilacher, 1970, 1992; Egenhoff *et al.*, 2007). In the past there has been taxonomic uncertainty surrounding *C. goldfussi* and the similar ichnospecies *Cruziana furcifera* d’Orbigny (1842), which is also part of the ‘*Cruziana rugosa* Group’ (cf. Kolb and Wolf, 1979; Fillion and Pickerill, 1990, Egenhoff *et al.*, 2007). Many of the ichnotaxobases of the ichnospecies *goldfussi* and *furcifera* are similar, and the two ichnospecies have been documented to intergrade (Mángano *et al.*, 2001). *Cruziana goldfussi* is considered to primarily differ from *C. furcifera* in having lateral grooves or ridges and finer scratch marks that do not exhibit the coarser rhombic criss-crossing pattern of scratches typical of *C. furcifera* (Lebesconte, 1883; Bergström, 1976; Fillion and Pickerill, 1990; Egenhoff *et al.*, 2007). In our material the lobes are heavily weathered and scratch marks are not preserved in enough detail to confirm a diagnosis, however lateral ridges are clearly preserved. The lateral margins have been generally interpreted as being the result of the

trace-maker (typically considered to be a trilobite) impressing genal and/or pygidial spines into the sediment during furrowing type behaviours (Crimes, 1970a). In the small section of our sample where scratch marks are visible, they run nearly parallel to the midline, which is consistent with the diagnosis of *C. goldfussi* (Fillion and Pickerill, 1990), but it is not possible to tell whether they make the diagnostic acute V-angle. The small size of this specimen (maximum 1.5 cm in total width) is slightly smaller than most documented occurrences of this ichnospecies, which usually report total widths of 2.5-8.5 cm (e.g. Fillion and Pickerill, 1990; Egenhoff *et al.*, 2007). As size is generally not considered to be a valid ichnotaxobase (Pickerill, 1994; Bertling *et al.* 2006), we do not consider this an obstacle to tentatively assigning our material to *C. goldfussi*.

The present material may also be compared with *Cruziana rouaulti* Lebesconte (1883) on the basis of the lateral margins. *Cruziana rouaulti*, which also belongs to the ‘*Cruziana rugosa* Group’, is characterized by its generally smooth lobes without prominent scratch marks, and small lateral ridges (Ergenhoff *et al.*, 2007). It is typically described as being less than 2 cm in total width, which is comparable to the material described here. While smooth lobes are characteristic of *C. rouaulti*, faint scratch marks orientated at a right angle to the trace axis have been documented (Ergenhoff *et al.*, 2007). The scratch marks visible in our material, albeit weathered, run parallel to the length of the lobe rather than perpendicular as in *C. rouaulti*. The lobes of *C. rouaulti* are also generally described as being flatter than the lobes observed in our specimens, which are slightly domed. The ichnotaxonomic status of *C. rouaulti* is contentious, and has been compared with *Didymaulichnus* (cf. Peneau, 1944; Crimes, 1970; Young, 1972; Durand,

1985). There are additionally morphological similarities with *C. semiplicata* (Salter, 1853) that has similar lateral ridges, a median furrow, and is of comparable size, however, *C. simplicata* is characterized by both endopodal and exopodal lobes containing complex lobe ornamentation that are not documented herein. Thus the ichnotaxobases present in our material do not merit assignment to this ichnospecies.

*Cruziana* ichnospecies are often used in biostratigraphic studies (e.g. Crimes, 1968, 1969; Seilacher, 1970, 1992, 1994). The ‘*Cruziana rugosa* Group’ has been described as being restricted to Lower Ordovician strata (Seilacher, 1970, 1992). However a recent study documenting all ‘*C. rugosa* Group’ ichnospecies (except for *C. rouaulti*) from Lower Ordovician to Upper Ordovician strata of Bolivia has cast doubt on the biostratigraphic relevance of *Cruziana* (Egenhoff *et al.*, 2007). If the specimens described herein from the Winterhouse Formation are confirmed to be *C. goldfussi*, this would provide another documentation of this ichnospecies in Upper Ordovician strata.

*Cruziana* isp.

Fig. 2.4 B-F

**Description:** Weathered straight to slightly curved burrows containing transverse ridges, gradationally preserved in positive through negative epirelief in fine grained sandstone beds (Fig. 2.4 B). Burrows are 3-5 cm wide and in excess of a meter in length. Unilobate forms were observed to intergrade with biolobate forms in the field. In transverse cross-

section, burrows with unilobate upper surfaces show bilobate lower surfaces (Fig. 2.4 E). Longitudinal cross-sectioning of a burrow preserved in positive epirelief shows shallow inclined back-fill consisting of fine-grained sandstone laminae 2.5-5 mm thick that superficially resemble ripple cross lamination in longitudinal section (Fig. 2.4 F) and the trace fossil *Teichichnus* in transverse section (Fig. 2.4 E). Cross-sectioning of burrow preserved in convex hyporelief shows that it is crosscut by *Trichichnus*, and aff. *Parahaentzschelinia* burrows (Fig. 2.4 E, F).

**Remarks:** While *Cruziana* is a fairly well recognized trace fossil, its formation is an area of contention (e.g. Seilacher, 1955, 1970, 1982; Crimes, 1975, Baldwin, 1977; Goldring, 1984). Some authors consider *Cruziana* to be a surface trail, whereby the trace-maker cut through mud at the sediment-water interface, and the trail was subsequently cast by newly deposited sand (e.g. Crimes, 1975; Baldwin, 1977). Whereas other authors have outlined an argument for an intrastratal formation, whereby the trace-maker ploughed into a sandy layer to an underlying muddy layer (e.g. Seilacher 1955, 1970, 1982; Goldring, 1984), or as true burrows or tunnels (Birkenmajer and Burton, 1971). A thorough understanding of the formation of *Cruziana* can only be achieved through complete sectioning of the trace fossil to allow for an interpretation of the relationship between the trace fossil and the adjacent sediment. However, although there has been considerable discussion regarding the formation of this trace fossil, such complete sectioning is rarely incorporated into studies (cf. Goldring, 1984). For this study a *Cruziana* sample preserved in positive epirelief from the Winterhouse Formation was sectioned longitudinally and transversely.

Longitudinal cross-sectioning of the burrow reveals inclined backfill of fine-grained sandstone (Fig. 2.4 F). Similar back-fill was observed in a longitudinal cross-section of a *Cruziana* specimen from Lower Ordovician deposits in Portugal (Goldring, 1984). The Portugal specimen was described as having “an irregular meniscus form” and was considered to possibly suggest a tunneling method of formation (Goldring, 1984). As with Goldring’s material, the sandy backfill within the specimen herein, and its preservation in positive epirelief, is considered to be suggestive of tunnelling as opposed to formation as an open surface trail on a muddy sediment-water interface.

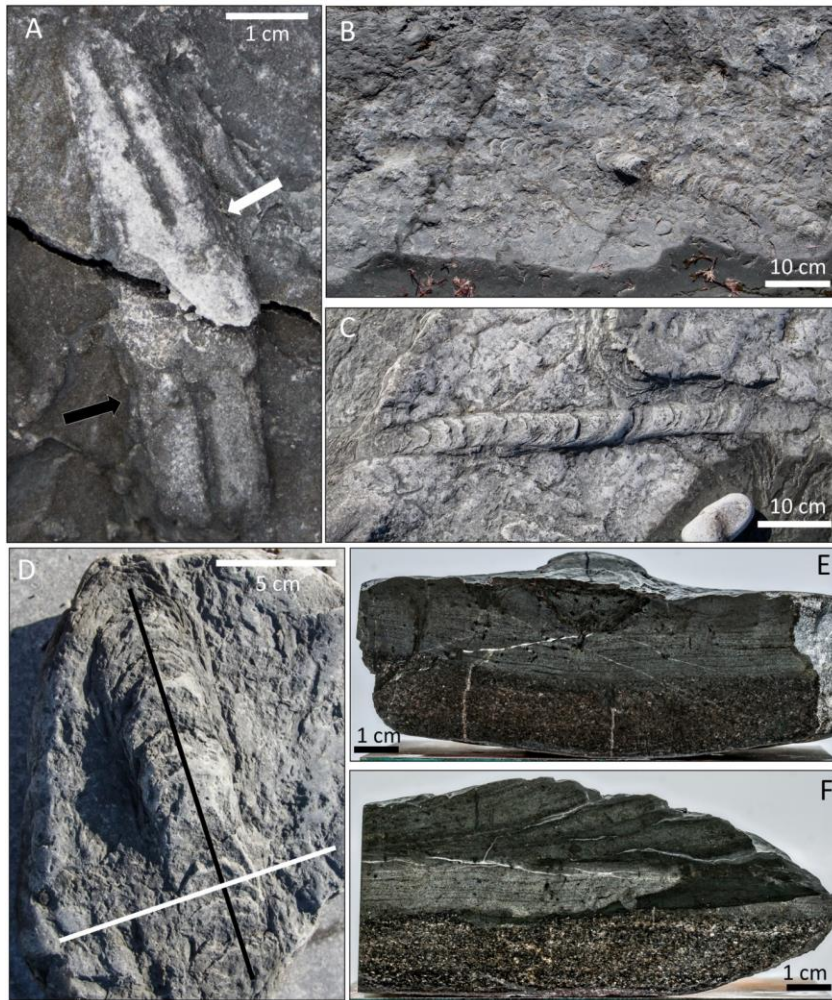


Fig. 2.4. A) *Cruziana* cf. *goldfussi* preserved in hyporelief on silty fine-grained sandstone base. Lateral ridges are preserved (black arrow). Faint scratch marks orientated almost parallel to median furrow are visible in one section of weathered lobes (white arrow); B-F) *Cruziana* isp.; B-C) *Cruziana* isp. preserved in positive through to negative epirelief in fine grained sandstone beds; D) Sample collected for cross-sectioning. White line shows transverse cross-section in E and black line shows longitudinal cross-section in F; E) Transverse cross-section through burrow with unilobate upper surfaces show bilobate lower surface; F) Longitudinal cross-section of a burrow preserved in positive hyporelief showing shallow inclined back-fill packages of 2.5-5 mm thick imbricated fine-grained sandstone, producing transverse ridges on upper surface.

Ichnogenus *Dictyodora*, Weiss, 1884

**Type Ichnospecies:** *Dictyodora scotia* (M'Coy, 1851)

**Ichnogeneric Diagnosis:** Complex three-dimensional burrow, roughly conical, vertical to bedding; apex of cone upward; very thin spreite with exterior surface delicately striated. On bedding plane, the structures appear as a meandering (or roughly spiralling) “band”, which corresponds to the intersection of the three-dimensional spreite with the bedding surface (From Benton, 1982; after Häntzschel, 1975).

**Remarks:** The diagnostic features of this three-dimensional trace fossil are the basal burrow and a dorsal vertical wall (Benton, 1982). Aside from *Dictyodora libeana* (a Carboniferous ichnospecies with a characteristic “corkscrew form”; see Benton, 1982), *Dictyodora* ichnospecies are differentiated based on the horizontal expression of the dorsal wall (Benton and Trewin, 1980; Benton, 1982; Pazos *et al.*, 2015). Comparison of burrow meanders and wall height of *D. zimmermanni* (described from Lower Paleozoic rocks) with those of *D. libeana* (known only from Carboniferous deposits) illustrates that *Dictyodora* burrows have increased in structural complexity through time, which is considered to reflect an increase in feeding efficiency of the trace maker (Seilacher 1967, 1974; Benton, 1982). The greater wall height potentially reflects the evolution of the Carboniferous organism to feed at greater depths in anoxic sediments (Benton, 1982).

*Dictyodora* has been described from Lower Cambrian to Carboniferous deposits, and is known primarily from flysch deposits (Häntzschel, 1975; Benton, 1982; Uchman, 2004). These burrows were potentially produced by soft bodied deposit feeders, however, no modern organisms have been observed to create *Dictyodora*-like burrows, and the trace-maker is unknown (Häntzschel, 1975; Benton, 1982).

*Dictyodora zimmermanni* Hundt 1913

Fig. 2.5

**Ichnospecific Diagnosis:** Three-dimensional structure consisting of a basal burrow and an overlying dorsal wall that tapers upwards. The dorsal walls are always in excess of 15 mm high, and are on average 25 mm high. Most common preservation is bedding plane view of horizontal section through wall, which is generally expressed in an irregular winding to broadly meandering pattern. Tight looping is uncommon (After descriptions in Benton, 1982).

**Description:** Hypichnial, irregularly winding to looping bands, ranging from >1-2.5 mm wide in a single specimen. Bands are filled with dark mudstone in the host sediment of fine-grained calcareous sandstone. Three-dimensional structure is apparent on uneven surfaces of rocks found in float (Fig. 2.5 A, B). The thin linear cross structures, seen particularly on upper bedding planes, are considered to be the cross sections of the dorsal



wall (Fig. 2.5 A), while the wider winding features on lower surfaces of beds (Fig. 2.5 B) are probably cross-sections of the basal burrow.

**Remarks:** *Dictyodora zimmermanni* is the simplest and most irregular ichnospecies of *Dictyodora* (Benton, 1982). This common Ordovician ichnospecies is characterized as irregular to broadly meandering, which exhibits frequent looping and is considered to be the least specialized form of *Dictyodora* (Seilacher, 1967b; Benton, 1982; Pazos *et al.*, 2015).

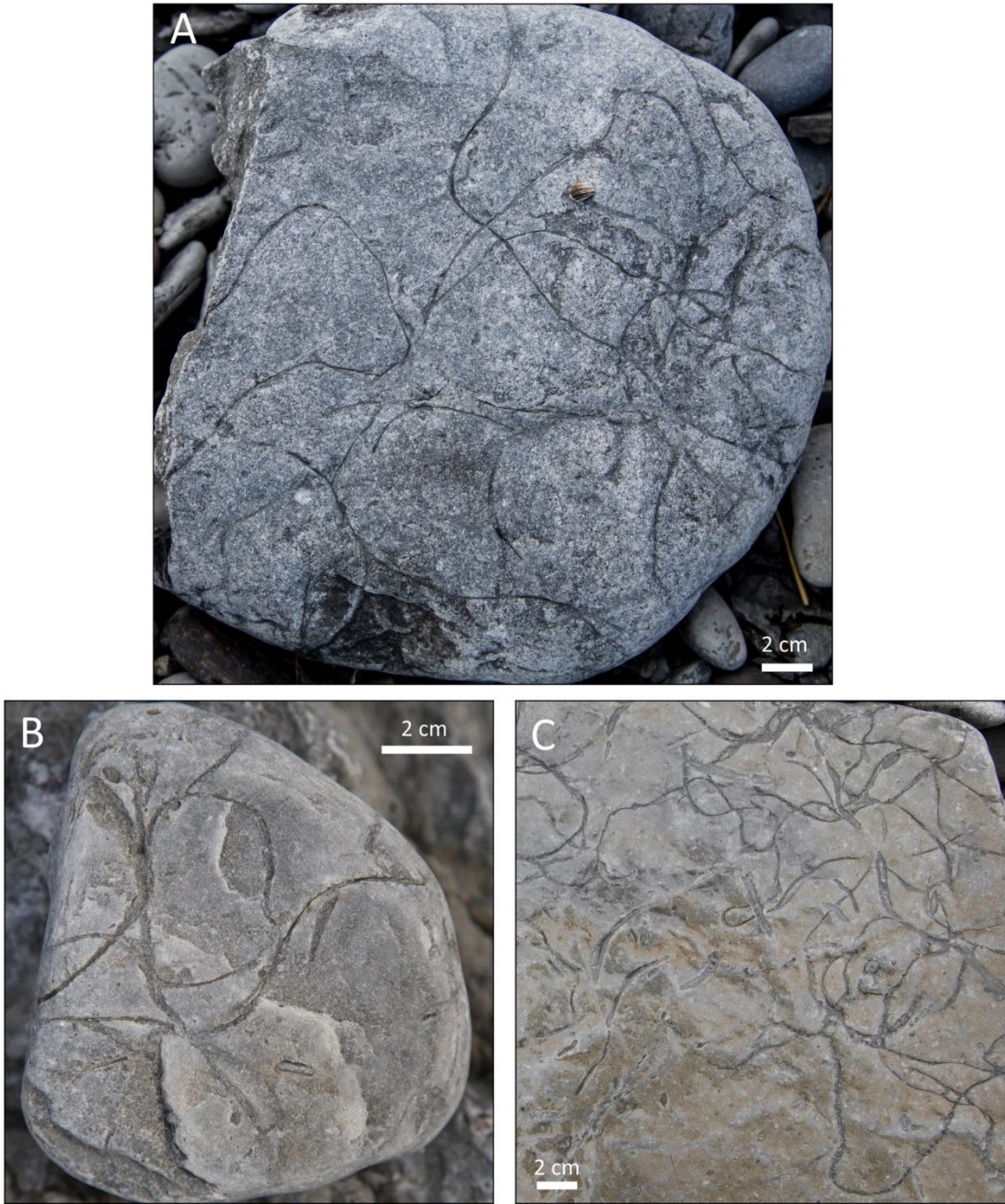


Fig. 2.5. *Dictyodora zimmermanni* preserved in silty fine-grained sandstone. A-B) Three-dimensional structure is apparent on weathered surfaces.

Ichnogenus *Halopoa* Torell, 1870

**Type Ichnospecies:** *Halopoa imbricata* Torell 1870

**Ichnogeneric Diagnosis:** Long, generally horizontal, trace fossils covered with longitudinal irregular ridges or wrinkles, which are composed of several imperfectly overlapping cylindrical probes (Emended by Uchman 1998).

*Halopoa imbricata* (Torell, 1870)

Fig. 2.6

**Emended Ichnospecific Diagnosis:** *Halopoa* with horizontal, relatively long and continuous furrows and wrinkles (Emended from Uchman, 1998).

**Description:** Horizontal, simple, cylindrical burrows preserved on the base of sandstone beds. Burrows are up to 26 cm long and range from 5-15 mm wide, with burrow width varying along the length of a single specimen. Burrows are unlined and covered with longitudinal anastomosing ridges or wrinkles. Specimens observed in the Winterhouse are branched, contra Uchman (1998).

**Remarks:** *Halopoa imbricata* was designated as the type ichnospecies of the ichnogenus *Halopoa* by Andrews (1955), and a lectotype was designated and illustrated by Martinson (1965). *Halopoa* was later transferred to the ichnogenus *Paleophycus* due to similarities with *P. sulcatus* (Jensen, 1997). This revision was rejected by subsequent authors on the basis that *Paleophycus* burrows display a burrow wall and have been interpreted as being passively filled open burrows (Pemberton and Frey, 1982). *Halopoa* does not have a burrow wall and has an actively produced burrow fill (Uchman, 1998).

The *Halopoa* burrows described herein are found on the base of sandstone beds and are interpreted as the post-depositional burrows of organisms exploiting the interface between the sandy event bed and the underlying mudstone. *Halopoa* is common on turbidite bases and is generally interpreted as the burrows of deposit-feeding organisms that reworked turbidite beds and exploited organic matter in mud buried below (Uchman, 1998; Monaco and Checconi, 2007).

*Halopoa* has been shown to consist of several stacked burrows in vertical cross-section, similar to the structure of *Teichichnus*, but are much less regular and vertically developed (Uchman, 1998). The irregular longitudinal striations or wrinkles have been interpreted as being the result of pushing out formerly reworked sediment of older burrows in the process of forming a new probe (Uchman, 1998).



Fig. 2.6. *Halopoa imbricata* preserved in positive hyporelief on the base of a silty fine-grained sandstone event bed.

Ichnogenus *Monomorphichnus* Crimes, 1970

**Type Ichnospecies:** *Monomorphichnus bilinearis* Crimes, 1970b by monotypy.

**Ichnogeneric Diagnosis:** A series of straight or slightly sigmoidal, parallel or intersecting striae, isolated or grouped in sets, in places repeated laterally and typically preserved in convex hyporelief (From Fillion and Pickerill, 1990; after Crimes 1970b).

**Remarks:** *Monomorphichnus* was originally interpreted as the trace of a trilobite propelled by currents raking the sediment surface with one side of its legs in search of food (Crimes, 1970b). Other authors have since argued this would be an inefficient feeding strategy, and instead suggested that these markings were simply due to a trilobite being swept along the sediment surface by oscillatory currents (Osgood, 1970; Banks, 1970; Fillion and Pickerill, 1990). The observation of abundant groove marks found in association with these specimens supports the latter suggestion (Fillion and Pickerill, 1990). Rare specimens have been observed without associated groove marks or other current-produced structures; these specimens are considered to be grazing traces (Fillion and Pickerill, 1990).



*Monomorphichnus lineatus* Crimes, Legg, Marcos and Arboleya, 1977

Fig. 2.7

**Ichnospecific Diagnosis:** *Monomorphichnus* composed of parallel, isolated, straight to slightly sigmoidal striae that may be repeated laterally (From Fillion and Pickerill, 1990; after Crimes *et al.* 1977).

**Description:** Slightly curved, more or less parallel lineations are preserved in hyporelief. Individual sets of lineations are composed of four to five ridges, approximately 0.8 mm wide. Ridges occasionally overlap. Spacing between ridges is 1-3 mm. The width of an set of associated ridges ranges from 10 to 20 mm.



Fig. 2.7. *Monomorphichnus lineatus* preserved in hyporelief on the sole of silty fine-grained sandstone bed. Lineations (arrowed) are slightly curved, are more or less parallel, and occur in sets of 4-5 lineations.



Ichnogenus *Paleodictyon* Meneghini, 1850

**Type Ichnospecies:** *Paleodictyon strozzii* Megeghini, 1850 by monotypy

**Ichnogeneric Diagnosis:** Three-dimensional burrow system consisting of horizontal net composed of regular to irregular hexagonal meshes and vertical outlets. Preferentially, the net is preserved (Emended by Uchman 1995).

**Remarks:** The taxonomy of *Paleodictyon* has recently been revised based on a redefined morphometric classification using maximum mesh size and tunnel diameter as the primary ichnotaxobases (Uchman, 1995; see also Sacco, 1888; Vialov and Golev, 1965; Książkiewicz, 1977; Uchman, 1999, 2003). Prior to this revision, 32 ichnospecies of *Paleodictyon* had been distinguished (cf. Uchman, 1995). According to the new classification, 13 ichnospecies are now recognized as valid (Uchman, 1995, 2003).

Early classifications of *Paleodictyon* proposed the use of ichnosubgenera (Seilacher, 1977). The ichnosubgeneric name *Glenodictyon* (von der Marck, 1863) was used for *Paleodictyon* forms with hexagonal meshes, *Squamodictyon* (Vyalov and Golev, 1960) was used for forms with scale-like meshes, and *Ramodictyon* (Seilacher, 1977) was used for forms with vertical shafts preserved (Seilacher, 1977). *Ramodictyon* is not considered to be a useful ichnotaxon as it represents a preservational variant that can also be present in other forms of *Paleodictyon* (Uchman, 1995). *Squamodictyon* has been

differentiated at the ichnogeneric level, leaving *Glenodictyon* as the sole ichnosubgenus of *Paleodictyon* (Uchman, 1999). The name *Glenodictyon* can then be considered as a junior synonym of *Paleodictyon* (Fürsich *et al.*, 2007) and thus the use of ichnosubgenera in the classification of *Paleodictyon* is considered redundant (Uchman, 1995, 1999).

*Paleodictyon* is one of the most distinctive graphoglyptid trace fossils, but there is still little consensus concerning the mode of formation of these structures. Some authors have suggested these structures are not trace fossils but are protozoan body fossils of Xenophyophores or other organisms (Karny, 1928; Swinbanks, 1982; Levin, 1994; Rona *et al.*, 2003; Rona, 2004). However they are generally interpreted as a system of open tunnels made by microbial farmers or for the trapping of meiofauna (Röder, 1971; Seilacher, 1977). Despite efforts to extract a trace maker from modern *Paleodictyon*-like networks, the trace maker remains unknown (Seilacher, 2007).

Modern structures comparable to *Paleodictyon* have only been observed in bathyal and abyssal environments (e.g., Wetzel, 1983; Ekdale *et al.*, 1984; Gaillard, 1991; Miller, 1991). *Paleodictyon* in the geologic record is most commonly recorded from deep water flysch deposits (e.g., Fuchs, 1895; Chamberlain, 1971; 1977; Książkiewicz, 1977; Seilacher, 1977; Crimes *et al.*, 1981; Yang, 1986, 1988; McCann and Pickerill, 1988; McCann, 1990; Loffler and Geyer, 1994; Uchman, 1995, 1999; Tunis and Uchman, 1996a, 1996b; Tchoumatchenco and Uchman, 2001). Early Paleozoic occurrences are documented over a much broader paleobathymetric range. Early Cambrian occurrences of *Paleodictyon* in shallow shelf environments are common (Crimes and Anderson, 1985; Paczeńska, 1985; Fürsich *et al.*, 2007), and their presence in shallow marine environments

continues through to the upper Ordovician (Stanley and Pickerill 1993a; 1993b; 1998). Some workers have suggested that the makers of these structures were originally more common in shallow-water environments, and were subsequently pushed to deeper environments as competition increased over time (e.g. Crimes *et al.*, 1992). It has also been suggested that the presence of these complex structures in shallow environments is due to the need for complex feeding strategies in Cambrian shallow seas with limited food availability (Mángano and Buatois, 2003b). It has also been suggested that its dominance in deep sea flysch deposits in the fossil record may be strongly governed by preservational factors (Fürsich *et al.*, 2007).

*Paleodictyon* is typically found as a cast on the soles of turbidites and tempestites and is considered a pre-depositional trace fossil (e.g. Peruzzi, 1881; Książkiewicz, 1954; Seilacher, 1962, 1977; Uchman, 2003). It has been proposed that *Paleodictyon* and other graphoglyptid burrows are produced in the upper few millimetres of mud on the seafloor and preservation as fossils depends on them being exhumed by erosion and subsequently immediately cast by rapidly deposited sand (Seilacher, 1974; 1977; Uchman, 1995; Tunis and Uchman, 1996a, 1996b). These conditions are generally present in low energy deep marine environments in association with turbidites, whereas in more proximal environments the preservation potential is much lower due to stronger wave activity and erosion (Fürsich *et al.*, 2007), and also due to bioturbation of shallow tiers. Preservational conditions similar to that of turbidites are present in the distal shelf, where tempestites cause shallow erosion and rapid casting of seafloor sediments (cf. Fürsich *et al.*, 2007).

The *Paleodictyon* specimens observed in the Winterhouse Formation are preserved on the base of sandstone tempestites.

*Paleodictyon gomezi* (Azpeitia-Moros, 1933)

Fig. 2.8

**Ichnospecific Diagnosis:** Very large *Paleodictyon*, mesh size more than 40 mm, string diameter more than 1.6 mm (After Uchman, 1995).

**Description:** Regular hexagonal meshes preserved in hyporelief on the base of fine-grained sandstone beds. Mesh diameters range from 5-6 cm with string diameters ranging from 4-6 mm. Hypichnial knobs are preserved on the corners of the hexagons (Fig. 2.8 A). Knobs are roughly circular with diameters of 1.5-2 cm. In some specimens only the knobs are preserved (Fig. 2.8 B).

**Remarks:**

All the examples of *Paleodictyon gomezi* documented herein are partially eroded, but knobs occur on all corners that are preserved, thus 6 knobs per hexagon are inferred to have been present in complete specimens (one at each corner). Hypichnial knobs preserved at the corners of the inferred hexagons are interpreted to have been ventilation

shafts ascending to the sediment-water interface (Seilacher, 2007). The ichnosubgenus *Ramidictyon* was proposed for *Paleodictyon* forms with vertical components preserved (Seilacher, 1977). Two ichnospecies were recognized: *R. tripatens* and *R. nodsum* (Seilacher, 1977). *Ramidictyon* is no longer recognized as a valid ichnosubgenus as it represents a taphonomic variant, however the ichnospecific names have been informally used at the ichnosubspecies level (Uchman, 1995). The knobs preserved in our specimens do not correspond to either of Seilacher's descriptions. The placement of the knobs at the corners of the hexagons are similar to similar to Seilacher's *R. tripatens*, however in *R. tripatens* only 3 knobs are present (one at every second corner). *Ramidictyon nodsum* on the other hand has 6 knobs, however they occur at the center of each tunnel in the hexagon, instead of at the corners of the hexagon as seen here.

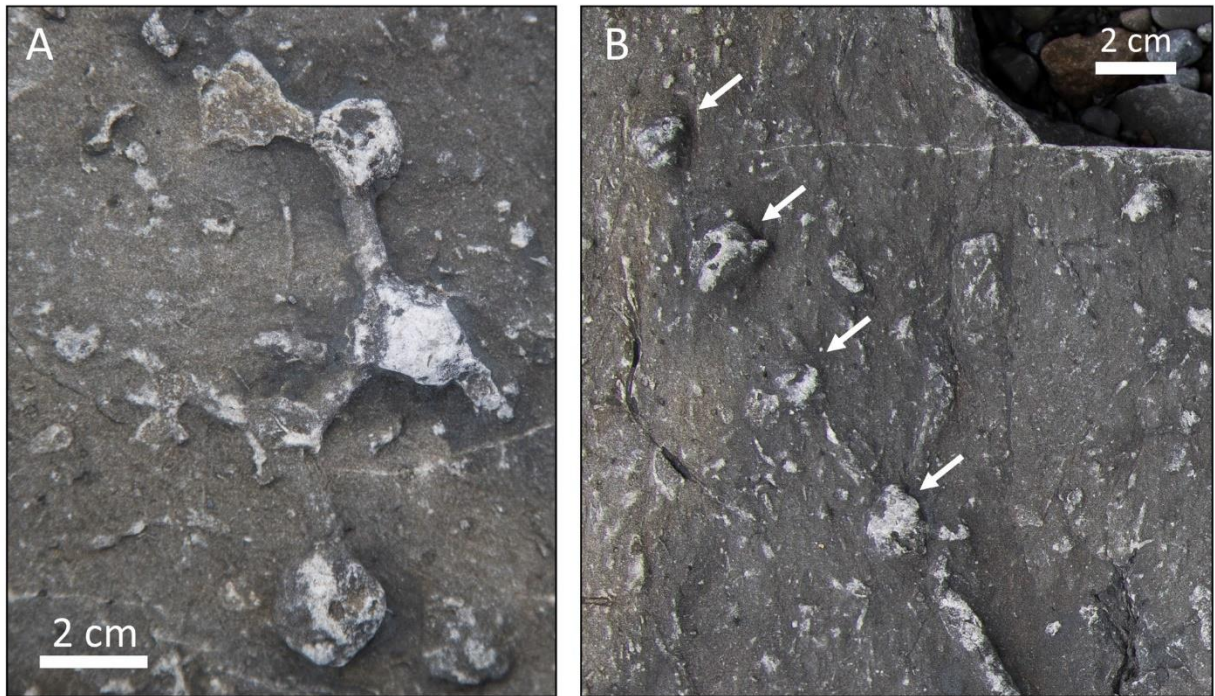


Fig. 2.8. *Paleodictyon gomezi* preserved in hyporelief on the base of fine-grained sandstone beds. A) Roughly circular hypichnial knobs are preserved on the corners of the hexagons; B) Only knobs (arrowed) are preserved in some specimens.

Ichnogenus *Parahaentzschelinia* Chamberlain, 1971

**Type ichnospecies:** *Parahaentzschelinia ardelia* Chamberlain, 1971

**Ichnogeneric Diagnosis:** Burrow system composed of numerous vertical shafts radiating vertically from one mastershaft. It may be preserved on interfaces as group of oval to circular pits, mounds, bulbs, and spots (From Uchman, 1995).

**Remarks:** The type material of *Parahaentzschelinia* was described from thin bedded sandstones of the Pennsylvanian Atoka Formation in Oklahoma (Chamberlain, 1971). Two ichnospecies of *Parahaentzschelinia* have been described: 1) the type specimen, *P. ardelia* Chamberlain, 1971 and; 2) *P. surlyki* Dam, 1990. The type ichnospecies, *P. ardelia*, was described as conical bundles of small, irregular tubes that are passively filled with mud or sand and radiate vertically and obliquely upward from a fixed point within the sediment (Chamberlain, 1971). Bedding plane cross-sections were described as conical depressions 15-60 mm across, with individual tubes being 1.5 mm wide, and a “narrow lateral (?) gallery” was suggested at the base of the conical structure (Chamberlain, 1971). Type material was collected and figured (cf. Chamberlain, 1971); however a formal diagnosis was not provided.

A second ichnospecies, *Parahaentzschelinia surlyki*, was described from the shallow marine Lower Jurassic Neill Klintner Formation in Greenland (Dam, 1990).

*Parahaentzschelinia surlyki* differs from *P. ardelia* in the following ways: 1) its much larger size, with tunnel diameters ranging from 4-20 mm and bedding surface cross-sections up to 120 mm in diameter; 2) its thick ornamented concentric mud linings up to 8 mm thick; 3) and a main vertical shaft up to 15 mm in diameter and 15 cm in length, as opposed to the lateral gallery suggested for *P. ardelia* (Dam, 1990). In the Neill Klintor Formation, *P. surlyki* was found to be numerous in fine-grained hummocky cross-stratified sandstones, and the long central shaft was suggested to be an escape burrow, while the thick wall was considered to be related to substrate cohesion (Dam, 1990). Owing to the very different thick wall structure, much wider tube diameters, and coarser sediment, it is suggested that *P. surlyki* be reassessed as it may possibly better fit within a new ichnogenus.

The first formal diagnosis of *Parahaentzschelinia* at the ichnogeneric level was provided by Uchman, 1995. Although a formal diagnosis had not been given for *P. ardelia*, an emended diagnosis for the ichnospecies was proposed based on material described from Late Carboniferous storm deposits in Poland (Gluszek, 1998). The proposed ichnospecific diagnosis included branched, horizontal tunnels with meniscate backfill (Gluszek, 1998). The Carboniferous material was studied from cross-sections on horizontal bedding planes, and consisted of rosette-shaped groups of small circular cross-sections of vertical tubes with concentric filling of the same material as the host rock, as well as short horizontal branched burrows with meniscate filling, comparable to *Macaronichnus segregatis* (Gluszek, 1998). The rosette-shaped groupings on bedding planes were reported up to 9 cm in diameter, with an average diameter of 3 cm, while



individual vertical burrow cross-sections were relatively consistent from 3 to 5 mm, and horizontal tunnels were up to 35 mm in length (Gluszek, 1998).

*Parahaentschelinia* has generally been interpreted as a dwelling and feeding burrow produced by a small deposit-feeding organism that repeatedly extended itself up and outward from a fixed point within the sediment in search of food (Chamberlain, 1971; Dam, 1990; Gluszek, 1998). Most authors have considered the trace-maker to be a small worm (Chamberlain, 1971; Gluszek, 1998), while others have suggested that the structure is similar to burrows constructed by siphonate bivalves (Fürsich et al., 2006).

?*Parahaentschelinia* isp.

Fig. 2.9

**Description:** Complex burrow systems consisting of conical clusters of radiating vertical to sub-vertical tubular burrows and associated branched horizontal burrows that make up three-dimensional tiered networks. Burrows are typically filled with very fine-grained sandstone or silty mudstone and have clay-rich linings. All specimens have a funnel-shaped cluster of sub-vertical tubes that radiate and diverge upward to produce the conical aggregation of mud-rich burrows that is characteristic of *Parahaentschelinia* (Fig. 2.9 A). Bedding plane cross sections are expressed as circular cross-sections that often have a conical depression at their center due to weathering and erosion as in the *Parahaentschelinia* type material. In many cases a similar, but typically narrower,

inverted conical aggregation of burrows is also present in the lower half of the structure, creating an overall broadly symmetrical “hour glass” structure that radiates outward in both the upward and downward direction (Fig. 2.9 B). Vertical tubes have consistent diameters within a cluster, ranging from 1 to 2 mm, and show no evidence of active burrow fill such as spreite and meniscate. In specimens that display only the upward radiating conical portion, as well as in specimens with the “hour glass” structure, the dense aggregation of vertical tubes cannot be traced into a single master burrow.

Bedding sole expressions consist of: 1) a central narrow sub-circular mud-rich depression that in vertical cross-section is shown to be the basal expression of dense mud-filled vertical and sub-vertical burrows; 2) short bedding-parallel radiating burrows surrounding the central portion (Fig. 2.9C); 3) sub-circular mud-rich depressions arranged concentrically around the perimeter of the basal expression (Fig. 2.9 D). Vertical sectioning of the concentric mud-rich depressions demonstrates that they are related to short upwardly-directed burrows extending a few millimetres upward into the silty sandstone from the base of the bed, as opposed to downwardly directed burrows within the sandstone bed. Given the radial arrangement around the conical basal expression of the sub-vertical burrows, it is inferred that these short tubes are related to radially arranged, downwardly-directed, burrows that passed into the underlying mudstone bed, and were recurved so as to meet the base of the siltstone, much like the spokes of an umbrella; 4) On bedding soles, sinuous horizontal burrows superficially similar to *Megagraption* commonly radiate from the base of the vertical burrow components (Fig. 2.9 E-I). These bedding-parallel burrows are around 2 mm in width, mud-lined and sand-

filled, and are backfilled in some sections. They are generally between 5 and 10 cm in length, and demonstrably link adjacent sub-vertical burrow components.

In some specimens, horizontal and oblique burrows branch from the upper few centimetres of the vertical component, creating an irregular three-dimensional polygonal tiered network orientated sub-parallel to bedding. As with the vertical tubes, the horizontal burrows are 1 to 2 mm in diameter and are sand-filled and mud-lined. Horizontal burrows bifurcate and ramify at both acute and obtuse angles, and commonly exhibit rounded Y-junctions or may rarely branch in a dendritic pattern similar to the primary successive probing style of *Chondrites*. The burrows do not display backfill, but some horizontal burrows consist of mud-lined sand-filled chambers approximately 2-4 mm in length. See Chapter 3 for a more complete discussion of aff. *Parahaentzschelinia* from the Winterhouse Formation.

**Remarks:** The morphology of the burrow system described from the Winterhouse Formation is much more complex and variable than previous descriptions of *Parahaentzschelinia*. The complex morphology is interpreted to represent a range of behaviours of the trace-making organism, primarily related to feeding, which may have changed through the lifetime of the trace maker. The trace-making organism is inferred to have exploited organic matter within the sandstone event beds as well as in muddier beds above and below the sandstone beds using a variety of behaviours. The most prominent portion of the burrow systems described herein is the funnel-shaped clusters of vertical to sub-vertical tubes that are morphologically comparable to *Parahaentzschelinia*. However

these burrows vary greatly in morphology, and are associated with other morphological components not described in the type material of *Parahaentschelina* (cf. Chamberlain 1971). The observation of horizontal components associated with the burrows described herein supports emendation of *Parahaentschelina ardelia* to include a horizontal component (cf. Gluszek, 1998), however meniscate backfill was not observed in specimens from the Winterhouse Formation. The figure provided by Gluszek (1998) does not demonstrate convincing evidence that meniscate backfill is present, and it is suggested that the material is re-examined and/or re-figured. Given the strong similarity between *Parahaentschelina* and the conical sub-vertical burrows described herein, our material is tentatively ascribed to this ichnotaxon. It is recommended that material from the *Parahaentschelina* type locality is re-sampled and compared with insights from this study (see Chapter 3 for a more complete discussion).

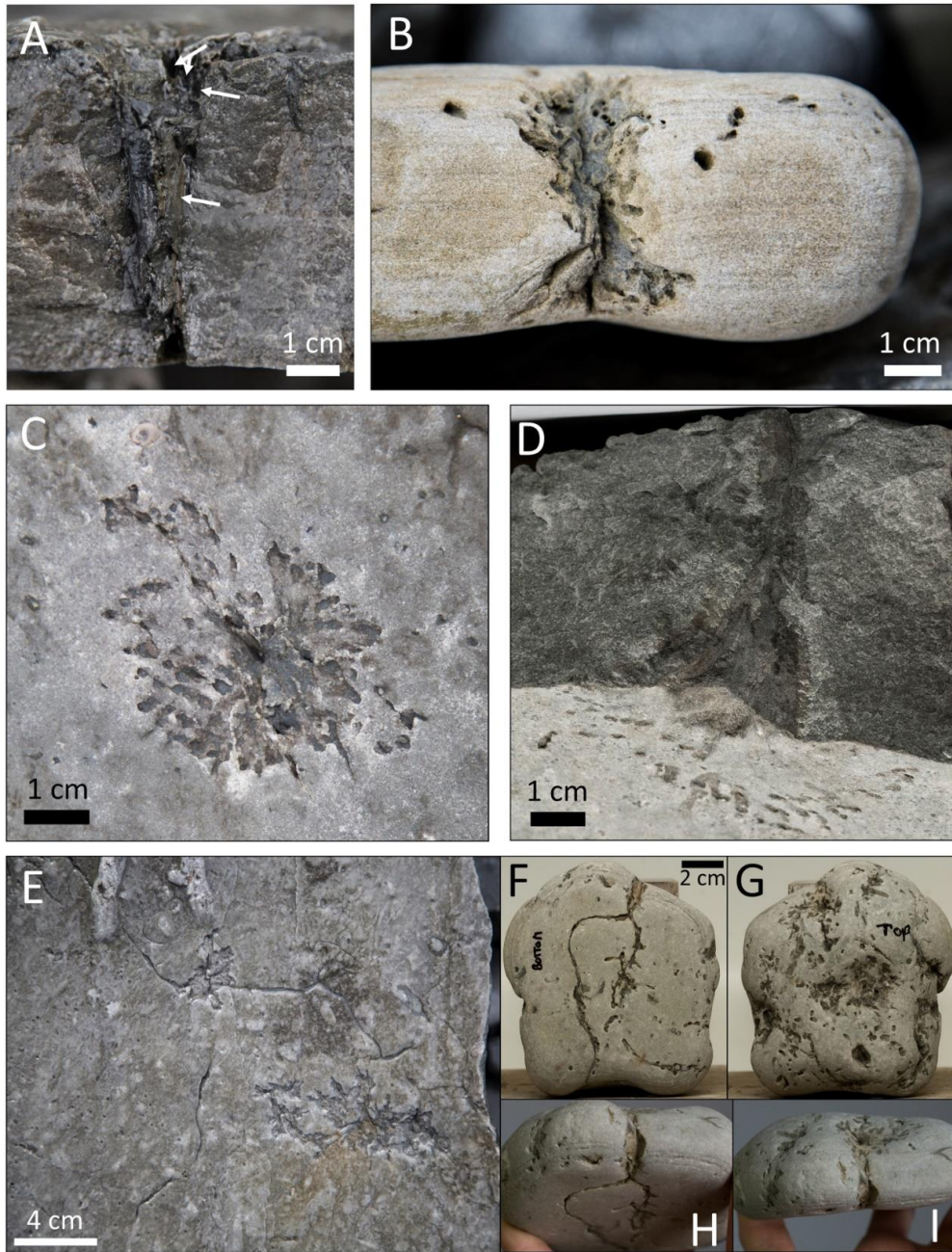


Fig. 2.9. Range of morphologies associated with burrows of aff. *Parahaentzschelinia*: A) funnel-shaped cluster of sub-vertical tubes (arrowed) that radiate and diverge upward to produce the conical aggregation of mud-rich burrows that is characteristic of *Parahaentzschelinia*; B) Inverted conical aggregation of burrows in the lower half of the structure, creating an overall broadly symmetrical “hour glass” structure that radiates

outward in both the upward and downward direction; C) Narrow sub-circular mud-rich depression represents the basal expression of dense mud-filled vertical and sub-vertical burrows. Central portion is surrounded by short bedding parallel radiating burrows; D) Basal expression of dense mud-filled vertical and sub-vertical burrows which is surrounded by sub-circular mud-rich depressions arranged concentrically around the perimeter. These mud-rich depressions are related to upwardly-directed burrows extending a few millimetres upward into the silty sandstone from the base of the bed, as opposed to downwardly directed burrows within the sandstone bed; E-I) Sinuous burrow network on bedding soles. Straight and curved bedding-parallel burrows superficially similar to *Megagraption* radiate from the base of *Parahaentzschelinia*-like burrows; E) These burrows demonstrably link adjacent vertical *Parahaentzschelinia*-like elements, between 5 and 10 centimetres apart; F) Bedding sole of sample containing *Megagraption*-like sinuous basal burrows; G) Upper surface of sample shown in F. *Parahaentzschelinia*-like sub-vertical conical cross-sections are visible; H-I) Sinuous horizontal burrows on bedding sole demonstrably connect sub-vertical *Parahaentzschelinia*-like component.

Ichnogenus *Phymatoderma* Brongniart, 1849

**Type Ichnospecies:** *Phymatoderma granulata* (von Schlotheim, 1822)

**Ichnogeneric Diagnosis:** Endobenthic burrow systems consisting of sets of branching, unlined tunnels oriented horizontally to subhorizontally. Tunnels lack sharply defined edges and usually occur in bunched sets either directed outward in one dominant direction (quadrant) from an area of initiation or in a semi-radial or radial pattern arising from a central area. Branching tunnels filled with faecal pellets often arranged crossways with respect to long axis of the tunnels. Pellets in many cases have a different color/composition compared to the surrounding sediment (emended by Miller 2011, based on Fu, 1991).

**Remarks:** Until its relatively recent revision the ichnogenus *Phymatoderma* was unstable, with many specimens being assigned or synonymized with other ichnotaxa such as *Chondrites* and *Zonarites* (Fu, 1991; see also Miller and Vokes, 1998; Uchman, 1999; Uchman and Gaździcki, 2010; Miller 2011). The perpendicular arrangement of fecal pellets is considered the diagnostic feature of the ichnogenus, along with branching pattern and irregular tunnel margins (Fu, 1991). It has since, however, been noted that the pellets are not always preserved (Uchman, 1999) and recent authors consider structural organization to be of primary diagnostic importance (Miller, 2011). The five ichnospecies

of *Phymatoderma* are distinguished based primarily on the arrangement and density of tunnels (Miller 2011).

*Phymatoderma* burrow systems are generally considered to be the result of non-selective, generally horizontal, deposit feeding by organisms that backfilled their burrows with fecal pellets (Seilacher, 2007; Uchman and Gaździcki, 2010; Miller, 2011). Faecal pellets are often composed of different material than the surrounding host sediment. This suggests the trace-maker potentially fed in a different zone to that of burrow construction such as underlying mudstones, or at the sediment-water surface, using these deep tunnels primarily for waste disposal (Miller and Vokes, 1998; Miller, 2011). Some reports note that pellets may have been subsequently reworked, potentially serving as an alternative food source after microbial maturation (Miller and Aalto, 1998; Uchman and Gaździcki, 2010).

*Phymatoderma granulata* (von Schlotheim, 1822)

Fig. 2.10 A-D

**Ichnospecific diagnosis** Endobenthic burrow systems consisting of bundles of branching tunnels that radiate outward in one dominant direction from a central axial shaft. Tunnels have inconsistent diameters, are unlined, have irregular burrow margins, and may be filled with pellets or appear structureless. Tunnels frequently overlap near the central axis and adjacent burrow systems frequently overlap and interpenetrate (based on descriptions in Miller and Vokes, 1998 and Miller and Aalto, 1998).



**Description:** Complex burrow systems composed of bundles of tunnels that branch outward from a central point and radiate in one dominant direction (digitate form; cf Miller 2011). Tunnel diameters are not consistent within a single specimen, and generally taper towards the center. Tunnel diameters range from 3-8 mm, and branches extend up to 15 cm in length. Tunnels are unlined and contain irregular margins and terminations. Burrow fill is composed of darker finer grained material than host rock. Some tunnels appear structureless, while others exhibit backfill (Fig. 2.10 B). Locally indistinct pellets are visible in some burrows. Burrow systems are up to 17 cm in diameter.

*Phymatoderma* aff. *granulata*

Fig. 2.10 E

**Description:** Long infrequently branched tunnels that branch outward in one dominant direction from a central point. Tunnels taper greatly towards the central convergence point, with tunnel widths of 1-2 mm near the center and up to 10 mm at their ends. Branches are up to 35 cm in length. Burrows are unlined and contain irregular margins and terminations. Burrow fill is structureless and composed of darker finer grained material than host rock.

**Remarks:** This specimen is less ramifying and has longer branches than other *Phymatoderma granulata* seen in the Winterhouse Formation, although *P. granulata* burrow systems from other locations have been documented to exceed 50 cm in diameter (Miller and Vokes, 1998). *Phymatoderma* in the Winterhouse Formation are morphologically highly variable. Many intermediate forms of this ichnogenus exist, with distinct ichnospecies representing end-members on a continuum (Miller 2011). This specimen may represent an intermediate form, but most closely resembles *P. granulata*.

*Phymatoderma melvillensis* (Uchman and Gaździcki, 2010)

Fig. 2.11

**Diagnosis:** Bunches of cylindrical probes filled with pelleted sediments that show local meniscate structure (From Uchman and Gaździcki, 2010).

**Description:** Bundle of slightly curved unbranched cylinders that overlap at their base. Cylinder diameters are relatively consistent throughout any given specimen, ranging from 7-11mm. Length of preserved tunnels are approximately 25 cm. Burrows are unlined and filled with densely packed ovoid pellets up to 1 mm in length (Fig. 2.11 B).



Fig. 2.10. *Phymatoderma* preserved on fine-grained sandstone surfaces. A-D) *P. granulata*. Burrow backfill is visible in B; E) *P. aff. granulata*. This specimen differs from typical *P. granulata* found in the Winterhouse Formation in having extremely long branches and few ramifications. This specimen most closely resembles *Phymatoderma granulata*, but is distinct from it.





Fig. 2.11. *Phymatoderma melvillensis*. Burrows are unlined and filled with densely packed ovoid pellets. Pelleted texture visible in B.

Ichnogenus *Rhizocorallium* Zenker, 1836

**Type Ichnospecies:** *Rhizocorallium jenense* Zenker, 1836

**Ichnogeneric Diagnosis:** Horizontal to oblique, U-shaped spreite burrow (Emended by Knaust, 2013).

**Remarks:** The taxonomy of *Rhizocorallium* has been revised and debated numerous times, with over 20 ichnospecies having been erected since its introduction more than 150 years ago (Fürsich 1974a; Knaust 2007; Schlirf, 2011; Knaust *et al.*, 2012; Knaust, 2013). Up until recently, most ichnologists followed the revised classification of Fürsich (1974a), in which three ichnospecies were considered valid: *R. jenense* Zenker, 1836, *R. irregular* Mayer, 1954b, and *R. uliarens* Firtion, 1958 (Fürsich, 1974a). Review of specimens from the type locality of *Rhizocorallium* demonstrated that the classification scheme of Fürsich (1974a) is oversimplified (Knaust 2007, Knaust *et al.*, 2012, Knaust, 2013). The classification scheme we use for *Rhizocorallium* in this paper is that of Knaust (2013), in which two ichnospecies (*R. jenense* and *R. commune* Schmid, 1876) are recognized as valid. In this classification, *R. commune*, which had previously been synonymized with *R. jenense* by Fürsich (1974a), is restored, while *R. irregulare* is considered a junior synonym of *R. commune*, and *R. uliarens* is classified as an ichnosubspecies of *R. commune* (Knaust 2013). The two valid ichnospecies are

differentiated using a combination of burrow orientation, fill, faecal pellets, scratches, branching, and substrate differences as ichnotaxobases (Knaust, 2013). *Rhizocorallium jenense* refers to steeply inclined passively-filled firmground burrows of suspension feeding organisms, while *R. commune* refers to mainly horizontally-oriented burrows exhibiting pronounced spreiten that are inferred to be produced by deposit feeding activities predominantly in softground substrates (Knaust, 2013).

*Rhizocorallium commune* is further differentiated at the ichnosubspecific level based on morphological differences, with *R. commune problematica* containing vertical retrusive spreite and *R. commune uliarensis* exhibiting a spiral morphology (Knaust, 2013). Two varieties of *R. commune* are also characterized using burrow dimensions, with large winding burrows and small tongue-shaped burrows assigned as the varieties *R. commune* var. *irregulare*, and *R. commune* var. *auriforme*, respectively (Knaust, 2013). The two ichnospecies have recently been considered to be continuous, representing combined suspension- and deposit-feeding (Knaust 2013). Compositional analysis of faecal pellets has been suggested (Knaust, 2013) to examine the additional possibility of gardening (cf. Fu and Werner 1995) and/or caching behaviour (cf. Jumars *et al.*, 1990; Löwemark *et al.*, 2004, Löwemark, 2015) in a manner similar to the paleobiological models proposed for *Zoophycos* (Löwemark *et al.*, 2004, Löwemark, 2015).

*Rhizocorallium commune (irregulare)* is documented from the Early Cambrian to Holocene, while *R. jenense* has, as yet, been documented only in Mesozoic and Cenozoic strata after the end-Permian mass extinction (Knaust, 2013).

*Rhizocorallium commune* Schmid, 1876

Fig. 2.12

**Ichnospecific Diagnosis:** Rarely branched burrows with a preferred subhorizontal orientation. The burrows are elongate, band-like, straight or winding, and may have subparallel longitudinal scratches on the wall. Faecal pellets (*Coprulus* isp.) are common within the actively filled spreite and the marginal tube (Emended by Knaust, 2013).

**Description:** All specimens have U-shaped marginal tunnels and occur on upper surfaces of silty fine-grained sandstone beds. Two morphological variations were observed: 1) smaller specimens displaying pronounced spreite with marginal tunnel diameters around 5 mm wide, overall widths of approximately 2 cm, and lengths up to 6 mm (Fig. 2.12 B, C); and 2) relatively larger specimens without spreite preserved, with marginal tunnels 10-28 mm wide, overall widths up to 5.5 cm and lengths up to 8 cm (Fig. 2.12 C, D).

**Remarks:** The smaller *Rhizocorallium* burrows observed from the Winterhouse Formation (Fig. 2.12 B, C) are considered to represent *R. commune* var. *auriforme*, based on their tube diameter to burrow width ratio. The larger burrows (Fig. 2.12 C, D) are poorly preserved so their true length is unknown, but are tentatively assigned to *R. commune* var. *irregulare* based on their much larger tube diameter (cf. Knaust, 2013).

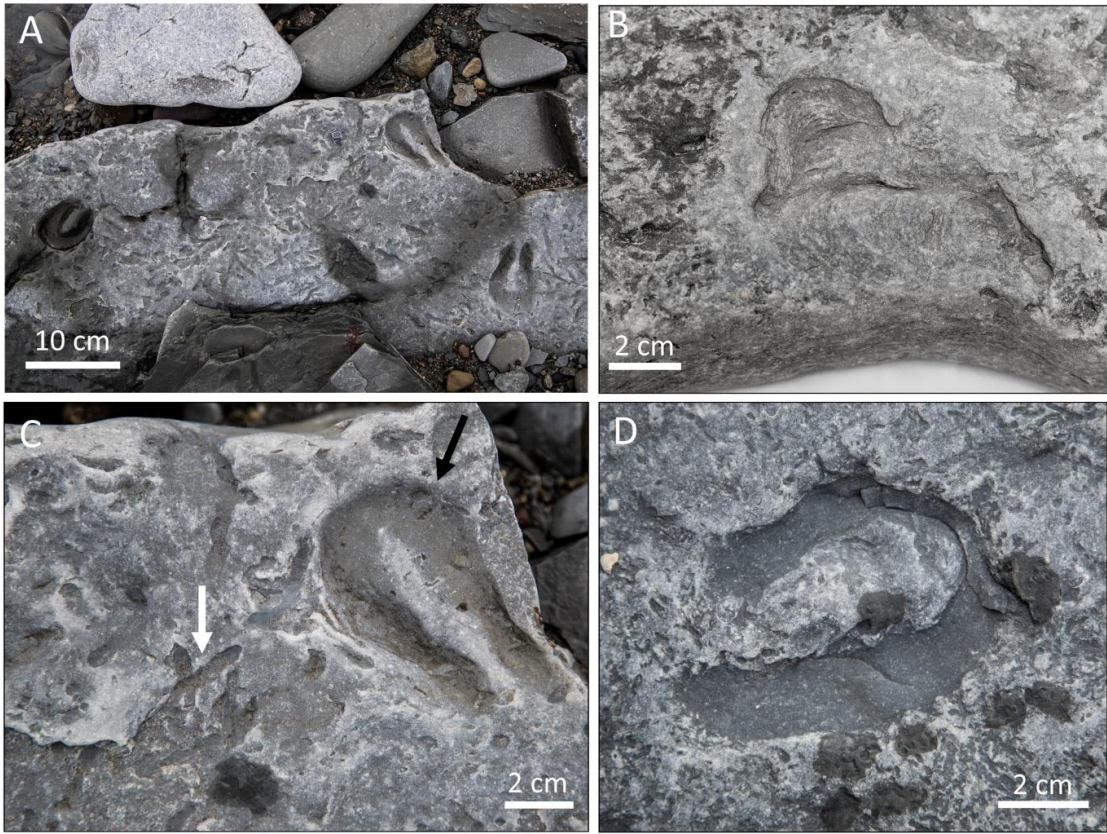


Fig. 2.12. *Rhizocorallium commune* preserved on silty fine-grained sandstone bed surfaces. B and C (white arrow) show small specimens with pronounced spreite (*R. commune* *ivar. auriforme*); C (black arrow) and D show relatively large, but poorly preserved, specimens (tentatively assigned to *R. commune* *ivar. irregulare* based on their much larger tube diameter).



Ichnogenus *Rusophycus* Hall, 1852

**Type Ichnospecies:** *Rusophycus clavatus* Hall, 1852, (Miller 1889)

**Ichnogeneric Diagnosis:** Shallow to deep, short, horizontal, bilobate burrows preserved in convex hyporelief. Lobes are parallel or merge posteriorly and may be smooth or exhibit transverse to oblique scratch marks in various arrangements, typically directed anteriorly. Coxal, exopodal, spinal, cephalic, and pygidial markings may be present (From Fillion and Pickerill, 1990; after Osgood 1970 and Alpert 1976).

**Remarks:** *Rusophycus* has traditionally been interpreted as the resting trace of arthropods, however the various often complex morphologies have been attributed to a variety of behaviours such as feeding, hunting, nesting, dwelling, and hiding/escape (Seilacher, 1953, 1959, 1970, 1985; Osgood, 1970; Crimes, 1970a; Bergström, 1973; Jensen, 1997; Mángano and Buatois, 2003a, 2004; Brandt, 2008). There has been considerable confusion and nomenclatural debate surrounding the distinction of *Rusophycus* from *Cruziana* in the past (see Osgood, 1970; Fillion and Pickerill, 1990; Keighley and Pickerill, 1996; Bromley, 1996). Although in many respects *Rusophycus* is morphologically comparable with *Cruziana*, most authors recognize the two ichnogenera as distinct. It has been suggested for clarity of the ichnogeneric differentiation between the two ichnotaxa that *R. biloba* Vanuxem (1842) be designated the type ichnospecies of *Rusophycus* over *R. clavatus* (see Fillion and Pickerill 1990).

Marine Paleozoic forms of *Rusophycus* are generally considered to have been formed by trilobite-like arthropods (e.g. Seilacher, 1953, 1985; Osgood, 1970; Crimes, 1975; Wright and Benton, 1987; Schlirf *et al.*, 2001; Hoffman *et al.*, 2012).

*Rusophycus* isp.

Fig. 2.13

**Description:** Bilobate specimens preserved in hyporelief on the base of silty fine-grained sandstone beds. Lobes are 8-16 mm in width, are separated by a shallow median furrow, and diverge anteriorly. Lobes contain fairly deep transverse scratch marks that appear relatively evenly spaced but are difficult to distinguish due to poor preservation. No markings are preserved within the furrow and no lateral margins are preserved. Overall width of burrow is 34 mm and length is 56 mm. Lobe margins are heavily weathered so overall shape of the lobes is difficult to determine.

**Remarks:** The only specimens of *Rusophycus* from the Winterhouse Formation are highly weathered and therefore cannot be confidently identified at the ichnospecific level. The coarse scratch marks are similar to those seen in *R. osgoodi*, described from the late Ordovician Georgian Bay Formation of Southern Ontario, although the fine scratch marks between lobes described in *R. osgoodi* are not present in our weathered specimens (Stanley and Pickerill, 1998). These specimens are also comparable to *Rusophycus didymus* (Salter, 1856) in having diverging lobes and transverse scratch marks, although

*R. didymus* is typically slightly smaller, being generally less than 10 mm in width (Fillion and Pickerill, 1990). The coarse striae observed in our material are also similar to those seen in *R. biloba* (Vanuxem, 1842), but our specimens lack the lateral ridges that are commonly observed in this ichnospecies (Osgood, 1970; Osgood and Drennen, 1975; Fillion and Pickerill, 1990).



Fig. 2.13. *Rusophycus* isp. preserved in positive hyporelief in silty fine-grained sandstone beds.

Ichnogenus *Skolichnus* Uchman, 2010

**Type Ichnospecies:** *Skolichnus hörnesii* Ettingshausen, 1863

**Ichnogeneric Diagnosis:** Numerous, horizontal to sub-horizontal, slightly winding simple cylinders radiating horizontally or sub-horizontally from a small central area or point at the base of a shaft (From Uchman, 2010).

*Skolichnus höernessi* (Ettingshausen, 1863)

Fig. 2.14

**Ichnospecific Diagnosis:** As for the ichnogenus.

**Description:** Material of *Skolichnus* from the Winterhouse Formation (a single specimen) has approximately 20 slightly curved horizontal rays radiating from a central point of convergence that is covered by overlying beds. Unlined rays are up to 15 cm in length, but are partially covered by overlying beds so some maximum ray-lengths are unknown. Width of the individual rays are relatively consistent, approximately 3 mm.

**Remarks:** The ichnogenus *Skolichnus* was proposed for *Chondrites höernesii* Ettingshausen (1863) on the basis of type material that had been re-discovered along with additional material (Uchman 2010). This ichnogenus is somewhat comparable to *Arenituba* Stanley and Pickerill (1995) and *Glockerichnus* Pickerill (1982), with the main differences being that: 1) the rays of *Skolichnus* radiate from the base of an inferred shaft whereas in *Arenituba* and *Glockerichnus* they radiate from the top of a vertical shaft; 2) *Arenituba* displays fewer rays; 3) *Glockerichnus* displays distinct dichotomously branched rays with perpendicular ribbing (see Uchman 2010 for full review). It is currently unclear whether or not rare branching can be present in *Skolichnus*. In the recent revision of *Skolichnus*, possible rare branching was described, however it was noted that this is very likely to be false branching (*sensu* D'Alessandro and Bromley 1987) due to overlapping rays (Uchman, 2010).

The specimen from the Winterhouse Formation is from the upper bedding surface of a calcareous silty sandstone exposed by erosion of the overlying beds. The specimen is partially covered by the overlying bed, so a complete radial form radiating from a central convergence point is inferred. It is not clear whether branching is present, but several curved rays overlap and there may be false branching. Bedding planes 2-8 cm above this exposure expose abundant *Chondrites* and *Phymatoderma*. *Skolichnus* has been described as generally occurring below the *Chondrites* tier (Uchman, 2010). This suggests that, potentially with a similar chemosymbiotic method of feeding as suggested for *Chondrites* (Fu, 1991; Seilacher, 1990), the trace-makers were capable of living in low oxygen conditions (Uchman, 2010).



Fig. 2.14. *Skolichnus höernessi* preserved on a calcareous silty sandstone bedding plane exposed by erosion of the overlying beds. The complete radial form radiating from a central convergence point is inferred as the specimen is partially covered by the overlying bed.

Ichnogenus *Squamodictyon*, Vyalov and Golev, 1960

**Type Ichnospecies:** *Squamodictyon tectiforme* (Sacco, 1886)

**Ichnogeneric Diagnosis:** Meshes without consistent angular bends, arranged like scales, or petals, around a center. Outline of the net, if preserved, is also rounded (From Seilacher, 1977).

**Remarks:** *Squamodictyon* was included as a subichnogenus of *Paleodictyon* by Seilacher (1977). He considered this “scale-like” or “petal-like” form to be constructed as the trace maker proceeded along a spiral around a central point (Seilacher, 1977). The ichnotaxonomic standing of *Squamodictyon* was later revised, and is currently differentiated from *Paleodictyon* at the ichnogeneric level (Uchman, 1999).

*Squamodictyon petaloideum* (Seilacher, 1977)

Fig. 2.15

**Ichnospecific Diagnosis:** Large form with relatively few and wide meshes of rather irregular shape, arranged like petals around center (From Seilacher, 1977).



**Description:** Slightly irregular, curved meshes preserved in convex hyporelief on the bases of fine-grained sandstone event beds. Irregular meshes are 1.5-3.8 cm in diameter with a string diameter of 2.5 mm.

**Remarks:** These specimens are considered to belong to *Squamodictyon petaloideum* on the basis of their irregularly curved, relatively large, meshes. *Squamodictyon petaloideum* has been described mainly from Paleozoic flysch deposits (Seilacher, 1977; Crimes and Crossley, 1991; Uchman *et al.*, 2005).

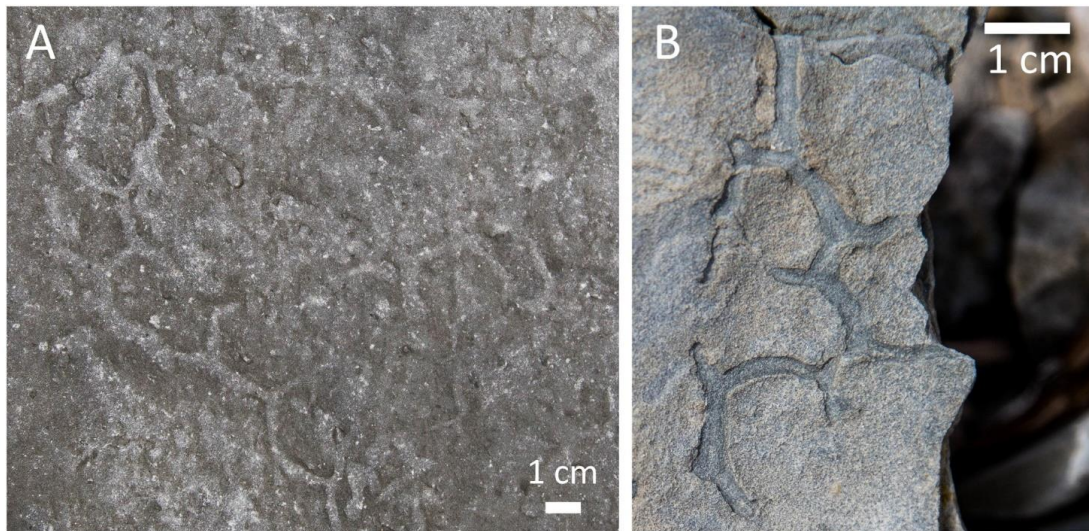


Fig. 2.15. *Squamodictyon petaloideum* preserved in convex hyporelief on the bases of fine-grained sandstone event beds.



Ichnogenus *Taenidium*, Heer, 1887

**Type Ichnospecies:** *T. serpentinum* Heer, 1877

**Ichnogeneric Diagnosis:** Variably oriented, unlined, straight, winding, curved, or sinuous, essentially cylindrical, meniscate backfilled trace fossils. Secondary successive branching may occur, but true branching is absent (Emended by Keighley and Pickerill, 1994).

*Taenidium* isp.

Fig. 2.16

**Description:** Horizontal to sub-horizontal slightly curved, cylindrical backfilled burrows. Burrows are unlined and composed of alternating light and dark thick gently arcuate meniscate packets. Menisci are relatively consistent width, from 3-4 mm, and are potentially pellet-filled. Burrows are up to 7 mm in width and 9 cm in length.

**Remarks:** Samples are small and weathered, thus are difficult to identify. The meniscate fill is comparable to that seen in *Taenidium satanassi* (D'Alessandro and Bromley, 1987), however, poor preservation leaves us unable to make an identification at the ichnospecies

level. Specimens are also superficially similar to the ‘Sclarituba’ preservation of *Nereites* (cf. Seilacher, 2007). Sclarituba is the endichnial preservation of *Nereites* as seen on split surfaces (cf. Seilacher, 2007). It is characterized by segmented, thick, clay-rich and potentially fecal pelleted backfill, and meandering to sinuous morphology (Conkin and Conkin, 1968, Seilacher, 2007). The back-fill packages of Sclarituba are typically more curved than those seen in the specimens described herein, however, and the overall burrow is typically more sinuous and meandering (cf. Conkin and Conkin, 1968; Seilacher, 2007). Furthermore, no other *Nereites* specimens were observed in the Winterhouse Formation, so it is more likely that the specimens described herein are attributable to *Taenidium*, as opposed to *Nereites* (Sclarituba preservation).



Fig. 2.16. *Taenidium* isp. Small weathered specimen with meniscate backfill superficially comparable to that of *Taenidium satanassi* preserved in fine grain silty sandstone.

Ichnogenus *Teichichnus*, (Seilacher, 1955)

**Type Ichnospecies:** *Teichichnus rectus* Seilacher, 1955, by monotypy

**Ichnogeneric Diagnosis:** Long wall-shaped septate structures consisting of a stack of gutter-shaped laminae (Fillion and Pickerill, 1990; after Seilacher, 1955b *trans. litt.*).

*Teichichnus rectus* Seilacher, 1955

Fig. 2.17

**Ichnospecific Diagnosis:** Straight, unbranched *Teichichnus* with an exclusively retrusive spreite (From Fillion and Pickerill, 1990; after Seilacher, 1955).

**Description:** Straight to gently curved, unbranched horizontal burrow exhibiting retrusive vertical spreiten. Preserved on silty sandstone surfaces. Burrow lengths up to 5 cm, the width of spreite range up to 6 mm, and observed burrow height up to 1 cm.

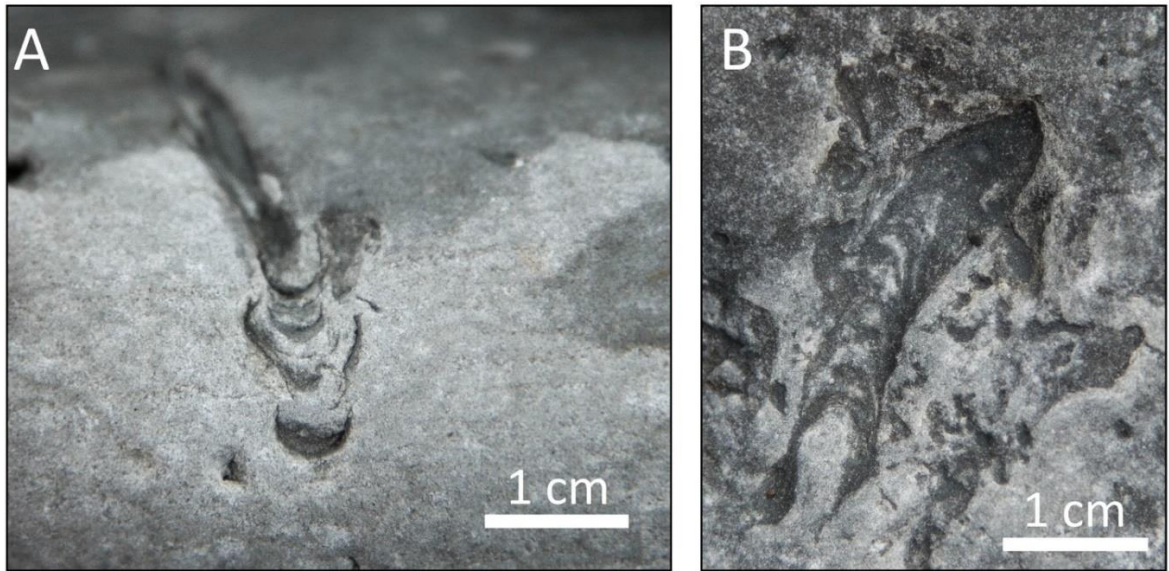


Fig. 2.17. *Teichichnus rectus* preserved on silty sandstone surfaces.

Ichnogenus *Trichichnus* Frey, 1970

**Type Ichnospecies:** *Trichichnus linearis* Frey, 1970, by monotypy

**Ichnogeneric Diagnosis:** Branched or unbranched, hairlike, cylindrical, straight to sinuous burrows distinctly <1 mm in diameter, oriented at various angles (mostly vertical) with respect to bedding. Burrow walls distinct or indistinct, lined or unlined (From Fillion and Pickerill, 1990; modified after Frey, 1970).

**Remarks:**

*Trichichnus* burrows can be branched or unbranched, and are most commonly vertical but can also have bedding parallel components (Frey, 1970; Fillion and Pickerill, 1990). The ichnogenus consists of two ichnospecies, *T. linearis* (Frey, 1970) and *T. simplex* (Fillion and Pickerill, 1990), which are differentiated based on the presence or absence of a burrow lining respectively (Fillion and Pickerill, 1990). Wall linings in *T. linearis* are commonly composed of pyrite and are very distinct. The burrows described herein from the Winterhouse Formation are identified as *T. simplex*, since the diagenetic halos surrounding some of the burrows are indistinct, and the wall linings observed in *T. linearis* are generally interpreted as a product of weathering.

The ichnogenus *Trichichnus* is in need of systematic review. The difference between *Trichichnus* and morphologically similar ichnotaxa such as *Polykladichnus* Fürsich (1981) and *Skolithos* Halderman (1840) is ambiguous. *Trichichnus* is generally distinguished based on its small size, which is considered to be less than 1 millimetre in diameter (Frey, 1970; Fillion and Pickerill, 1990; Blissett and Pickerill, 2004). However, aside from some cases of extreme relative size differences causing differences in overall morphology (cf. Bertling *et al.*, 2006; Uchman *et al.*, 2012), burrow size is not considered a valid ichnotaxobase (see Pickerill, 1994 for discussion).

The ichnogenus *Polykladichnus* (Fürsich, 1981) is characterized by vertical to sub-vertical tubes with single or multiple Y- or U-shaped bifurcations, and slight enlargements at the burrow junctions (Fürsich, 1981; Schlirf and Uchman, 2005). *Polykladichnus* burrow diameters are described as typically ranging from 1-2 millimetres,

thus slightly overlapping with typically described *Trichichnus* diameters. While branching is not a diagnostic necessity for *Trichichnus* burrows, it is for *Polykladichnus*. There are two ichnospecies of *Polykladichnus*, *Polykladichnus irregularis* (Fürsich, 1981) and *Polykladichnus aragonensis* (Uchman and Álvaro, 2000). As with the two ichnospecies of *Trichichnus*, these ichnospecies are differentiated based on the presence or absence of a burrow lining (Schlirf and Uchman, 2005). The similarities between these two ichnogenera suggests that the two could potentially be synonymized. If this did occur, *Trichichnus* would have taxonomic priority, rendering *Polykladichnus* a junior synonym of *Trichichnus*. Both *Polykladichnus* and *Trichichnus* are generally interpreted as the dwelling and/or feeding burrows of an organism (Fürsich, 1981; Ekdale *et al.*, 1984; Fillion and Pickerill, 1990).

The burrows documented herein from the Winterhouse Formation consist of unbranched vertical tubes, Y-branching, and horizontal tubes. Burrow diameters range from 0.5 to 2 millimetres. The diameter of the Y-branched burrows are greater than 1 millimetre, thus some authors would potentially assign them to *Polykladichnus*. However we do not consider size to be a valid ichnotaxobase (cf. Pickerill, 1994). Furthermore no swelling is observed at burrow junctions in these specimens, thus all of these burrows are assigned to *Trichichnus*.

*Trichichnus linearis* Frey, 1970

Fig. 2.18

**Ichnospecific Diagnosis:** Rarely branched, dominantly vertical, threadlike, cylindrical trichichnid burrows having distinct walls, commonly lined with diagenetic minerals (After Frey, 1970).

**Description:** Straight to gently curved cylindrical burrows are primarily vertical in orientation, with some horizontal branching present (Fig. 2.18 C). Burrow diameters range from 0.5 to 2 mm and burrow depths range from 1 to 7 cm. The burrow fill is finer grained than the host rock and there is no distinct wall lining, but patchy diagenetic halos are present in some specimens. Some specimens are unbranched, while others exhibit Y-branching close to the top of beds.



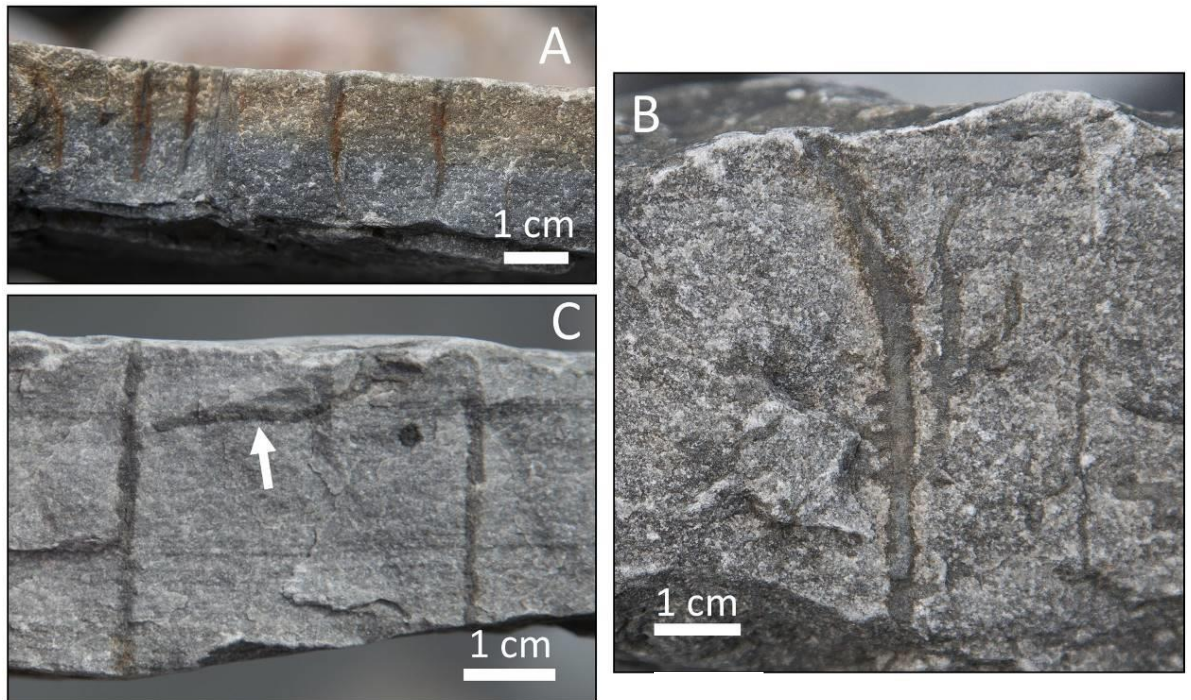


Fig. 2.18. *Trichichnus linearis* displaying patchy diagenetic halos visible in A and B; B) Y-branching; C) Vertical burrows and a bedding parallel branch (white arrow).



Unknown open gallery burrow system

Fig. 2.19

**Description:** Large sinuous central gallery associated with narrower, irregularly dichotomous, branches. Central gallery is a consistent width of 7 mm, with smaller branches ranging from 1.5-4 mm in diameter. Galleries appear to show scratch marks. Circular portion at the end of the central gallery may indicate where trace-making organism changed levels in the sediment. Numerous circular burrows within close proximity may represent vertical portions of this burrow network.

**Remarks:** Only one specimen was observed preserved in concave epirelief on fine-grained sandstone surface. Specimen cross-cuts *Chondrites targionii*. The different burrow sizes in the same structure is intriguing and may represent comensallism, later-state re-burrowing by a smaller organism, the burrows of juveniles, or chance association.

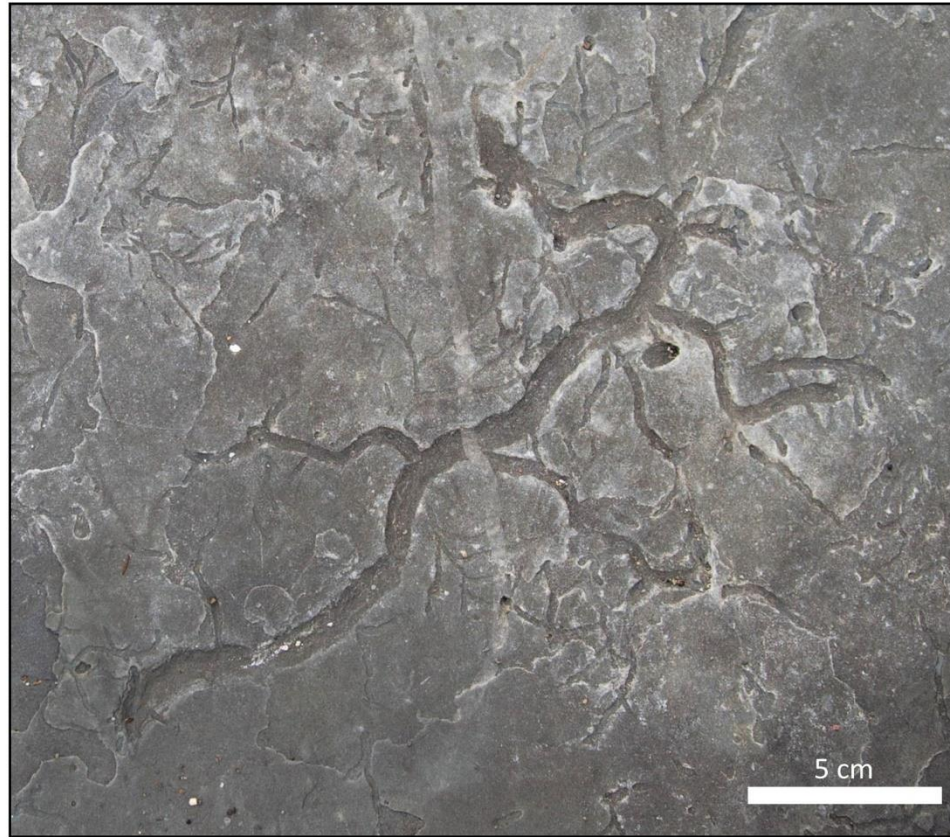


Fig. 2.19. Unknown sinuous burrow with large central gallery and smaller irregular dichotomous branches. The unknown burrow is visibly cross cutting *Chondrites targionii*.

#### 4. Conclusion

This study provides the first systematic documentation of the ichnological assemblage of the Upper Ordovician Winterhouse Formation, which is exclusively exposed on the Port au Port Peninsula of Western Newfoundland (Fig. 2.1). The exposed section consists of approximately 320 m of upward-coarsening parasequences made up of inter-bedded carbonaceous silt-rich mudstones and silt-rich fine-grained sandstones with abundant trace fossils (Fig. 2.2 A), with minor limestone breccias and slump deposits. Bioturbation is common in the inter-bedded decimetre-scale mudstone beds and centimetre-scale sandstone beds of the lower section of the Formation. Ripple cross-laminated sandstone beds are normally graded, have erosive bases with tool marks, and both sinuous crested wave ripples and interference ripples on their upper surfaces (Fig. 2.2). This association of sedimentary structures are considered herein to be indicative of storm deposits including tempestites deposited from hypopycnal flows (cf. Aigner and Reineck, 1982). These deposits contain a, hitherto undescribed, well-preserved and diverse assemblage of trace fossils.

Twenty ichnotaxa are documented herein from the mudstone and sandstone storm deposits of the Winterhouse Formation. Nineteen ichnospecies are assigned to 15 ichnogenera, and one additional unknown burrow system is described. The described ichnofossil assemblage reflects a diverse array of interpreted trace-maker behaviours, including dwelling, locomotion, and a variety of different feeding strategies. Many of the trace fossils are considered to be related to post-depositional colonization of tempestites and buried mudstones. This systematic ichnological study presents the first catalogue of

the ichnofaunal assemblage of the Winterhouse Formation. The information provided herein can be used to enhance the understanding of the paleoecology of the Winterhouse Formation, and can be used for comparison in other ichnological studies, particularly those focused on the Ordovician Anticosti Basin and other eastern Laurentian basins that are elsewhere prospective for hydrocarbons (Hannigan and Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011).

## **5. Acknowledgements**

This work was supported by an NSERC discovery grant to DMc. R. Reynolds thanks Chris Boyd for assistance with sample collection from the Winterhouse Formation. Dr. Stephen Hubbard and Dr. Renata Netto are thanked for their helpful review and suggestions.

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## CHAPTER 3

Detailed three-dimensional morphological analysis of  
*Parahaentschelina*-like burrow systems

**Detailed three-dimensional morphological analysis of  
*Parahaentzschelinia*-like burrow systems**

Robyn Reynolds, Duncan McIlroy

Memorial University of Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive,  
St. John's, Newfoundland, A1B 3X5, Canada

**KEYWORDS**

*Parahaentzschelinia*; Serial grinding; three dimensional; reconstruction;  
ichnology; Winterhouse Formation; Newfoundland, Canada

Corresponding author: Robyn Reynolds, Memorial University of  
Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive, St.  
John's, Newfoundland, A1B 3X5, Canada, Robyn.reynolds@mun.ca; 709  
864-6762; 709 864-7437 (fax)

## 1. Abstract

Serial grinding and three-dimensional reconstruction of aff. *Parahaentzschelinia* specimens from the Winterhouse Formation reveals complex three-dimensional tiered network systems associated with more typical *Parahaentzschelinia*-like conical bundles of sub-vertical tubes. The complex morphology of the burrow system is interpreted as an indication of the complex behaviour of the trace-making organism. The trace-making organism is inferred to have exploited organic matter within the sandstone event beds as well as in muddier beds above and below the sandstone beds using a variety of behaviours. Potential burrow irrigation and microbial cultivation associated with gardening behaviour is also inferred. The trace-making organism is unknown, but comparisons are drawn between the structures observed herein and those produced by both modern polychaetes and bivalves.

## 2. Introduction

This study describes complex burrow systems from Upper Ordovician calcareous sandstones of the Winterhouse Formation on Long Point on the Port au Port Peninsula in Newfoundland, Canada (Fig. 3.1). The main sub-vertical component of the burrow systems is comparable to *Parahaentzschelinia* (Chamberlain, 1971). The morphology of the burrow systems described is however much more complex and variable than descriptions of the type material of *Parahaentzschelinia* (cf. Chamberlain, 1971).

*Parahaentzschelinia* has been defined by a system of numerous vertical burrows radiating vertically from one master shaft (Chamberlain, 1970; Uchman, 1995). The type material of *Parahaentzschelinia* was described from thin bedded sandstones of the Pennsylvanian Atoka Formation in Oklahoma (Chamberlain, 1971). The type ichnospecies, *P. ardelia*, was described as conical bundles of small (1.5 mm wide), irregular, tubes that are passively filled with mud or sand and radiate vertically and obliquely upward from a fixed point within the sediment (Chamberlain, 1971). Bedding plane cross-sections were described as conical depressions 15-60 mm across, and a “narrow lateral (?) gallery” was suggested at the base of the conical structure (Chamberlain, 1971).

The aims of this paper are to: 1) document and describe the various morphological components of complex *Parahaentzschelinia*-like burrow systems from the Winterhouse Formation; and 2) compare these burrows to similar modern and fossil burrows to allow a reconsideration of the trace-maker’s ethology and paleobiology.

Complex morphologies of trace fossils generally reflect a range of behaviours by the trace-making organism(s) (Hansell, 1984; Dawkins, 1989; Miller and Aalto, 1998). Thorough understanding of the range of morphologies within a taxon is critical for both interpreting trace-maker ethology and avoiding oversimplified paleobiological interpretations (cf. Miller, 1998; Miller and Aalto, 1998; Miller, 2011). While most ichnological taxa are described for simple or idiomorphic examples of the taxon, the lack of documentation of the range of morphological



disparity within the type series is found to be a shortcoming of the description of *Parahaentzschelina* that is probably true for many taxa (see also Miller, 2011).

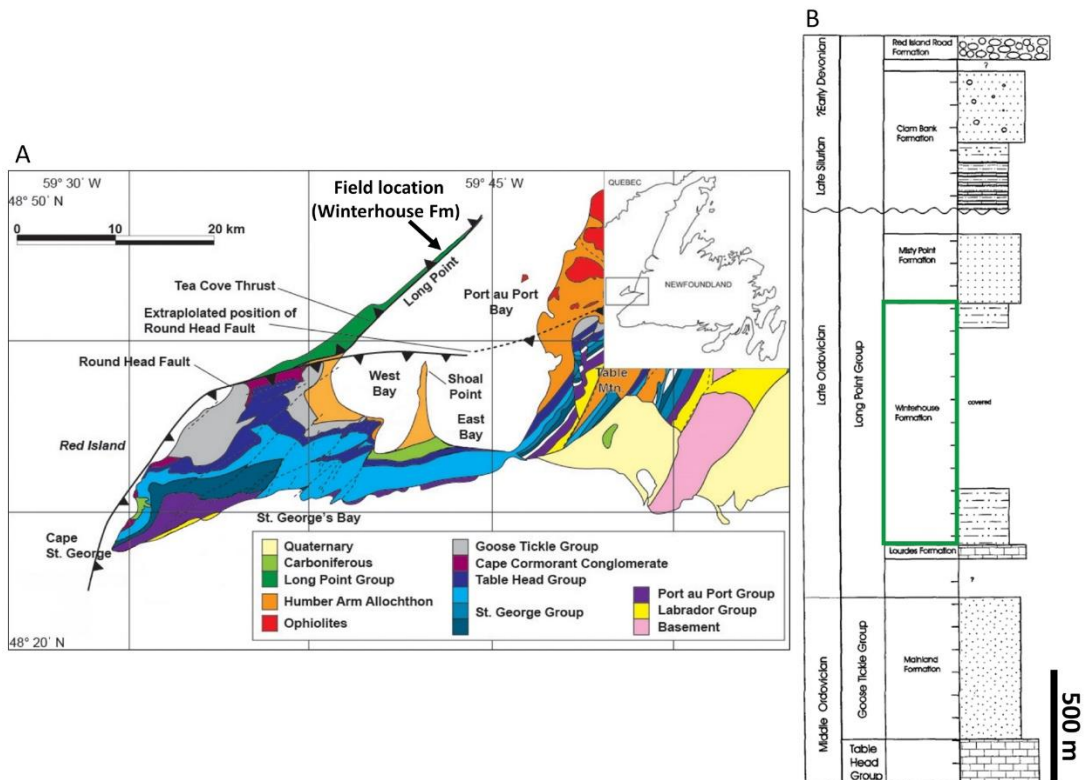


Fig. 3.1. A) Geologic map of the Port au Port Peninsula of Newfoundland, including the Winterhouse Formation as part of the Long Point Group (arrowed). Inset is an outline of a map of the island of Newfoundland, showing the (boxed) location of the Port au Port Peninsula (after Cooper *et al.*, 2001); B) Stratigraphic column of the foreland basin succession of the Port au Port Peninsula containing the Long Point Group. The green box highlights the Winterhouse Formation (after Quinn *et al.*, 1999).

### 3. Geological and paleoenvironmental setting

The Upper Ordovician Winterhouse Formation of the Long Point Group is a mixed siliciclastic/carbonate succession that is thought to represent shallow marine storm-dominated shelf deposits (Quinn *et al.*, 1999). The Winterhouse Formation gradationally overlies the shallow marine fossiliferous limestones of the Lourdes Formation, and is conformably overlain by the marginal marine and deltaic red sandstones of the Misty Point Formation (Quinn *et al.*, 1999). The Long Point Group is part of the foreland basin fill which was deposited between the Taconic and Acadian orogenies (e.g. Waldron *et al.*, 1993). The only onshore exposure of the Long Point Group is on the Port au Port Peninsula in Western Newfoundland (Fig. 3.1), though there is likely to be extensive sub-crop below the Gulf of St. Lawrence (Sinclair, 1993). The lower 320 metres of the Winterhouse Formation is well exposed on the Port au Port Peninsula but the upper approx. 540 m do not currently outcrop (Quinn *et al.*, 1999). The Winterhouse Formation shows net progradation and is composed of trace fossil-rich interbedded carbonaceous silty mudstones and sandstones with limestone breccias and slump deposits at some intervals (Quinn *et al.*, 1999).

The exposed section generally consists of coarsening upward parasequences made up of centimetre to decimetre scale inter-beds of carbonate-rich silty mudstone and silt-rich fine-grained sandstone, capped by marine flooding surfaces (Fig. 3.2 A). In the lower portion of the section bioturbation is common in inter-bedded decimetre-scale mudstone beds and centimetre-scale sandstone beds. Individual sandstone beds

increase in thickness and frequency toward the top of the section, with sandstone beds reaching thicknesses upwards of 50 cm in the upper portion of the exposed section. These upper beds are commonly tabular cross-bedded, and bioturbation is less common.

Normally graded, ripple cross-laminated sandstone beds have erosive bases with tool marks and have sinuous crested wave ripples, and interference ripples on their upper surfaces (Fig. 3.2). The association of sedimentary structures is considered herein to be indicative of storm deposits including tempestites deposited from hypopycnal flows (cf. Aigner and Reineck, 1982). Many of the thicker sandstone beds near the top of parasequences show hummocky cross-stratification, indicating shallowing of the parasequences to above storm wave base.

*Parahaentzschelina*-like burrows are common throughout the section, especially in thin silt-rich sandstone beds, cutting through beds up to 10 cm thick (Fig. 3.2 G). Burrow density in a single bed can be high, with aff. *Parahaentzschelina* burrows commonly occurring in clusters/chains in which they are typically around 5 to 10 cm apart. *Trichichnus*, *Phymatoderma* and *Chondrites* are also common in these beds (Fig. 3.2 H). In addition to sole marks, the erosional bases to hypopycnal event beds commonly cast a pre-event assemblage rich in graphoglyphid burrows (e.g. *Megagraption* and *Paleodictyon*) cut by post-depositional *Halopoa*.



Fig 3.2. Sedimentology of the Winterhouse Formation exposed in Long Point: A) Upward coarsening decimetre-scale carbonate-rich silty mudstone beds inter-bedded with centimetre-scale silty fine-grained sandstone event beds; B) Normally graded, ripple cross-laminated sandstone bed with erosive base sand wave and interference ripples on upper surfaces; C) Hummocky cross-stratified sandstone; D) Upper surface of sandstone bed with wave-generated interference ripples; E) Hummocky cross-stratified sandstone bed with shell debris at base; F) Base of sandstone bed containing tool marks (arrowed); G) *Trichichnus* and aff. *Parahaentzschelinia* burrows penetrating centimeter-scale sandstone event beds; H) *Chondrites* burrows in centimeter-scale ripple-cross-laminated sandstone beds.

#### 4. Materials and Methods

Material for this study was collected both from float and in-situ, and is augmented by hundreds of field photographs. High-resolution three-dimensional morphological models were produced from two samples using the precision serial grinding and modelling methods described by Bednarz *et al.* (2015). Each sample was encased in a plaster block to create a consistent frame of reference, and sequentially ground in consistent precise increments using a diamond carbide grinding tool operated by a computer guided milling machine at Memorial University of Newfoundland. Grinding increments for this study were 0.1 mm, enabling the high-resolution reconstruction of sub-millimetre-scale structures. After each cut, samples were photographed both dry and wet with oil under identical lighting conditions. The photos were then aligned and processed in Adobe Photoshop™. The burrows were isolated from each photo and imported into the modeling software VG Studio Max™, producing high-resolution models of the burrows that can be manipulated and sectioned in any plane. Two models were produced: one sample was ground in the bedding-parallel direction, and the other perpendicular to bedding. Full block models comparable to a standard CT image array were also produced by importing the aligned block photographs into the modelling software, as opposed to extracting the burrows from each photograph. This enabled the capability to clip through each of the full samples in any orientation, and the observation of near burrow sedimentary structures on any plane cut through a model of the sample.

## 5. Descriptive ichnology

In the description of new ichnotaxa the material chosen for publication is typically the most symmetrical specimens, representing ‘ideal’ forms which are often found amongst a much wider range of morphologies. These idiomorphic specimens typically form the basis of a taxon, and the ichnotaxonomic diagnoses seldom include a type series (see also Miller, 2011). Ichnotaxonomic descriptions and diagnoses often conform to some ideal of morphology imposed on the taxon by the author. Since in most cases a burrow is formed by an organism for a range of purposes (e.g. feeding, moving, creating a safe dwelling etc.), and also involves interactions with both the burrowed substrate and the ambient environment, divergence from the idiomorphic form is to be expected.

The behaviour of burrowing organisms living in semi-permanent burrows may be seasonal, but may also vary in response to other environmental changes. Modern organisms have been observed to change burrow morphology through time depending on their ontogenetic age, changes in sediment properties, distribution of nutrients, and feeding strategy employed (Herringshaw *et al.*, 2010). Such facultative changes in behaviour, and concomitant changes in burrow morphology, can result in the progressive creation of complex, highly variable structures.

The trace fossil discussed herein includes several morphological components in a single trace and is, in many regards, a hypidiomorphic trace. The most prominent portion of the described compound burrow is a sub-vertical radial component that is morphologically comparable to *Parahaentzschelinia*. The sub-vertical burrows

themselves vary greatly in morphology, are associated with other burrow components not described in the type material of *Parahaentzschelinia* (cf. Chamberlain 1971), and are connected to neighbouring sub-vertical burrows by horizontal galleries. Due to the complex hypidiomorphic nature of this trace fossil, the various morphologic components are described separately for clarity.

### 5.1 Sub-vertical burrow clusters

The main morphological element of the described burrow system is a sub-vertical component composed of conical clusters of sub-vertical tubular burrows with dark mud-linings (Fig. 3.3). The tubes are typically filled with calcareous silty fine-grained sandstone similar to the host sediment or silty mudstone, have clay-rich linings, and show no evidence of active burrow fill such as spreite and meniscate (Fig. 3.4). All specimens have sub-vertical tubes that diverge upward in a radial fashion from the vertical component to produce a conical cluster of mud-rich burrows (Figs 3.3 and 3.5). In many cases a similar, but typically narrower, conical aggregation of burrows is also present at the base of the burrows in the lower portion of the bed (Fig. 3.3). In cases where the downwards splaying of burrows is absent, the bed is typically thin, and the cone tapers the full depth of the bed (Fig. 3.5). Burrows have been observed to penetrate fine-grained sandstone event beds up to 10 cm thick (Fig. 3.2 G). The morphology of this component is very similar to the descriptions of the type material of *Parahaentzschelinia*, except that *Parahaentzschelinia* has been described as having a single common master shaft from which the galleries branch, and has not

previously been associated with downward branching (cf. Chamberlain, 1970; Uchman, 1995).



Fig. 3.3. Broadly “hourglass-shaped” conical clusters of sub-vertical tubular burrows diverging and radiating outward in both the upward and downward direction. A conical zone of deformed laminae bent inwards in a funnel shape surrounding the sub-vertical component of burrow is interpreted as a “collapse cone” structure (see Section 6).



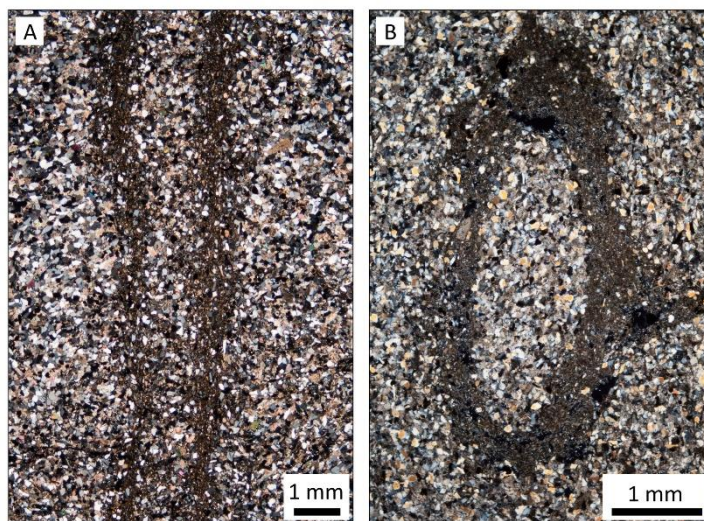


Fig. 3.4. Thin section of sub-vertical tubular burrows viewed under cross polarized light. A) Longitudinal cross-section of sub-vertical tubular burrow; B) Oblique cross-section of sub-vertical tubular burrow. These tubular burrows diverge upward in a radial fashion to produce a conical cluster of burrows. Burrows are filled with calcareous silty fine-grained sandstone similar to the host sediment, have clay-rich linings, and show no evidence of active burrow fill such as spreite and meniscate.

#### 5.1.1 Upwardly diverging burrow clusters

The primary morphologic component persistent throughout this trace fossil system is the funnel-shaped association of vertical and oblique upwardly diverging mud-lined burrows (Fig. 3.5). The burrows are closely packed and can result in localised dense areas of mudstone that are easily weathered. On bedding plane surfaces the conical aggregation of sub-vertical burrows are expressed as circular cross-sections that often have a conical depression at their center due to weathering and erosion as in the *Parahaentzschelinia* type material (Fig. 3.6; Chamberlain,

1971). The dense aggregation of sub-vertical burrows that form the mud-rich cone are most easily examined in polished surfaces. The diameter of the vertical tubes range from 1 to 2 mm, and have a relatively consistent diameter within a burrow cluster (Figs 3.4 and 3.5). The dense aggregation of burrows cannot be traced into a single master burrow. The circular surface expression of the conical aggregations of burrows has diameters that vary from less than 2 cm to upwards of 7 cm.

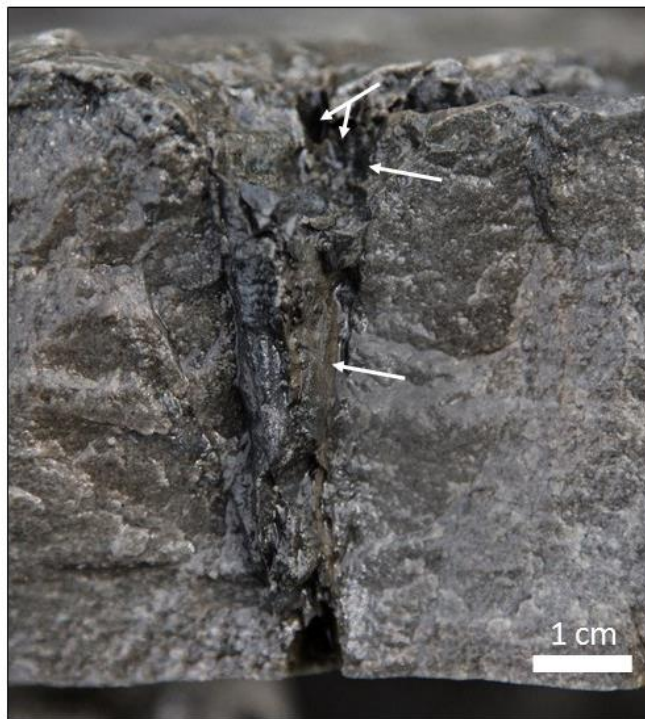


Fig. 3.5. Field specimen showing multiple sub-vertical sand-filled mud-lined tubes (white arrows) that diverge upward in a radial fashion to produce a conical cluster of mud-rich burrows. This specimen does not exhibit downward branching.



Fig. 3.6. A-C) Circular cross-sections of conical aggregation of sub-vertical tubes on upper bedding plane surfaces of samples from the Winterhouse Formation. There is often a conical depression in the centre due to erosion where the tubes are most heavily concentrated; D) Similar upper bedding plane cross-section in type specimen of *Parahaentzschelinia ardelia* from the type locality Atoka Formation in Oklahoma (Photo from University of Wisconsin Geology Museum).

### 5.1.2 Downward branching

In addition to the funnel-shaped aggregations of upwardly directed burrows described from the type material (Chamberlain, 1971), some specimens also exhibit downward radiating tubes similar to that seen in the upward branching portion (Fig. 3.3). These downward radiating portions are generally not as wide and deep as the upper funnel-shaped portions, and are typically more focused and contain fewer burrows. This morphology creates a broadly symmetrical “hour glass” structure that radiates outward in both the upward and downward direction (Fig. 3.3).

### 5.1.3 Bedding sole expression of downward-branching

The lower bedding surface, where it is intersected by the downward branching morphological element, is typically seen to have a narrow sub-circular central mud-rich depression (Figs 3.7 and 3.8) that, when sectioned, can be demonstrated to be composed of dense mud-filled burrows (Fig. 3.9). This central mud-rich portion is commonly surrounded by either short bedding-parallel radiating burrows (Fig. 3.7), or concentric sub-circular mud-rich depressions arranged radially around the perimeter of the basal expression (Figs 3.8 and 3.9). The concentric mud-rich depressions are demonstrated by serial grinding to relate to small upwardly-directed mud-filled tubes that extend a few millimetres into the siltstone, rather than downwardly directed burrows within the sandstone bed (Figs 3.9 and 3.10). Given that they are concentrically arranged around the downwardly expanding conical portion of the burrow it is reasonable to infer that radially arranged downwardly-directed burrows

passed into the underlying mudstone bed, and were recurved so as to meet the base of the siltstone, much like the spokes of an umbrella (Figs 3.8, 3.9 and 3.10). It has not yet been possible to observe the inferred recurved burrows in any underlying mudstone to date.



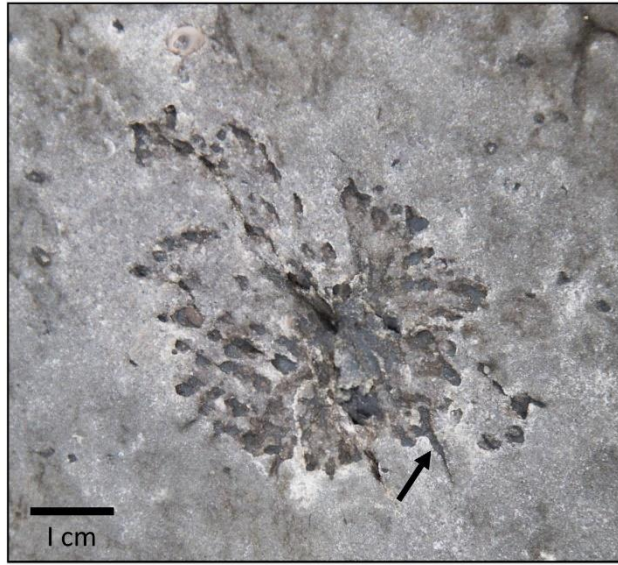


Fig. 3.7. Basal cross-section of downward branching morphological element expressed as circular groupings of short sub-vertical to bed-parallel radiating burrows (ie. black arrow) surrounding a central sub-circular mud-rich depression.

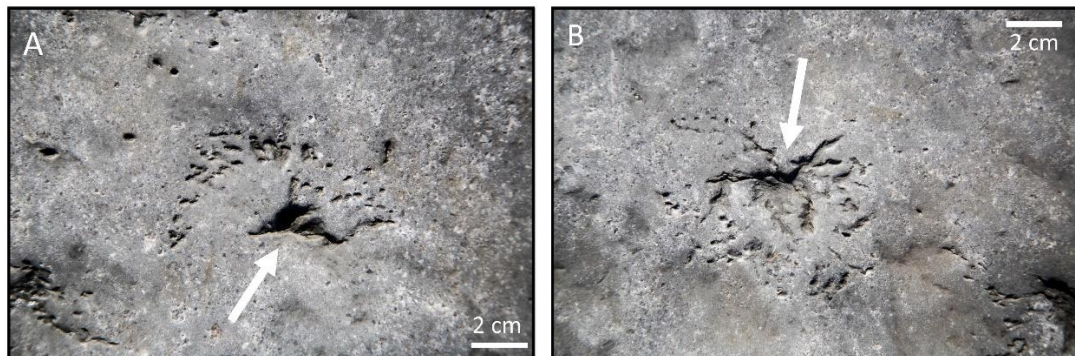


Fig. 3.8. Basal cross-sections showing narrow sub-circular central mud-rich portion (white arrow) surrounded by concentric sub-circular mud-rich depressions. The concentric mud-rich depressions do not relate to downwardly-directed burrows within the sandstone bed but are instead related to upwardly-directed burrows (Figs 3.9 and 3.10).

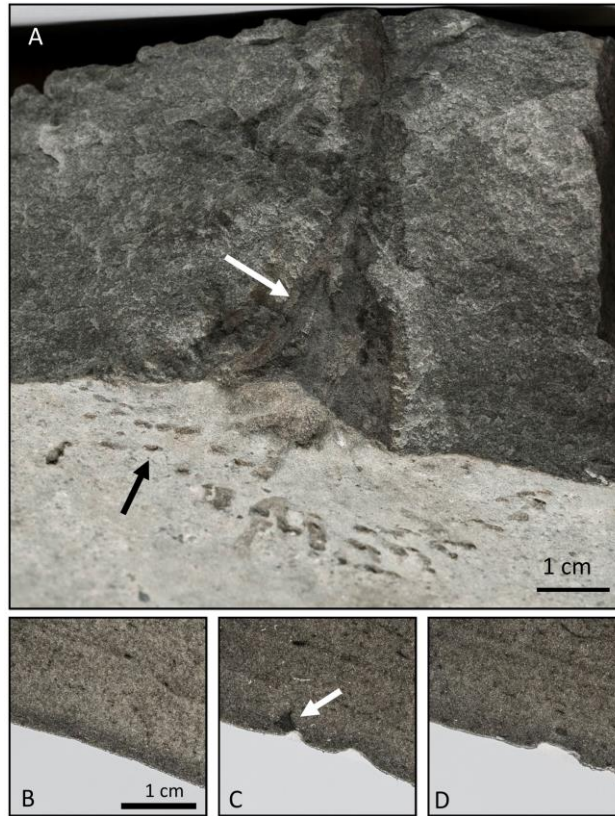


Fig. 3.9. A) Vertical cross-section of the burrow shown in Fig. 3.8 A. Multiple sub-vertical sand-filled mud-lined tubes extending through the bed and radiating outward are visible (white arrow in A). Cross-sections of concentric sub-circular mud-rich depressions are radially arranged around the base of the sub-vertical downward radiating tubes (black arrow); B, C, and D) Sequential grind images (spanning 2 mm in the bedding perpendicular direction) of cross-sections of a vertical tube (white arrow in C) extending upward approximately 3 mm. On basal surfaces of beds the cross-sections of these short vertical tubes are expressed as conical sub-circular depressions arranged radially around the base of the sub-vertical *Parahaentzschelinia*-like components (shown in Fig. 3.8 A and Fig. 3.9 A). Vertical tubes (white arrow in C) only extend a few millimetres upward from the base of the sandstone beds before ending, and do not visibly connect to the upper sub-vertical component of the burrow.

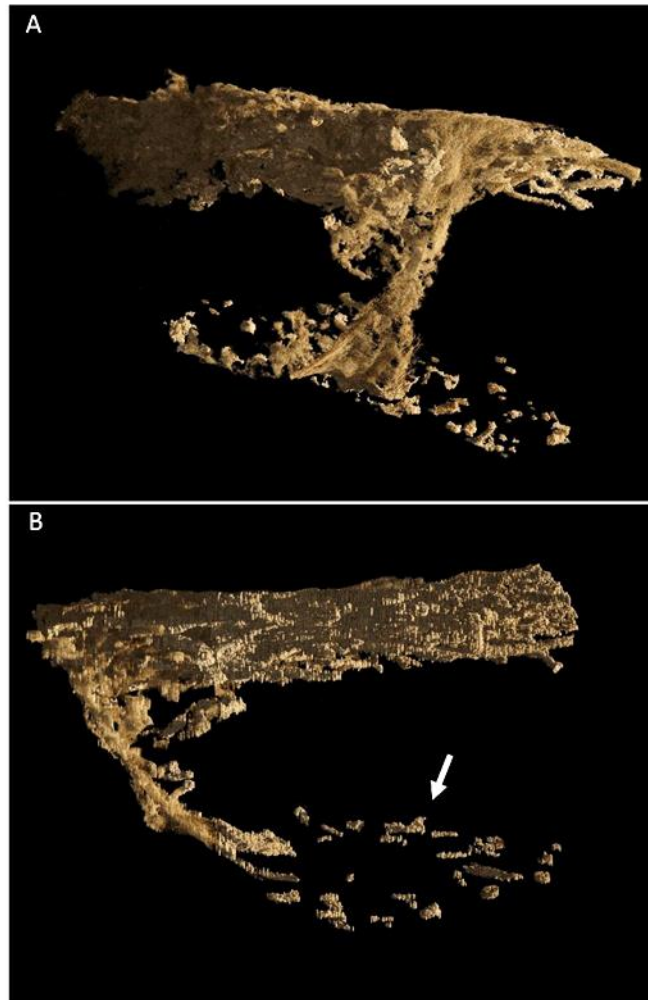


Fig. 3.10. Three-dimensional model of burrow shown in Figs 3.8 A and 3.9, produced by serial grinding and modelling methods described by Bednarz *et al.* (2015). The full burrow was not modelled, as the sample was cracked in half, exposing burrow cross-section (shown in Fig. 3.9 A). A) View of model in same orientation as rock sample in Fig. 3.9 A; B) Side view of model. The short millimetre-scale vertical tubes arranged concentrically around the base of the sub-vertical component of the burrow are visible at the base of the model in B (white arrow). These tubes do not visibly connect to the main sub-vertical component of the burrow. An upper horizontal network component is also visible branching from the sub-vertical component in the upper 2 centimetres of model (see section 5.2.1).



#### 5.1.4 Chambers within the conical sub-vertical burrow clusters

The upper conical portion of some burrows have been found, by serially grinding, to contain numerous mud-lined sub-spherical chambers 2 to 3 mm in diameter. The chambers have a lining rich in clay similar to the linings of the associated burrows, but are filled with a much darker grey material than the fill of the vertical tubes (Fig. 3.11). The chambers are concentrated at 2 to 3 cm depth within the funnel-shaped portion of the burrows. Chamber-like structures in burrows are commonly inferred to have been fermentation chambers for microbial farming (e.g. Bromley 1996; Leaman *et al.*, 2015). In this material there is no indication of an increased organic matter content in the chambers that would support a gardening model.

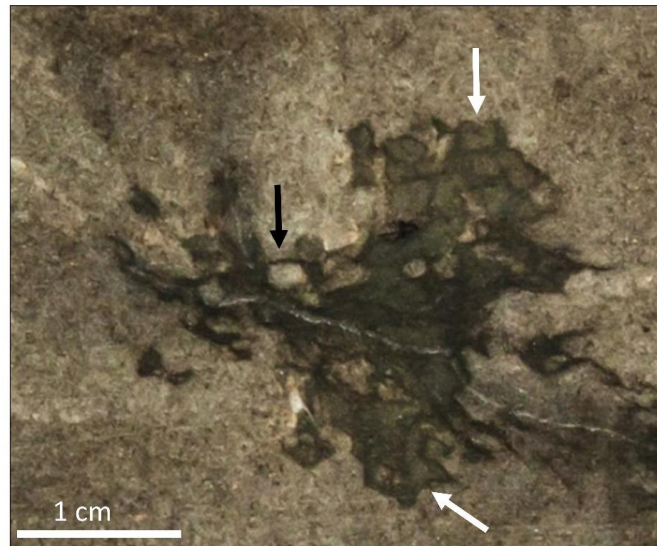


Fig. 3.11. Grind image showing bedding-parallel cross-section of numerous chambers within the conical sub-vertical burrow clusters. Numerous mud-lined sub-spherical

chambers 2-3 mm in diameter (white arrows) are connected to the sub-vertical component of the burrow. Chambers have a lining rich in clay similar to the linings of the associated sub-vertical tubular burrows, but are filled with a much darker grey material than the fill of the vertical tubes. Cross-sections of mud-lined sand-filled vertical tubes that make up the sub-vertical portion of the burrow are highlighted by the black arrow. Chambers are concentrated at 2-3 mm depth of some sub-vertical burrows.

## 5.2 Horizontal branching

The sub-vertical structures comparable to *Parahaentschelina* present in the field in the Winterhouse Formation can—using serial grinding and reconstruction—be demonstrated to branch horizontally in a number of distinctive ways that are not hitherto described in association with *Parahaentschelina*. The range of morphologies represented, while being clearly linked to the vertical *Parahaentschelina*-like structures, bear close morphological resemblance to other discrete taxa.

### 5.2.1 *Multina*-like polygonal tiered network

Horizontal and oblique anastomosing straight to curved burrows branch from the vertical *Parahaentschelina*-like burrow component in the upper 2 cm of the bed (Figs 3.10 and 3.12). These burrows are sand-filled and have mud-rich burrow linings comparable to the sub-vertical burrows of the *Parahaentschelina*-like elements. The

horizontal and oblique burrows bifurcate and ramify at both acute and obtuse angles to create an irregular three-dimensional polygonal network orientated sub-parallel to bedding (Fig. 3.12). These burrows are generally 1-2 mm in diameter and commonly exhibit Y-branching (Fig. 3.13). Y-shaped junctions are rounded, indicating these burrows were open and patrolled. Portions of the burrows curve upward and downward to connect up to three tiers of the burrow network.

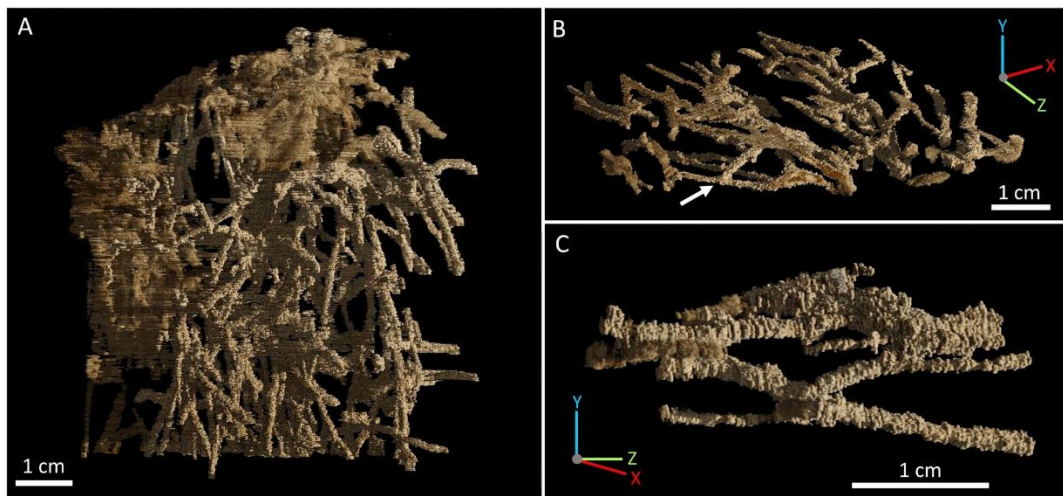


Fig. 3.12. Three-dimensional model of burrow shown in Figs 3.8 A, 3.9, and 3.10. A) Model viewed bedding parallel from above showing three-dimensional horizontal polygonal tiered network of tubes; B) Segment of three-dimensional model showing horizontal polygonal network; Two tiers are seen connected by oblique tube (white arrow); C) Segment of model showing oblique three-dimensional polygon (in B and C, the Z axis indicates grinding direction and Y indicates way up.)

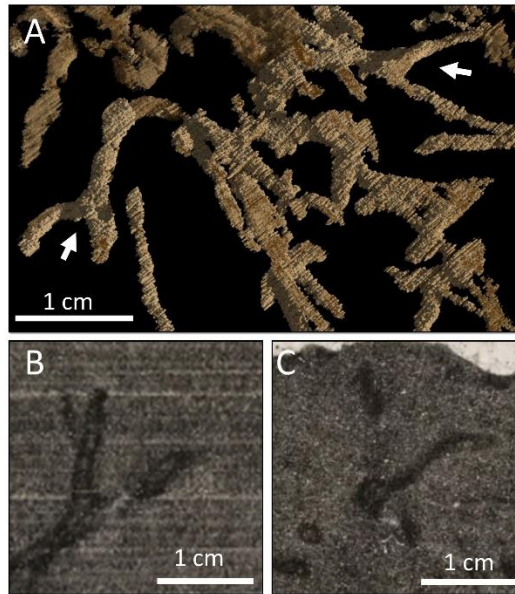


Fig. 3.13. Rounded Y-shaped junctions of horizontal tubes making up *Multina*-like polygonal network. A) White arrows point to Y-shaped branching in cross-section of three-dimensional model (viewed obliquely from above); B) Y-shaped branching in cross-section viewed obliquely from above; C) Upward Y-branching viewed in cross-section perpendicular to bedding.

### 5.2.2 *Chondrites*-like elements

Infrequently horizontal burrows exhibit regular bifurcations to produce a dendritic pattern comparable to the probing pattern seen in *Chondrites* (Fig. 3.14). The burrows differ from *Chondrites* in having a burrow lining which is not present in that taxon. The similar branching style is thus clearly due to convergence, and given that the burrow lining and diameter are comparable to the *Parahaentzschelinia*-like elements we are confident that they are part of the same burrow system.



Fig. 3.14. Composite image viewed bedding parallel from above, generated by stacking 15 serial grind images, showing regular acute branching in dendritic pattern (white arrow) similar to the probing pattern seen in *Chondrites*. Horizontal burrows branch from the conical bundle of sub-vertical burrows (black arrow).

### 5.2.3 Chambered mud-lined burrows

While many horizontal burrows in the structure are simply mud-lined and sand-filled, some horizontal sand-filled burrows include vertical partitions, producing chambers approximately 2-4 mm in length (Fig. 3.15). The segmented burrows are generally slightly larger in diameter than the non-segmented horizontal burrow segments (generally no less than 2 mm), with individual segments being up to 4 mm in width.

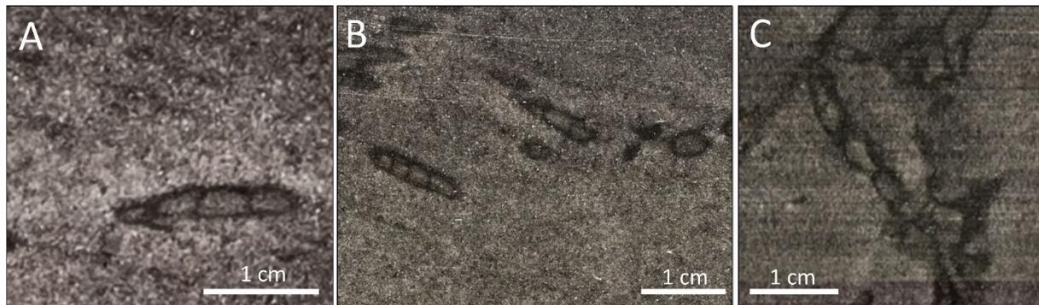


Fig. 3.15. Grind images showing cross-sections of horizontal burrows containing sand-filled mud-lined partitions/chambers. Both A and B are cut perpendicular to bedding. C is orientated parallel to bedding.

#### 5.2.4 *Megagraption*-like sinuous network (on bedding sole)

Sinuuous bedding parallel burrows typically found on the bases of fine-grained silty sandstone beds, and are centred upon the points where the *Parahaentzschelinia*-like sub-vertical burrows meet the lower surface of beds. The burrows may be both straight and curved, and exhibit Y and T branching (Fig. 3.16). The mud-lined burrows are sand-filled and approximately 2 mm in width. Possible backfill is present in some sections of the burrows. Burrow segments between branches are typically between 5 and 10 cm in length (Fig. 3.16). The open irregular networks are superficially similar to *Megagraption* Książkiewicz, 1977 in cross section, though *Megagraption* is not generally associated with vertical burrows. The burrows documented herein are clearly connected to the *Parahaentzschelinia*-like sub-vertical components, and include short lateral probes and demonstrably link the adjacent vertical *Parahaentzschelinia*-like elements (Fig. 3.16).





Fig. 3.16. Sinuous burrow network on bedding soles. Straight and curved bedding-parallel burrows superficially similar to *Megagraption* radiate from the base of *Parahaentzschelinia*-like sub-vertical burrows; A) Sinuous horizontal burrows demonstrably link adjacent vertical *Parahaentzschelinia*-like elements between 5 and 10 centimetres apart; B) Bedding sole of sample containing *Megagraption*-like sinuous basal burrows; C) Upper surface of sample shown in B. *Parahaentzschelinia*-like sub-vertical conical cross-sections are visible; D-E) Sinuous horizontal burrows on bedding sole demonstrably connect to sub-vertical *Parahaentzschelinia*-like component.



## 6. Near burrow effects

The vertical cross sections of multiple sub-vertical *Parahaentzschelinia*-like burrows from the Winterhouse Formation reveal conical zones of deformed laminae bent inwards in a funnel shape surrounding the sub-vertical component of the burrow systems (Figs 3.3 and 3.17). These sedimentary structures are considered to be “collapse cones” – conical zones of sediment collapse created by the burrowing behaviour of the trace-making organism (cf. Leaman *et al.*, 2015). Some of the observed collapse structures may be related to pre-existing burrows reworked by the trace-maker of the *Parahaentzschelinia*-like shafts (Fig. 3.17 A). Other collapse cones do not appear to be related to pre-existing burrows and are thus interpreted to have been formed during the construction of the *Parahaentzschelinia*-like burrows (Fig. 3.17 B).

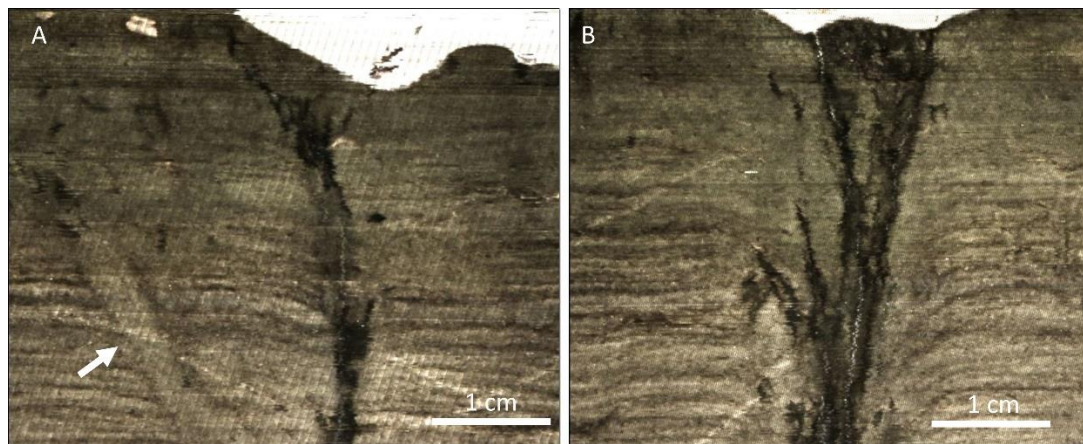


Fig. 3.17. Conical zones of deformed laminae bent inwards in a funnel shape (“collapse cone”) surrounding the vertical and sub-vertical *Parahaentzschelinia*-

like burrows in the Winterhouse Formation; A) Collapse cone surrounding *Parahaentzschelinia*-like burrow appears to be related to pre-existing J-shaped burrow (arrowed). The J-shaped burrow is potentially similar to those constructed by the lugworm *Arenicola marina*. The *Parahaentzschelinia*-like burrow trace-maker may have facultatively exploited a pre-existing collapse cone; B) Collapse cone associated with a different *Parahaentzschelinia*-like burrow does not appear to be associated with a pre-existing burrow, thus appears to have been constructed with the *Parahaentzschelinia*-like burrow.

## 7. Discussion

### 7.1 Paleobiological interpretation/Biological affinities

The complex hypidiomorphic morphology of the burrow system described herein from the Winterhouse Formation is interpreted as an indication of the diversity and range of behaviour of the trace-making organism. In addition to generally only reporting 'ideal' idiomorphic morphologies when discussing and typifying new ichnotaxa, many ichnologists assign a single behaviour to an ichnotaxon (cf. Miller, 1996 a, b; Miller and Aalto, 1998). Most burrows are formed through a range of behaviours for a range of purposes and also involve interactions with both the burrowed substrate and the ambient environment (see Herringshaw *et al.* 2010). The behaviour of burrowing organisms living in semi-permanent burrows may be seasonal, but may also vary in response to other environmental changes and changing stimuli (ie. food availability, pre-existing or adjacent burrows, etc.). It is especially difficult to consider the range of possible trace-maker behaviours when the range of morphologies in a trace fossil or ichnological assemblage is not fully described. This

study highlights the importance of documenting the range and variability in burrow morphology when describing ichnotaxa (cf. Miller, 1998; Miller and Aalto, 1998; Miller, 2011). If a thorough discussion of morphological variability is not included in ichnotaxonomic descriptions and diagnoses, the information that is available to interpret trace-maker ethology and paleoenvironmental conditions is limited (see McIlroy 2008).

The burrow system described herein is interpreted to represent a combination of behaviours primarily related to feeding. The trace-making organism is unknown, but is considered to exhibit facultative, and possibly sequential feeding strategies. Based on comparison to structures built by modern organisms, the trace-maker is considered to potentially have been a polychaete-like organism, possibly similar to modern nereidids, although some components of the burrows are also similar to burrows constructed by modern bivalves (Wikander, 1980; Allen, 1983; Bromley, 1996). Since the complex morphology is interpreted to represent a combination of behaviours, the paleobiological interpretation of each morphological element is discussed separately.

#### 7.1.1 Interpretation of sub-vertical burrow clusters

The sub-vertical component of the described burrow system is interpreted to primarily represent deposit feeding and detritus feeding activity. The trace-making organism probably searched for organic matter within the storm beds as well as in muddier sediments above and below the sandstone event beds. The morphology of

this component is very similar to the descriptions of the type material of *Parahaentzschelinia*, except that *Parahaentzschelinia* has been described as having a single common master shaft or gallery from which the numerous sub-vertical tubes branch, and has not been previously associated with downward branching (cf. Chamberlain, 1970; Uchman, 1995).

*Parahaentzschelinia* has generally been interpreted as a feeding burrow in which the lateral and radial shifting of the burrow was produced as the trace-maker repeatedly extended itself up and outward from the central fixed point within the sediment in search of food (Chamberlain, 1971; Dam, 1990). Most authors have considered the trace-maker to be a small worm (Chamberlain, 1971), while others have suggested that the structure is similar to burrows constructed by siphonate bivalves (Fürsich et al., 2006).

The burrows described herein are typically found in centimetre-scale fine-grained tempestite sandstone beds. The initial colonization of tempestites and similar event beds in modern settings is typically by polychaetes (Shull, 1997; McIlroy, 2004). Burrowing polychaetes have also been observed to exhibit facultative changes in behaviour and associated changes in burrow morphology depending on their ontogenetic stage, changes in sediment properties, distribution of nutrients, and feeding strategy employed (Herringshaw *et al.*, 2010). In experimental conditions the modern nereidid *Alitta virens* produces a wide variety of burrow morphologies similar to several of the morphologic elements observed in the burrow system described here (cf. Herringshaw *et al.*, 2010).

The modern tellinid bivalve *Abra longicallus* produces burrows during deposit feeding and possible gardening activity that are comparable to the sub-vertical *Parahaentzschelinia*-like burrows described herein (Wikander, 1980; Allen, 1983; Bromley, 1996). *A. longicallus* has been observed to deposit feed within the subsurface sediment, and deposit faecal pellets at feeding level at depth (Wikander, 1980; Allen, 1983). This activity was interpreted as gardening behaviour by Allen (1983). The abandoned canals created from siphonal activity also form systems of branching galleries (Wikander, 1980; Bromley 1996). *Scrobicularia plana* is an infaunal bivalve of intertidal settings, which surface deposit feeds during low tide, and both deposit feeds on sediments in the anoxic zone and suspension feeds during high tide (Hughes, 1969; Bromley, 1996).

#### 7.1.2 Interpretation of the bedding sole expression of downward branching

The short mud-rich tubes arranged concentrically around the basal expression of the main sub-vertical burrow (Figs 3.8 and 3.9) are considered to represent the terminal portions of recurved mud-filled J-shaped tubes. These tubes are inferred herein to be burrows that extend downward and radially outwards—like the spokes of an inverted umbrella—into the underlying mudstone. The mudstone fill of the terminal portion of the tubes at the sandstone-mudstone junction suggests that they were either actively mud-filled in life, or remained open and the fill is taphonomically generated. The purpose of the J-shaped “spokes” remains enigmatic since we have been unable to demonstrate their fill or morphology in the field. The presence of a

high surface area burrow structure in deeply buried muds that were connected to more oxygenated pore-waters of the overlying sands and open burrow is suggestive of either chemosymbiosis (cf. Seilacher, 1990; Fu, 1991) or microbial gardening (cf. Aller and Yingst, 1978; Reise, 1981; Dufour *et al.*, 2008; Herringshaw *et al.*, 2010). Radial spoke-like burrows around the base of a vertical shaft have also been described from *Arenicola marina* in organic-matter rich sediment (Rijken, 1979; Bromley 1996).

#### 7.1.3 Interpretation of mud-lined chambers

Numerous mud-lined sub-spherical chamber-like structures are concentrated at 2 to 3 cm depth within the sub-vertical mud-rich conical portion of some burrows (Fig. 3.11). Similar mud-lined chambers occur within several horizontal tunnels branching from the sub-vertical components (Fig. 3.15). Chamber-like structures rich in organic detritus described from fossil burrows are commonly inferred to be fermentation chambers for microbial farming (e.g. Bromley 1996; Leaman *et al.*, 2015). Alternative organic sources in such chambers might be fecal pellets which are stored for re-ingestion after a period of microbial production has elapsed (i.e. a combination of microbial farming and autocoprophagy) (cf. Bromley, 1996). Subsurface chambers in modern burrows are also storage sites for organic matter, particularly where delivery of organic matter to the seafloor is pulsed and patchy (Jumars *et al.*, 1990; Levin *et al.*, 1997). These food caches are then used to feed on when the supply of organic material becomes low (Jumars *et al.*, 1990; Levin *et al.*, 1997). The burrow fill of the

chambers observed within the upper mud cone is darker and a slightly more greenish-grey color than the fill of the surrounding burrows (Fig 3.11) which could also be due to berthierine or glauconite rich sediment, which can be produced by in-vivo weathering of sediment grains by sediment-ingesting organisms (McIlroy *et al.*, 2003)

#### 7.1.4 Interpretation of the *Multina*-like polygonal tiered network

The polygonal network component of this burrow system is morphologically similar to the irregular networks of *Multina*. The horizontal component of the network burrows described herein commonly exhibit rounded Y-shaped junctions, suggesting that some burrows within the network were open and patrolled by the trace-maker, possibly due to microbial farming, and cropping of microbes from the burrow wall as seen in modern nereidid burrows (see discussion in Herringshaw *et al.* 2010). Modern nereidid polychaetes in aquaria produce horizontal and vertical burrows similar to those in the present material that link to form complex branching networks (Fig 3.18; Herringshaw *et al.*, 2010). The galleries of *Alitta virens* burrows are maintained as open galleries lined with either mucous-bound fines or mud (Herringshaw *et al.*, 2010). The mucous linings of burrows stabilize the burrow walls and may both trap and be used as a substrate to culture microorganisms for food (Reise, 1981; Dufour *et al.*, 2008; Herringshaw *et al.*, 2010). As mucus linings are absent from the fossil record, there is no way to confirm whether fossilized burrows were mucus lined, however the burrows observed in the Winterhouse Formation

appear to have been open and are lined with mud so it reasonable to suggest the burrow walls were originally mucus-lined.

The presence of multiple tiers of galleries connected by short inclined shafts is similar to *Multina*, and enables highly efficient occupation of sediment volumes (cf. Bednarz and McIlroy, 2012). The connection of the layers of galleries to the sediment-water interface may have allowed bioirrigation of the burrow network providing microbial nutrients to increase microbial productivity on the burrow walls and thus nutriment for the trace-maker (cf. Aller and Yingst, 1978; Reise, 1981; Dufour *et al.*, 2008; Herringshaw *et al.*, 2010).

The morphology of the *Alitta virens* burrow networks produced in aquaria is comparable to the networks described herein (Fig. 3.18; Herringshaw *et al.*, 2010). It is reasonable to suggest that the behaviour of the trace-making organism that constructed the networks described from the Winterhouse Formation exhibited behaviour similar to the nereidids (cf. Herringshaw *et al.*, 2010).



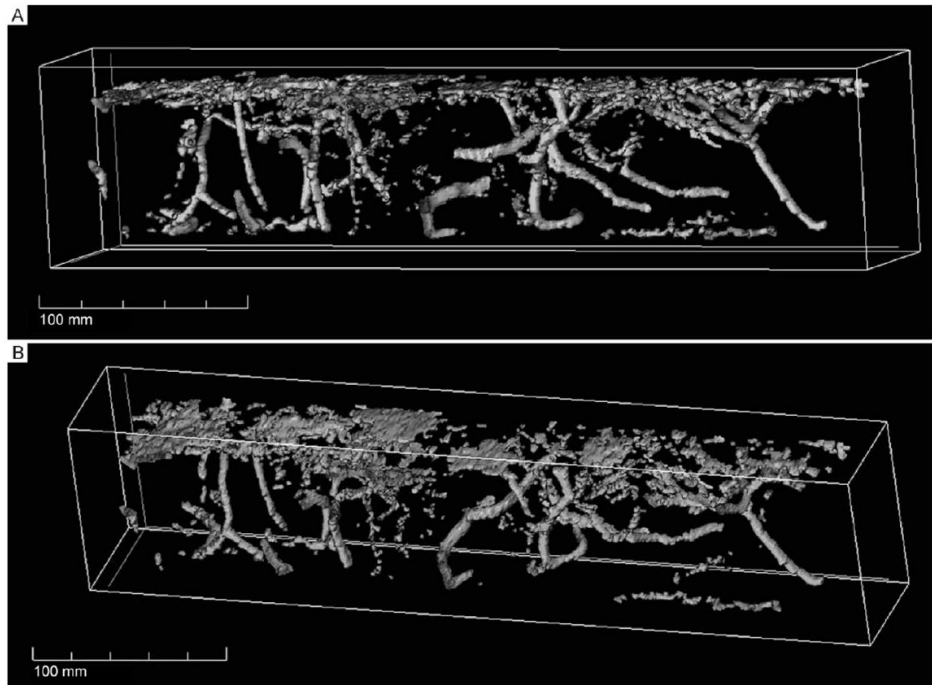


Fig. 3.18. Volume-rendered stack of CT-scanned transverse images showing burrow morphologies produced by the nereidid *Alitta virens*, which are similar to the burrow morphologies discussed here from the Winterhouse Formation. A) Side view; B) View obliquely from above. (From Herringshaw *et al.*, 2010).

#### 7.1.5 Interpretation of *Chondrites*-like elements

Rare horizontal to sub-horizontal burrows with dendritic bifurcations at acute angles are found in the burrow systems described herein (Fig. 3.14). The branching pattern is similar to the primary successive branching characteristic of *Chondrites*, though we note that burrow linings are not described from that taxon. *Chondrites* has been interpreted as the systematic probing trace of an organism feeding in organic-

rich sediment, possibly using a retractable proboscis (Osgood, 1970), though most modern consensus points towards a chemosymbiotic function (Seilacher, 1990; Fu 1991). *Chondrites sensu-stricto* is common in the Winterhouse Formation, however—unlike the burrows described herein—they are unlined and they do not connect to sub-vertical *Parahaentschelinia*-like components.

#### 7.1.6 Interpretation of *Megagraption*-like sinuous network on bedding sole

The back-filled sinuous bedding parallel burrows radiating from the base of the *Parahaentschelinia*-like sub-vertical burrows on bedding soles are interpreted to represent deep deposit-feeding behaviour. The trace-making organism likely exploited the base of these event beds, searching for organic matter in the muddy sediments below. Similar burrow morphologies have been created in aquaria by nereidid polychaetes in association with sub-surface deposit feeding (Herringshaw *et al.*, 2010). Such deposit feeding activity is inferred to exploit microbial growth and organic matter decay due to bioirrigation of the burrows, as well as fines transported into the burrows by bioirrigation (Herringshaw *et al.*, 2010, Herringshaw & McIlroy 2013).

#### 7.1.7 Interpretation of collapse cones

Collapse cone structures can be formed by infaunal organisms either deliberately or accidentally by a variety of behaviours, ranging from simple structural collapse to

microbial gardening (Bromley, 1996; Buck and Goldring, 2003). The lugworm *Arenicola marina* is a detritus feeder that usually constructs a J-shaped mucus supported burrow in loose sand, with the aid of a conical head shaft of collapsing sediment (or, a ‘collapse cone’) (Wells, 1945; Schäfer, 1962; Rijken, 1979; Bromley, 1996). A conical pit is formed at the sediment-water interface above the cone that acts as a trap for detritus to accumulate, which is subsequently incorporated into the sediment cone (Lampitt, 1985). *Arenicola* pumps water in through the tail shaft, and back out through the head shaft, which oxygenates the collapse cone, increasing microbial productivity in the cone—in a form of microbial farming—for subsequent ingestion (Longbottom, 1970).

Collapse is obvious in the burrow systems described herein. Some collapse structures appear to be related to pre-existing J-shaped burrows (Fig. 3.17), while other collapse cones appear to have been constructed by the trace maker of these *Parahaentzschelina*-like burrows (Fig. 3.17).

## 7.2 Overview of and comparison with previous descriptions of

### *Parahaentzschelina*

The type material of *Parahaentzschelina* was described from thin bedded sandstones of the Pennsylvanian Atoka Formation in Oklahoma (Chamberlain, 1971). The type ichnospecies, *P. ardelia*, was described as conical bundles of small, irregular, tubes that are passively filled with mud or sand and radiate vertically and

obliquely upward from a fixed point within the sediment (Fig. 3.19A; Chamberlain, 1971). Bedding plane cross-sections were described as conical depressions 15-60 mm across, with individual tubes being 1.5 mm wide, and a “narrow lateral (?) gallery” was suggested at the base of the conical structure (Chamberlain, 1971). Type material was collected and figured (cf. Chamberlain, 1971); however a formal diagnosis was not provided.

The sub-vertical components of the burrow systems described herein are very similar to the description of the type material, except that the structures described herein cannot be traced to a single master burrow, but rather have several vertical and sub-vertical tubes that diverge and radiate upward, and sometimes downward (Fig. 3.20). It is possible that multiple shafts are actually present in the type material of *Parahaentzschelinia ardelia*, as opposed to a single master shaft, since multiple tubes are not always easily observed on unpolished surfaces, and could possibly be mistaken for a single shaft if not studied from polished surfaces.

Although a formal diagnosis had not been given for *Parahaentzschelinia ardelia*, an emended diagnosis for the ichnospecies was proposed based on material described from Late Carboniferous storm deposits in Poland (Gluszek, 1998). The proposed diagnosis included branched, horizontal tunnels with meniscate backfill (Gluszek, 1998). The Carboniferous material was studied from cross-sections on horizontal bedding planes, and consisted of rosette-shaped groups of small circular cross-sections of vertical tubes with concentric filling of the same material as the host rock, as well as short horizontal branched burrows with meniscate filling, comparable to *Macaronichnus segregatis* (Gluszek, 1998). The rosette-shaped groupings on bedding

planes were reported up to 9 cm in diameter, with an average diameter of 3 cm, while individual vertical burrow cross-sections were relatively consistent from 3 to 5 mm, and horizontal tunnels were up to 35 mm in length (Gluszek, 1998).

This work supports the emendation of *Parahaentschelinia ardelia* to include a horizontal component (Fig. 3.20), however meniscate backfill was not observed in specimens from the Winterhouse Formation. The figure provided by Gluszek (1998) does not demonstrate convincing evidence that meniscate backfill is present, and it is suggested that the material is re-examined and/or re-figured.

A second ichnospecies, *Parahaentschelinia surlyki*, was described from the shallow marine Lower Jurassic Neill Klint Formation in Greenland (Dam, 1990). *P. surlyki* differs from *P. ardelia* in the following ways: 1) its much larger size, with tunnel diameters ranging from 4-20 mm and bedding surface cross-sections up to 120 mm in diameter; 2) its thick ornamented concentric mud linings up to 8 mm thick; 3) and a main vertical shaft up to 15 mm in diameter and 15 cm in length, as opposed to the lateral gallery suggested for *P. ardelia* (Fig. 3.19; Dam, 1990). In the Neill Klint Formation, *P. surlyki* was found to be numerous in fine-grained hummocky cross-stratified sandstones, and the long central shaft was suggested to be an escape burrow, while the thick wall was considered to be related to substrate cohesion (Dam, 1990). Owing to the very different thick wall structure, much wider tube diameters, and coarser sediment, it is suggested that *P. surlyki* be reassessed as it may possibly better fit within a new ichnogenus.

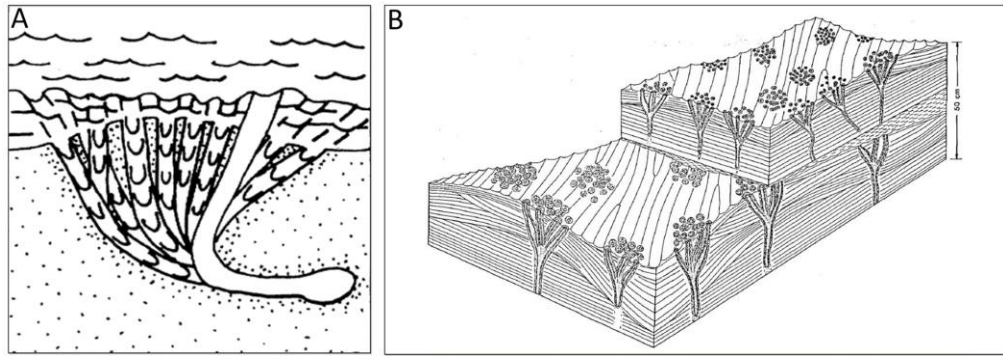


Fig. 3.19. A) idealized sketch of type specimen of *Parahaentzschelinia* (*P. ardelia*) (Chamberlain, 1971); B) idealized sketch of *P. surlyki* (Dam, 1990).

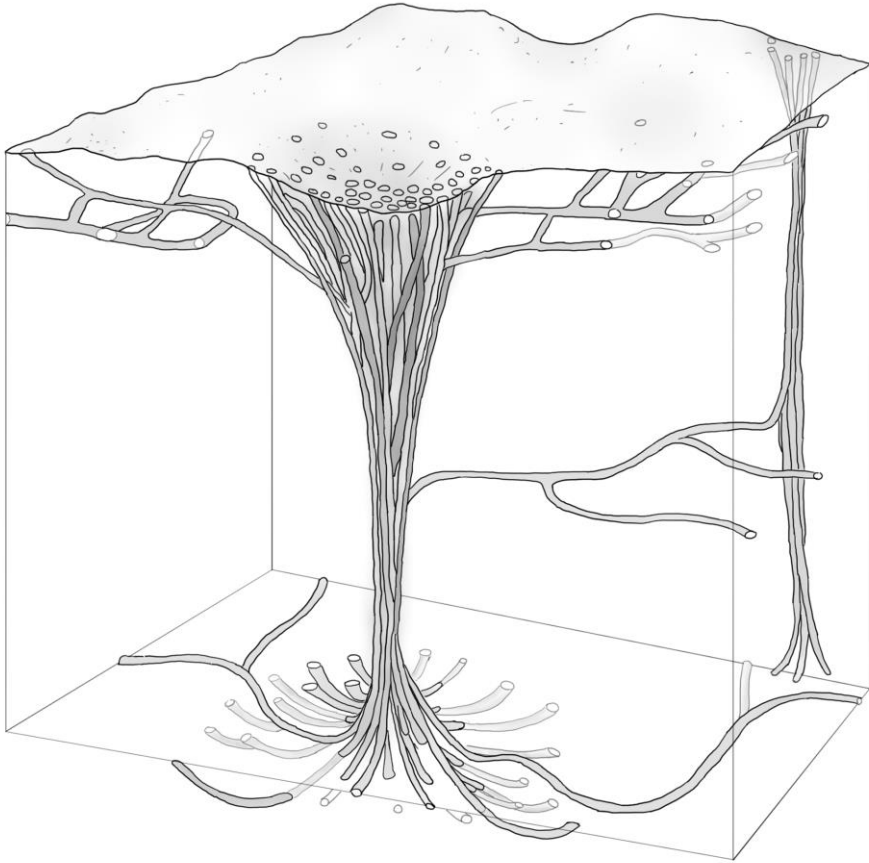


Fig. 3.20. Idealized sketch of burrows observed in this study.

## 8. Conclusion

The sub-vertical *Parahaentschelina*-like component of the burrow system described herein differs from the description of the type material of *Parahaentschelina* (cf. Chamberlain, 1971) in the following ways:

1. The type material of *Parahaentschelina* has been described as having a single common shaft from which the radiating tubes branch. The structures described herein have several vertical and sub-vertical tubes that cannot be traced into a single master shaft and as such cannot be confidently assigned to *Parahaentschelina*.

2. The type material of *Parahaentschelina* is described as having a funnel-shaped aggregation of upward radiating tubes, but no downward radiating portion. An upward radiating portion is present in every specimen described herein, but the specimens described herein also commonly exhibit a downward radiating portion. This morphology creates a broadly symmetrical “hour glass-shaped” structure that radiates outward in both the upward and downward direction. This portion of the burrow systems is interpreted to be related primarily to deposit- and detritus-feeding behaviour. The vertical connection to the sediment-water interface could also play a role in bioirrigation of the network.

3. Short sub-vertical mud-filled tubes approximately 1-2 mm in length are present on many bedding soles radially surrounding the base of many sub-vertical *Parahaentschelina*-like burrows. Serial grinding demonstrates that these tubes do

not connect to the sub-vertical component, but given their radial arrangement around the base of multiple samples, they are considered to be the tips of recurved J-shaped burrows that extend from the base of the vertical and sub-vertical *Parahaentzschelinia*-like burrows into the underlying mudstone, with only the tips reconnecting to the sandstone. They are inferred to be the result of deposit feeding or microbial farming at the burrow-mud junction.

4. Chambers 2-3 mm in diameter have been observed, by serially grinding, to connect to the sub-vertical tunnels that make up the conical portion of the *Parahaentzschelinia*-like burrows. These chambers are considered to represent possible “fermentation chambers” used for culturing of microbes as a food source (cf. Bromley, 1996; Leaman *et al.*, 2015).

5. Zones of sediment collapse (“collapse cones”) not described in association with the type material have been observed to surround the sub-vertical burrows described herein.

6. Horizontal and oblique burrows are observed to branch from the sub-vertical *Parahaentzschelinia*-like components. These burrows bifurcate and ramify at both acute and obtuse angles and can be demonstrated to create complex three-dimensional tiered polygonal networks orientated parallel and oblique to bedding. These networks are similar to the trace fossil *Multina*. Rounded Y-shaped junctions at some branching points indicate these burrows were open and patrolled. Vertical connections to the surface suggest the network was bioirrigated by overlying seawater, potentially playing a role in the cultivation of microbes for food.



7. Some horizontal burrows observed to connect to the sub-vertical *Parahaentschelinia*-like components exhibit dendritic branching patterns similar to primary successive branching (*sensu* D'Alessandro and Bromley, 1987) that is characteristic of *Chondrites*. These burrows may represent exploratory probing of the surrounding sediment in search of organic-rich sediments.

8. Sinuous bedding-parallel burrows superficially similar to *Megagraption* are observed on bedding soles. These burrows are back-filled and are interpreted as the result of the trace-making organism exploiting the muddy sediments below the event beds in search of organic-matter. These burrows are also demonstrated to connect chains of adjacent sub-vertical *Parahaentschelinia*-like burrow components.

The complex hypidomorphic morphology of the burrow system described herein is interpreted to represent a variety of complex facultative behaviours primarily related to feeding. The trace-making organism is inferred to have exploited organic matter within the sandstone event beds as well as in muddier beds above and below the sandstone beds using a variety of behaviours. Potential burrow irrigation and microbial cultivation associated with gardening behaviour is also inferred. The trace-making organism is unknown, but comparisons are drawn between the structures observed herein and those produced by both modern polychaetes and bivalves. At present it is not possible to speculate as to a likely trace-maker even at the level of phylum.

This study highlights the importance of thoroughly documenting the complexity and range of burrow morphologies in a type series, rather than just a single

idiomorphic specimen, when creating diagnoses and descriptions. Accurate understanding of complex burrow morphologies, including the range in morphology, is important for interpreting trace-maker behaviour (cf. Miller, 1998; Miller and Aalto, 1998; Bednarz and McIlroy 2009; Miller, 2011). Incomplete morphological understanding causes problems when inferring trace-maker ethology, leading to oversimplified paleobiological and paleoenvironmental interpretations. Idealizing morphological descriptions of type material and omitting a discussion of the variability of morphologies in the diagnoses of type specimens also has the potential to create ichnotaxonomic conundrums (cf. Miller, 2011). For example, workers may erect extraneous ichnotaxa when attempting to identify structures that vary from morphologically 'ideal' type material descriptions, which later require synonymization.

Considering the strong similarity between *Parahaentzschelinia* and the sub-vertical burrow components described herein, it is likely that the Winterhouse material could be ascribed to that taxon, but it is recommended that the type locality of *Parahaentzschelinia* be re-sampled and analysed in the light of this study. If the variety of morphologies described herein can be found in material from the type locality then an emended ichnogenic diagnosis would be required. If the described morphologies are not found in association with the type material of *Parahaentzschelinia*, then the establishment of a new ichnotaxon based on the burrows described in this study should be considered.

## 9. Acknowledgements

This work was supported by an NSERC DG grant to DMc. R. Reynolds thanks Edgars Rudzitis and Chris Boyd for their assistance with serial grinding and photography at the beginning of the project. Dr. Stephen Hubbard and Dr. Renata Netto are thanked for their helpful review and suggestions. UW Geology Museum is thanked for providing photographs of the type material of *Parahaentzschelinia ardelia*.

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## CHAPTER 4

The relationship between *Parahaentschelinia*-like burrows and natural fracture propagation patterns in the Winterhouse Formation

**The relationship between *Parahaentzschelinia*-like burrows  
and natural fracture propagation patterns in the  
Winterhouse Formation**

Robyn Reynolds and Duncan McIlroy

Memorial University of Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive, St.  
John's, Newfoundland, A1B 3X5, Canada

**KEYWORDS**

Natural fractures; *Parahaentzschelinia*; unconventional reservoirs; serial  
grinding; three dimensional reconstruction; ichnology; Winterhouse  
Formation; Newfoundland, Canada

Corresponding author: Robyn Reynolds, Memorial University of  
Newfoundland, Department of Earth Sciences, 300 Prince Philip Drive,  
St. John's, Newfoundland, A1B 3X5, Canada, Robyn.reynolds@mun.ca;  
709 864 6762; 709 864-7437 (fax)

## 1. Abstract

Three-dimensional reconstructions illustrate the relationship between the *Parahaentzschelina*-like burrows and associated natural mineral-filled fractures in cemented silt-rich fine-grained sandstones of the Winterhouse Formation, which is considered analogous to a “tight” sandstone reservoir facies. Two natural fracture systems are identified within a cemented fine-grained silty sandstone sample from the Winterhouse Formation: 1) sub-parallel fracture sets orientated at c. 40° to bedding that deflect towards and cut burrows; and 2) sub-vertical fractures directly associated with trace fossils comparable to *Parahaentzschelina*, which clearly originate from the burrows. The models produced in this study demonstrate that the *Parahaentzschelina*-like burrows create planes of weakness within the cemented sandstone sample, along which the natural fractures preferentially propagate. This suggests that these trace fossils create mechanical heterogeneities that can steer natural (and potentially artificial) fracture development. Within the modelled sample, where multiple burrows are connected in chains, the fractures propagate along the connecting tunnels. In some sections of the sample, the two fracture systems intersect, suggesting that interconnected burrow networks can lead to the formation of similarly interconnected fracture networks. In producing cemented fine-grained “tight” reservoir facies, if such burrow-related fracture systems remain open and connect to the wellbore, they have the potential to be a source of substantially increased porosity and permeability in an otherwise tightly cemented matrix, thereby increasing the surface area of potential fluid flow conduits within the otherwise

impermeable reservoir. Reservoir calculations and drilling simulations that do not incorporate an understanding of ichnofabrics could therefore be significantly flawed.

## **2. Introduction**

Unconventional hydrocarbon plays such as tight gas and shale gas plays are currently a key source of global energy. These plays are much more poorly understood than conventional reservoirs, and are typically composed of heterogeneous clay-rich mudstone or cemented “tight” fine-grained strata with ineffective micro-porosity and very little conventional permeability (Curtis, 2002; Holditch, 2006). Unconventional plays cannot produce economic volumes of hydrocarbons at economic flow rates without assistance from reservoir stimulation treatments or special recovery processes and technologies that enhance the permeability of reservoir rocks (Holditch, 2003). In shale hydrocarbon, and tight gas plays hydraulic fracturing is typically used to create open fracture networks as conduits through which hydrocarbons can flow to the wellbore from otherwise impermeable media. Permeability can be improved by either accessing pre-existing natural fracture systems or by inducing new fractures (Curtis, 2002). Current unconventional reservoir exploitation processes are therefore highly dependent on the susceptibility of the reservoir rock to form open fracture networks that are connected to the wellbore (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013).

Predicting the rheologic properties and fracture susceptibility of unconventional shale hydrocarbon and tight gas reservoir facies is a significant challenge that requires more attention (cf. Bednarz and McIlroy 2012). Successful exploitation of such unconventional reservoirs relies upon the recognition of stratigraphic intervals that may be artificially fractured (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013). The recognition and assessment of pre-existing natural fractures, zones of enhanced brittleness in otherwise ductile shales, and planes of weakness, along which induced fractures may propagate, is critical in this process (e.g., Bowker *et al.*, 2007; Cipolla *et al.*, 2009, 2010; Bednarz and McIlroy, 2012; Bustin and Bustin, 2012). Producing realistic models of the mechanical properties of unconventional reservoirs is challenging and requires consideration of all lithologic anisotropies (e.g. sedimentary fabrics and ichnofabrics). Ichnofabrics in shale gas and tight gas facies are, however, often overlooked, generalized, or misidentified by petroleum geologists, and are currently not adequately incorporated into reservoir models and drilling simulations (Bednarz and McIlroy, 2012)

Bioturbation can result in the redistribution and sorting of sediment grains, thereby producing anisotropies that can have a dramatic effect on a range of reservoir properties (cf. Pemberton and Gingras, 2005; Spila *et al.*, 2007; Tonkin *et al.*, 2010; Lemiski *et al.*, 2011; Bednarz and McIlroy, 2012; Gingras *et al.*, 2012, 2013). Enhanced fluid flow in some tight sandstones, siltstones, and mudstones is considered to be possible because of high porosities associated with trace fossils such as

*Phycosiphon*, *Zoophycos*, and *Chondrites* (Pemberton and Gingras, 2005, Spila *et al.*, 2007; Lemiski *et al.*, 2011; Bednarz and McIlroy, 2012; Gingras *et al.*, 2012, 2013; La Croix *et al.*, 2013). It has also been proposed that the fracture susceptibility of unconventional reservoirs is affected by burrow spacing and connectivity (Bednarz and McIlroy, 2012). It has been proposed that silt-rich *Phycosiphon*-like burrows in shales increase fracture susceptibility by creating brittle quartz frameworks that may act as loci for fracture propagation in otherwise ductile mudstones (Bednarz and McIlroy, 2012). In low-permeability cemented sandstone facies, fracture porosity is required to facilitate production. Maximizing the surface area of fluid flow pathways that are connected to the well-bore, by creating and/or accessing complex interconnected fracture networks in otherwise impermeable reservoir facies, is a critical factor in productivity (e.g., Cipolla *et al.*, 2009, 2010; Wang and Reed, 2009; Fan *et al.*, 2010; Khan *et al.*, 2011, 2012; Bust *et al.*, 2013). Complex, interconnected three-dimensional trace fossil networks within “tight” sandstone reservoir facies can potentially create complex, interconnected planes of weakness along which fractures may preferentially propagate, thereby significantly increasing the surface area of fracture networks.

To date no studies have directly studied the relationship between trace fossils and fracture susceptibility in tight sandstones. This study presents three-dimensional reconstructions illustrating the relationship between a vertical burrow (aff. *Parahaentzschelina*) that occurs in meandering chains, and associated natural

mineral-filled fractures in cemented silt-rich fine-grained sandstones of the Winterhouse Formation in Western Newfoundland.

The complete nature and extent of the relationship between burrows and fracture propagation patterns cannot be fully appreciated and understood from two-dimensional cross sections in outcrop, core or hand sample. A three-dimensional understanding of burrow morphology, connectivity, and spatial distribution is critical in assessing the potential influence on fracture development. This study is a pilot study aimed to create an understanding of the relationship between burrows and natural fracture distribution that is pertinent for realistic reservoir characterization of bioturbated reservoirs where induced fracturing techniques may be employed.

## **2.1 Rationale**

This study builds upon the hypothesis that trace fossils have the potential to directly affect the fracture susceptibility of bioturbated sediment (Bednarz and McIlroy, 2012). Using the three-dimensional modelling techniques of Bednarz *et al.* (2015) this study aims to document the three-dimensional relationship between the natural fracture patterns and the distribution of the trace fossil aff.

*Parahaentzschelinia* in the cemented fine-grained silty sandstones of the Winterhouse Formation.

## 2.2 Geologic setting and tectonic overview of the study area

The Winterhouse Formation is a part of the Humber Zone of western Newfoundland, which represents the early Paleozoic continental margin of Laurentia (Williams *et al.*, 1996). The Humber Zone was deformed in two main orogenic events: the Taconian Orogeny (Mid-Ordovician), and the Acadian Orogeny (Silurian-Devonian) (Stockmal *et al.*, 1995). During the Middle-Late Ordovician, sedimentation along the eastern margin of Laurentia was in a foreland basin (Lavoie, 1994; Dietrich *et al.*, 2011). These deposits include the Table Head Group, the Goose Tickle Group, and the Long Point Group (Lavoie, 1994; Dietrich *et al.*, 2011). The Long Point Group is considered to represent a foreland basin fill that was deposited between the Taconic and Acadian orogenies (Stockmal *et al.*, 1995; Quinn *et al.*, 1999). The Long Point Group comprises three formations: The Middle Ordovician limestones of the Lourdes Formation, overlain by the mixed siliciclastic/carbonate Winterhouse Formation, and capped by the red sandstones of the Misty Point Formation (Waldron *et al.*, 1993; Quinn *et al.*, 1999; Dietrich *et al.*, 2011; Fig. 4.1).

The Upper Ordovician Winterhouse Formation only outcrops on the Port au Port Peninsula of Western Newfoundland (Quinn *et al.*, 1999; Fig. 4.1). The Winterhouse Formation consists of upward-coarsening parasequences of inter-bedded silt-rich calcareous mudstones and fine-grained silty sandstones with abundant trace fossils. The succession shows net progradation and is thought to represent shallow marine storm-dominated shelf-deposits (Quinn *et al.*, 1999). The Winterhouse Formation is considered analogous to unconventional tight gas reservoir facies in the region. The



natural fractures in the bioturbated sandstones of the Winterhouse Formation allow this investigation of fracture susceptibility in relation to trace fossil distribution.

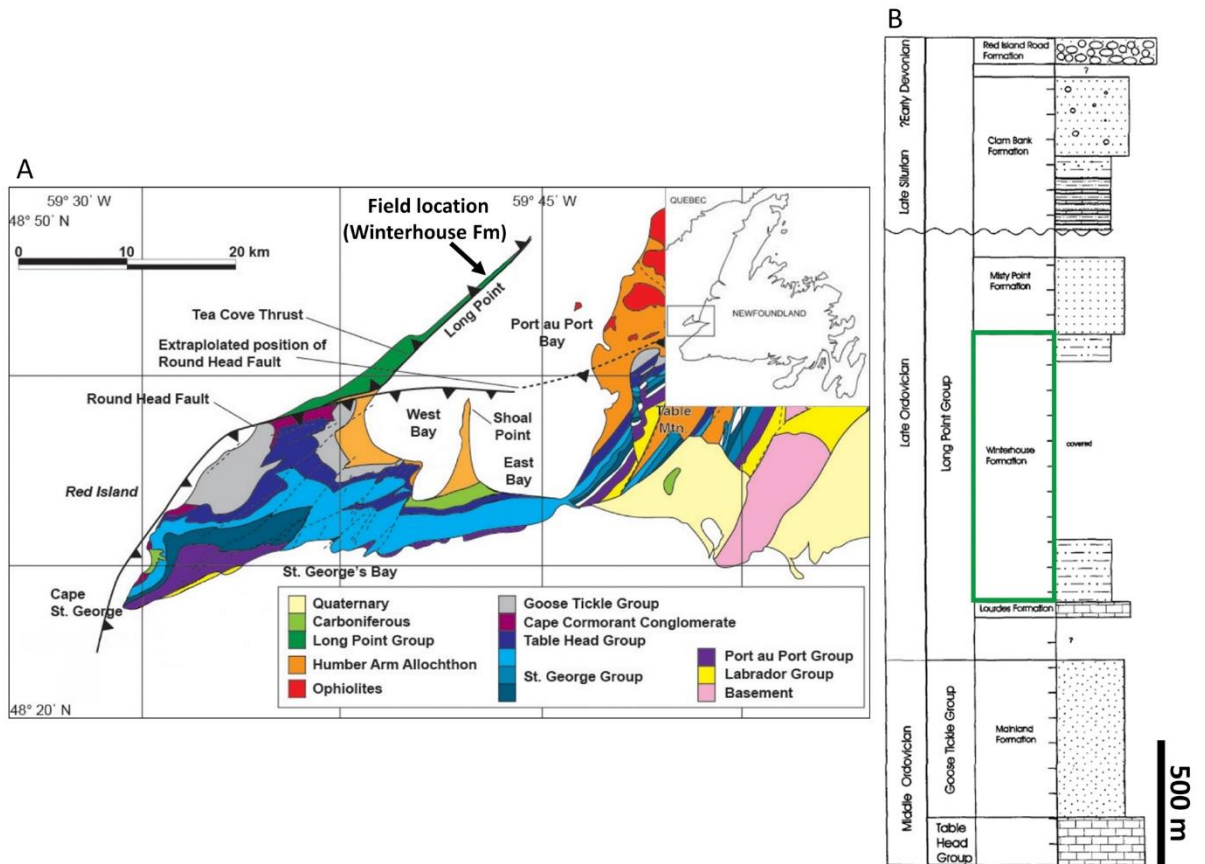


Fig. 4.1. A) Geologic map of the Port au Port Peninsula of Newfoundland, including the Winterhouse Formation as part of the Long Point Group (arrowed). Inset is an outline of a map of the island of Newfoundland, showing the (boxed) location of the Port au Port Peninsula (after Cooper *et al.*, 2001); B) Stratigraphic column of the foreland basin succession of the Port au Port Peninsula containing the Long Point Group. The green box highlights the Winterhouse Formation (after Quinn *et al.*, 1999).

### 3. Methodology

The hand-sample modelled in this study was chosen based on the abundance of natural fractures that propagated from *Parahaentschelinia*-like burrows. The sample was processed using the precision serial grinding and photography methods described by Bednarz *et al.* (2015). After being encased in a plaster block to create a consistent frame of reference in the photos, the sample was sequentially ground in a bedding parallel direction in consistent precise increments of 0.1 mm using a diamond carbide grinding tool operated by a computer guided milling machine. Photos were taken after each sequential cut under consistent lighting conditions. The sample was photographed both dry and wet with oil, as some features were more easily studied while wet while others were only visible while dry. Two generations of fractures were identified from the sample, and modelled in the three dimensional modelling software separately using different colours. The *Parahaentschelinia*-like burrow system around which the fractures were focussed was also modelled separately.

Two generations of fractures were distinguished from one another based on their differing orientation and cementation. The two fracture systems were tracked separately and manually selected from photographs spaced at 0.4 mm intervals. One fracture system is completely cemented and is more visible in wet rock images, whereas the other system occurs within the burrows and is better visualized when the polished rock surfaces are dry. For this reason both dry and wet images were processed and aligned in Adobe Photoshop™. After both sets of fractures were selected, the fractures were isolated from each photo and imported into the three-

dimensional modelling software VG Studio Max™. High-resolution models of both fracture systems were produced and compared to the distribution of trace fossils in the same volume.

#### **4. Results**

Two separate fracture systems were identified in the sample based on their differing orientation and fill (Fig. 4.2). One system consists of two opposing sets of fully mineralized fractures inclined at an angle of 40° relative to bedding (Fig. 4.2 D, E). These fractures are typically planar and extend through the entirety of the sample, but curve towards the burrows as they near or transect them (Fig. 4.3).

The other generation of fractures are primarily sub-vertical, discontinuous, and are directly related to the burrow network, with the burrows clearly being the loci of fracture propagation (Figs 4.2 and 4.4). These fractures are not as tightly cemented as the planar fracture system, and follow the position of burrows, only extending up to a centimetre horizontally beyond the burrow walls and frequently terminating in a Y-shaped bifurcation with an angle of approx. 60° (Fig. 4.4 D). Where multiple burrows are connected in chains (Chapter 3), these fractures extend along the connecting tunnels, creating an interconnected fracture network (Fig. 4.4). In some places the two fracture systems connect to form a larger network (Fig. 4.4 E, F).

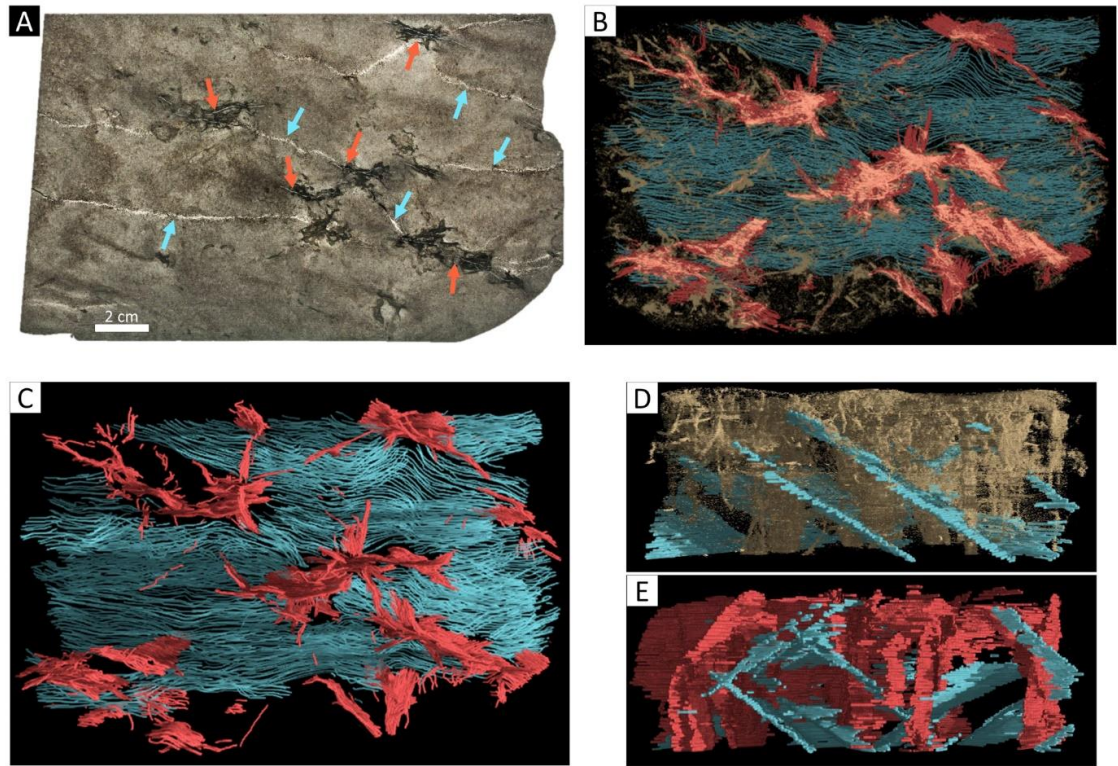


Fig. 4.2. A) Top down image of the sample that was modelled for this study showing aff. *Parahaentzschelinia* burrows connected in chains, as well as the two fracture systems that were identified in the sample. Blue and red arrows indicate the two different fracture systems (the fracture models are false coloured accordingly); B) Model viewed bedding parallel from above, showing the two fracture systems (in red and blue) and the burrow network (sand colour). These images were produced using the rendering settings “Maximum Projection” which combines the models based on their image levels, and displays them such that overlapping portions are highlighted. Where the red-coloured fracture system and the burrows overlap is clearly visible in the highlighted portions, illustrating that these fractures are contained within the burrow network, and run along the burrow tunnels; C) Fracture models only, viewed bedding parallel from above. These images were produced using the rendering settings “Scatter HQ” which displays the exterior of the selection; D) Side view of models of the planar fracture system (blue) and burrows; E) Opposite side view of the two fracture systems; D and E clearly demonstrate the orientation of the planar fracture system (blue) is inclined at an angle c  $40^\circ$  from bedding parallel.

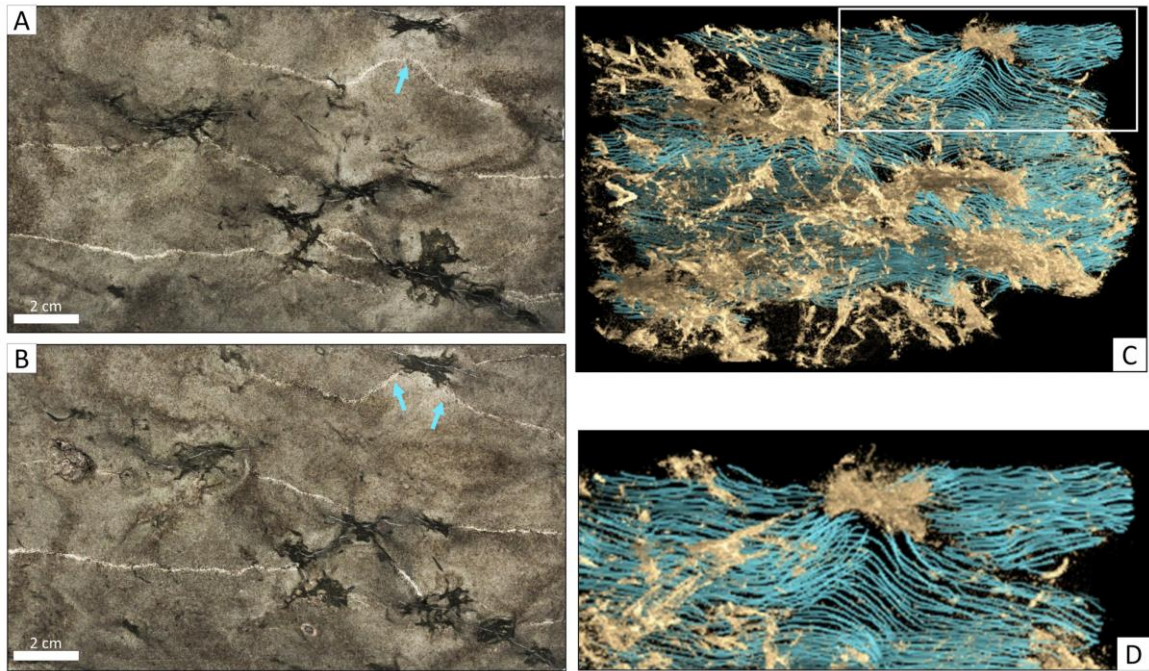


Fig. 4.3. A and B) Photographs of the sample cut parallel to bedding, showing the planar fracture system (arrows) preferentially deflecting toward the burrows (A) and then propagating through them and continuing on (B); C) The model (viewed bedding parallel from above) shows that the fractures (blue) run in a generally straight orientation through the sample, but where the burrows are present they preferentially deflect toward the burrow networks and propagate through them (area highlighted in D).



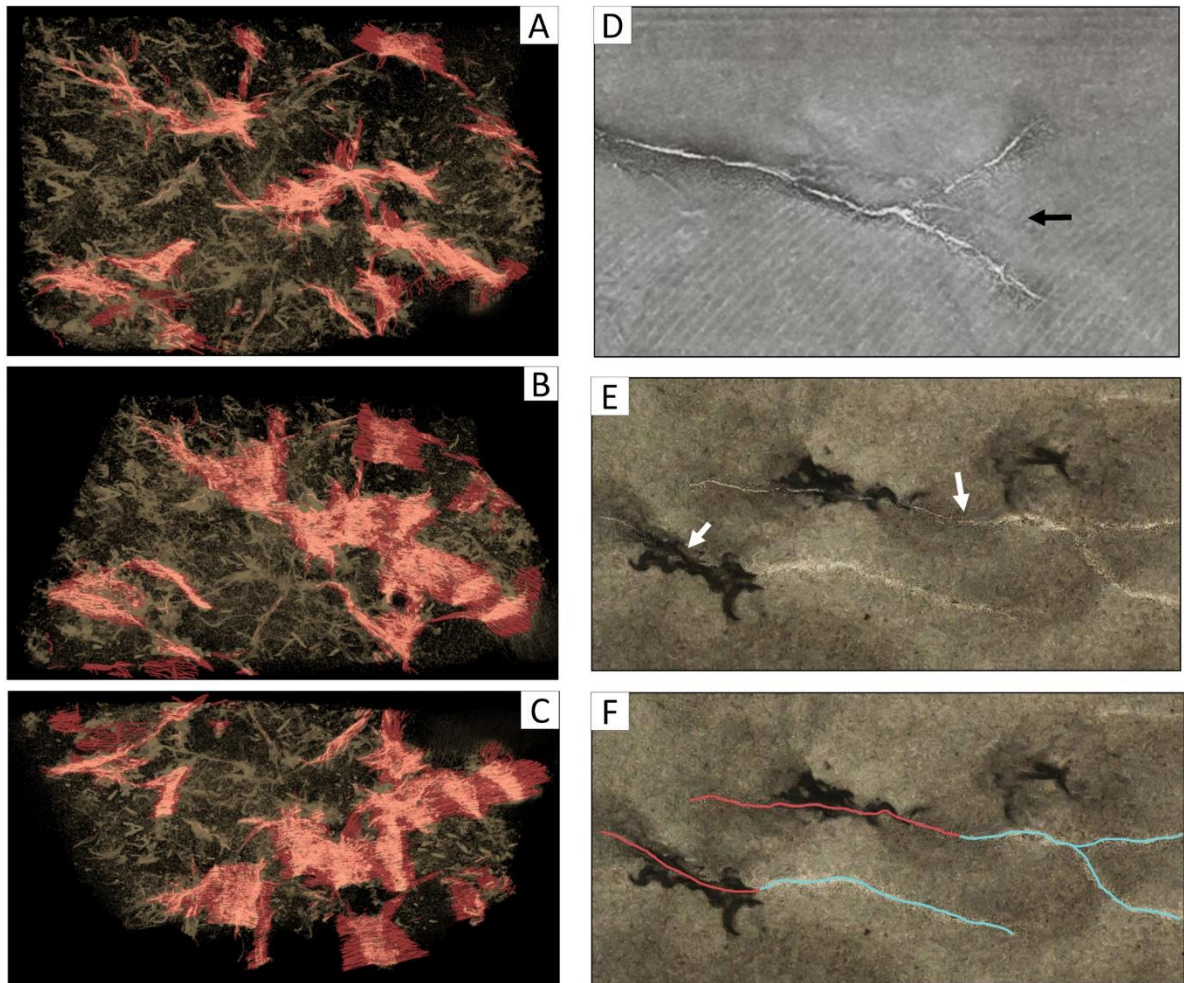


Fig. 4.4. A-C) Models of sub-vertical fracture system (red) and burrows (brown) highlighting overlapping portions of the models illustrating that this fracture system is directly related to the burrow network. The fractures are contained within the burrow network running along the burrow tunnels, with the burrows clearly acting as the loci of crack propagation creating a larger interconnected fracture network; A) Viewed bedding parallel from above; B) Viewed obliquely from above; C) Viewed obliquely from below; D) Dry surface illustrating the common Y-shaped bifurcation with an angle of c.  $60^\circ$  (arrowed); E-F) Wet surfaces illustrating the overlap between the two fracture systems that connect forming a larger network (arrowed in E).

## 5. Discussion

The redistribution and sorting of sediment grains by burrowing organisms results in anisotropies that can have a dramatic effect on a range of reservoir properties (cf. Pemberton and Gingras, 2005; Spila *et al.*, 2007; Tonkin *et al.*, 2010; Lemiski *et al.*, 2011; Bednarz and McIlroy, 2012; Gingras *et al.*, 2012, 2013). The impact of bioturbation on porosity and permeability has already been shown to be significant (e.g. Pemberton and Gingras, 2005; Gingras *et al.*, 2007, 2012; 2013; Tonkin *et al.*, 2010; Lemiski *et al.*, 2011; La Croix *et al.*, 2013), however, further study into the relationship between trace fossils and fracture susceptibility is needed (cf. Bednarz and McIlroy, 2012). A three-dimensional understanding of burrow morphology, connectivity, and spatial distribution is critical in assessing the potential influence on fracture development. In this regard, there is a need for improved three-dimensional morphological understanding of ichnofabric-forming trace fossils (cf. Leaman and McIlroy, 2015) and their relationship to the rheological properties of both brittle and ductile sedimentary facies (Bednarz and McIlroy, 2012).

In low-permeability shale and cemented sandstone unconventional reservoir facies, productivity is highly dependent on the formation of open fracture networks that act as conduits through which hydrocarbons can flow to the wellbore from the otherwise impermeable reservoir (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013). Maximizing the surface area of interconnected fracture networks throughout the reservoir, through which hydrocarbons may flow to the to the well-bore from otherwise impermeable

media, is a critical factor in productivity (e.g., Cipolla *et al.*, 2009, 2010; Wang and Reed, *et al.*, 2009; Fan *et al.*, 2010; Khan *et al.*, 2011, 2012; Bust *et al.*, 2013).

The clay-lined sand-filled *Parahaentzschelina*-like burrow networks of the Winterhouse Formation are demonstrated herein to locally influence the fracture susceptibility of the cemented fine-grained silty sandstone facies by creating planes of weakness along which natural fractures demonstrably preferentially propagate (Figs. 4.2, 4.3, and 4.4). In some cases the burrows are clearly the point of origin of fracture propagation (Fig. 4.4). This suggests that these trace fossils create mechanical heterogeneities that can steer natural, and potentially artificial, fracture development. Where multiple *Parahaentzschelina*-like burrows are connected in chains (Chapter 3), fractures extend along the connecting tunnels, creating an interconnected fracture network (Fig. 4.4). Furthermore, the two fracture systems reconstructed herein are demonstrated to connect to one another (Fig 4.4 E, F). This suggests that the presence of three-dimensional burrow networks can lead to the formation of large-scale interconnected fracture networks. If such burrow-related fracture systems are present and remain open and connect to the wellbore in producing “tight” unconventional reservoir facies, they have the potential to be a source of substantially increased porosity and permeability, thereby increasing the surface area of potential fluid flow conduits within the otherwise impermeable reservoir.

Bioturbation and natural fractures related to ichnofabrics, may also pose a risk for some plays. Heterogeneities in the stress profile of reservoir facies, caused by pre-existing natural fractures and lithologic anisotropies (such as thin cemented beds,



nodules, burrows, and other planes of weakness) can potentially result in the termination of fracture propagation (e.g. Renshaw and Pollard, 1995; Mahrer, 1999; Gu and Weng, 2010; Gu *et al.*, 2011; Fu *et al.*, 2013; Chuprakov *et al.*, 2013; McClure *et al.*, 2015). It is conceivable that mud-lined burrows may also act as fracture barriers by absorbing induced stress rather than fracturing and transmitting it. In this study, however, the burrows did not stifle the propagation but instead provided a conduit for fracture growth as evidenced by the fractures preferentially propagating through the burrows.

Understanding the structure and distribution of trace fossils in potential reservoir facies is essential for accurate calculations of reservoir properties and for geomechanical modelling. The sandstone from the Winterhouse Formation is considered to be analogous to brittle unconventional “tight sandstone” reservoir facies; however this methodology could also be employed in shale facies to investigate the effect of bioturbation on fracture susceptibility in shale gas reservoir facies.

## **6. Conclusion**

The permeability of unconventional reservoir rocks must be enhanced by special recovery techniques in order to stimulate economic production. Conduits through which hydrocarbons can flow to the wellbore from the otherwise impermeable reservoir are typically created artificially by hydraulic fracturing (e.g.,

Curtis, 2002; Holditch, 2003, 2006). The productivity of unconventional reservoirs is therefore highly dependent on the identification of stratigraphic intervals through which fractures may preferentially propagate and form open fracture networks that are connected to the wellbore (e.g., Narr and Currie, 1982; Jacobi *et al.*, 2008; Jenkins and Boyer, 2008; Ross and Bustin, 2009; Bust *et al.*, 2013). Maximizing the surface area of interconnected fracture networks throughout the reservoir is a critical factor in productivity (e.g., Cipolla *et al.*, 2009, 2010; Wang and Reed, 2009; Fan *et al.*, 2010; Khan *et al.*, 2011, 2012; Bust *et al.*, 2013).

There is currently a need to develop a better understanding of the factors that influence fracture susceptibility in unconventional hydrocarbon reservoirs. The production of realistic geomechanical models of unconventional reservoirs is challenging and requires consideration of all lithologic anisotropies (e.g. sedimentary fabrics and ichnofabrics). Subtle lithologic and ichnological heterogeneities can dramatically affect reservoir properties, including rheologic properties and fracture susceptibility, and therefore should not be overlooked. Currently, ichnofabrics in shale gas and tight gas facies are often overlooked, over-generalized or misidentified, but are demonstrated herein to be a significant source of mechanical heterogeneity that can affect fracture development.

This study recognizes two natural fracture systems within a cemented fine-grained silty sandstone sample from the Winterhouse Formation, which is considered analogous to a “tight” sandstone reservoir facies: 1) sub-parallel fracture sets orientated at c. 40° to bedding that deflect towards and cut burrows; and 2) sub-

vertical fractures directly associated with trace fossils comparable to *Parahaentzschelina*, which clearly originate from the burrows.

The models produced herein demonstrate that the *Parahaentzschelina*-like burrows create planes of weakness within the cemented sandstone sample, along which the natural fractures preferentially propagate. This suggests that these trace fossils create mechanical heterogeneities that can steer natural (and potentially artificial) fracture development. Within the modelled sample, where multiple burrows are connected in chains, the fractures propagate along the connecting tunnels. Since these trace fossils are commonly interconnected throughout any given bed, it is likely that the associated fractures would be similarly continuous. In some sections of the sample, the two fracture systems connect. This suggests that interconnected burrow networks can lead to the formation of similarly interconnected fracture networks. In producing cemented fine-grained “tight” reservoir facies, if such burrow-related fracture systems remain open and connect to the wellbore, they have the potential to be a source of substantially increased porosity and permeability in an otherwise tightly cemented matrix, thereby increasing the surface area of potential fluid flow conduits within the otherwise impermeable reservoir. Reservoir calculations and drilling simulations that do not incorporate an understanding of ichnofabrics could therefore be significantly flawed.

This work is a proof of concept study aiming to lead to reservoir-specific future studies integrating rock mechanics, structural geology, petrology, petrophysics, petroleum geology, and ichnology. The impact of trace fossils on reservoir quality

will change depending on an array of lithologic, tectonic, and petrophysical properties. Extensive studies incorporating different lithologies, controlling stresses and other reservoir properties are required in order to further understand the effect that trace fossils and associated pre-existing natural fractures would have on artificial fracture susceptibility and ultimately on reservoir quality.

## **7. Acknowledgements**

This work was supported by an NSERC DG grant to DMc. Nick Timms of Curtin University is thanked for helpful initial discussion and suggestions of ideas for future work. Dr. Stephen Hubbard and Dr. Renata Netto are thanked for their helpful review and suggestions.

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# CHAPTER 5

## Summary

# Chapter 5 – Summary

## 1. Introduction

The overarching purpose of this thesis was to investigate the ichnology of the Upper Ordovician Winterhouse Formation, which is exclusively exposed on the Port au Port Peninsula in Western Newfoundland. The first manuscript presented in this thesis provides the first systematic documentation of the complete ichnological assemblage of the Formation. The second manuscript provides a detailed morphologic analysis of a complex *Parahaentzschelinia*-like burrow system that is prolific throughout the formation. This detailed morphologic analysis allowed for a reconsideration of the trace-maker's ethology and paleobiology, and highlights a need for a systematic review of *Parahaentzschelinia*. The third and final manuscript illustrates the relationship between the *Parahaentzschelinia*-like burrows and natural fractures within the Winterhouse Formation, using the serial grinding and three-dimensional reconstruction techniques of Bednarz *et al.* (2015). This is the first time the relationship between trace fossils and fracture susceptibility in tight sandstones has been directly studied, and this work aims to lead to reservoir-specific future studies integrating rock mechanics, structural geology, petrology, petrophysics, petroleum geology, and ichnology.

The three manuscripts in this thesis, while all centered around the ichnology of the Winterhouse Formation, provide information that is relevant to a range of studies

involving bioturbated sandstone facies, particularly studies focused on the Ordovician Anticosti Basin and other eastern Laurentian basins that are elsewhere prospective for hydrocarbons (Hannigan and Basu, 1998; Weissenberger and Cooper, 1999; Lavoie *et al.*, 2005; Dietrich *et al.*, 2011). A detailed summary of the main conclusions from each manuscript are presented below.

## **2. Chapter 2 - Systematic ichnology of the Ordovician Winterhouse Formation of Long Point, Port au Port, Newfoundland, Canada**

This study provides the first systematic documentation of the well-preserved and diverse ichnological assemblage of the Winterhouse Formation. The 20 ichnotaxa documented in this study are: *Chondrites targionii*, *Chondrites recurvus*, *Cruziana goldfussi*, *Cruziana* isp., *Dictyodora zimmermanni*, *Halopoa imbricata*, *Monomorphichnus lineatus*, *Paleodictyon gomezi*, *?Parahaentzschelinia* isp., *Phymatoderma granulata*, *Phymatoderma* aff. *granulata*, *Phymatoderma melvillensis*, *Rhizocorallium commune*, *Rusophycus* isp., *Skolichnus hoernessi*, *Squamodictyon petaloideum*, *Taenidium* isp., *Teichichnus rectus*, *Trichichnus linearis*, and an unknown open gallery system. The described ichnofossil assemblage reflects a diverse array of interpreted trace-maker behaviours, including dwelling, locomotion, and a variety of different feeding strategies. Many of the trace fossils are considered to be related to tempestite deposition. This systematic ichnological study can be used to enhance our understanding of the paleoecology of the Winterhouse Formation, and can be used for comparison in other ichnological studies.

### 3. Chapter 3 - Detailed three-dimensional morphological analysis of *Parahaentzschelina*-like burrow systems

Three-dimensional reconstructions of aff. *Parahaentzschelina* burrow systems from the Winterhouse Formation reveal complex hypidiomorphic burrow morphologies. The main morphological element of the described burrow system is a *Parahaentzschelina*-like sub-vertical component composed of conical clusters of radiating sub-vertical and oblique tubular burrows with dark mud-linings (Fig. 3.3). Serial grinding and three-dimensional reconstruction reveals that the *Parahaentzschelina*-like components are associated with many burrow morphologies not described in the type material of *Parahaentzschelina* (cf. Chamberlain, 1971) and that the sub-vertical burrows themselves are also highly morphologically variable.

The morphologies documented in this study allowed for a reconsideration of the trace-maker's ethology and paleobiology. The complex hypidomorphic morphology of the burrow system is interpreted to represent a variety of complex facultative behaviours primarily related to feeding. The trace-making organism is inferred to have exploited organic matter within the sandstone event beds as well as in muddier beds above and below the sandstone beds using a variety of behaviours. Potential burrow irrigation and microbial cultivation associated with gardening behaviour is also inferred. The trace-making organism is unknown, but comparisons are drawn between the structures observed herein and those produced by both modern polychaetes and bivalves.

The following differences between the *Parahaentschelinia*-like burrow system described from the Winterhouse Formation and the type material of *Parahaentschelinia* are documented:

1. The type material of *Parahaentschelinia* has been described as having a single common shaft from which the radiating tubes branch. The structures described herein have several vertical and sub-vertical tubes that cannot be traced into a single master shaft (Figs 3.5, 3.9A and 3.19).

2. In addition to the funnel-shaped aggregations of upwardly directed burrows similar to the morphology described from the *Parahaentschelinia* type material (cf. Chamberlain, 1971), many specimens described from the Winterhouse Formation also exhibit conical bundles of downward radiating tubes similar to that seen in the upward branching portion (Fig. 3.3). These downward radiating portions are generally not as wide and deep as the upper funnel-shaped portions, and are typically more focused and contain fewer burrows. This morphology creates a broadly symmetrical “hour glass” structure that radiates outward in both the upward and downward direction (Fig. 3.3). This portion of the burrow systems is interpreted to be related primarily to deposit- and detritus-feeding behaviour. The vertical connection to the sediment-water interface could also play a role in bioirrigation of the network.

3. Short sub-vertical mud-filled tubes approximately 1-2 mm in length are present on many bedding soles radially surrounding the base of many sub-vertical *Parahaentschelinia*-like burrows (Fig. 3.8). Serial grinding demonstrates that these tubes do not connect to the sub-vertical component (Figs 3.9 and 3.10), but given their

radial arrangement around the base of multiple samples, they are considered to be the tips of recurved J-shaped burrows that extend from the base of the vertical and sub-vertical *Parahaentzschelinia*-like burrows into the underlying mudstone, with only the tips reconnecting to the sandstone (Fig. 3.19A). They are inferred to be the result of deposit feeding or microbial farming at the burrow-mud junction.

4. Numerous mud-lined chambers 2-3 mm in diameter have been observed, by serially grinding, to connect to the sub-vertical tunnels that make up the conical portion of the *Parahaentzschelinia*-like burrows (Fig. 3.11). Similar mud-lined chambers occur within several horizontal tunnels branching from the sub-vertical components (Fig. 3.15). These chambers are considered to represent possible “fermentation chambers” used for culturing of microbes as a food source (cf. Bromley, 1996; Leaman *et al.*, 2015). Alternative organic sources in such chambers might be fecal pellets which are stored for re-ingestion after a period of microbial production has elapsed (i.e. a combination of microbial farming and autocoprophagy) (cf. Bromley, 1996).

5. Zones of sediment collapse (“collapse cones”) not described in association with the type material have been observed to surround the sub-vertical burrows described herein (Fig. 3.17). Some collapse structures appear to be related to pre-existing J-shaped burrows (Fig. 3.17), while other collapse cones appear to have been constructed by the trace maker of these *Parahaentzschelinia*-like burrows (Fig. 3.17).

6. Horizontal and oblique burrows are observed to branch from the sub-vertical *Parahaentzschelinia*-like components. These burrows bifurcate and ramify at both

acute and obtuse angles and can be demonstrated, by serially grinding, to create complex three-dimensional tiered polygonal networks orientated parallel and oblique to bedding (Figs 3.12 and 3.13). These networks are similar to the trace fossil *Multina*. Rounded Y-shaped junctions at some branching points indicate these burrows were open and patrolled. Vertical connections to the surface suggest the network was bioirrigated by overlying seawater, potentially playing a role in the cultivation of microbes for food.

7. Some horizontal burrows observed to connect to the sub-vertical *Parahaentschelinia*-like components exhibit dendritic branching patterns similar to primary successive branching (*sensu* D'Alessandro and Bromley, 1987) that is characteristic of *Chondrites* (Fig. 3.14). These burrows may represent exploratory probing of the surrounding sediment in search of organic-rich sediments.

8. Sinuous bedding-parallel burrows superficially similar to *Megagraption* are observed on bedding soles (Fig. 3.16). These burrows are back-filled and are interpreted as the result of the trace-making organism exploiting the muddy sediments below the event beds in search of organic-matter. These burrows are also demonstrated to connect chains of adjacent sub-vertical *Parahaentschelinia*-like burrow components.

This study highlights the importance of thoroughly documenting the complexity and range of burrow morphologies in a type series, rather than just a single idiomorphic specimen, when creating diagnoses and descriptions. Incomplete morphological understanding causes problems when inferring trace-maker ethology,



leading to oversimplified paleobiological and paleoenvironmental interpretations. Idealizing morphological descriptions of type material and omitting a discussion of the variability of morphologies in the diagnoses of type specimens also has the potential to create ichnotaxonomic conundrums (cf Miller, 2011). While most ichnological taxa are described for simple or idiomorphic examples of the taxon, the lack of documentation of the range of morphological disparity within the type series is found to be a shortcoming of the description of *Parahaentzschelinia* that is probably true for many taxa (see also Miller, 2011). The strong similarity between *Parahaentzschelinia* and the sub-vertical burrow components described herein suggests that this material could be ascribed to that taxon, but it is recommended that the type locality of *Parahaentzschelinia* be re-sampled and compared with findings from this study. If similar variations in morphology are indeed discovered at the type locality, an emended ichnogenic diagnosis would be required.

#### **4. Chapter 4 - The relationship between *Parahaentzschelinia*-like burrows and natural fracture propagation patterns in the Winterhouse Formation**

The final manuscript presented in this thesis builds upon the hypothesis that trace fossils have the potential to directly affect the fracture susceptibility of bioturbated sediment (Bednarz and McIlroy, 2012). This study presents three-dimensional reconstructions illustrating the relationship between the aff. *Parahaentzschelinia* burrows and associated natural mineral-filled fractures in

cemented silt-rich fine-grained sandstones of the Winterhouse Formation, which is considered analogous to a “tight” sandstone reservoir facies.

Two natural fracture systems were identified within a cemented fine-grained silty sandstone sample from the Winterhouse Formation: 1) sub-parallel fracture sets orientated at c. 40° to bedding that deflect towards and cut burrows (Figs 4.2 and 4.3); and 2) sub-vertical fractures directly associated with trace fossils comparable to *Parahaentschelinia*, which clearly originate from the burrows (Figs 4.2 and 4.4). The models produced in this study demonstrate that the *Parahaentschelinia*-like burrows create planes of weakness within the cemented sandstone sample, along which the natural fractures preferentially propagate (Figs. 4.2, 4.3, and 4.4). This suggests that these trace fossils create mechanical heterogeneities that can potentially also steer artificial fracture development. Within the modelled sample, where multiple burrows are connected in chains, the fractures propagate between the burrows along the connecting tunnels. These trace fossils are commonly interconnected throughout the formation, so it is likely that the associated fractures would be similarly continuous. The two fracture systems also connect in some areas (Fig. 4.4 E, F). This suggests that interconnected burrow networks can create interconnected pathways of weakness that lead to the formation of similarly interconnected fracture networks. If such burrow-related fracture systems are present and remain open and connect to the wellbore in producing “tight” unconventional reservoir facies, they have the potential to significantly increase the surface area of potential fluid flow conduits within the otherwise impermeable reservoir. This demonstrates that trace fossils can have a

significant effect on geomechanical properties and therefore reservoir calculations and drilling simulations that do not account for ichnofabrics could be significantly flawed.

This work is a proof of concept study aiming to lead to reservoir-specific future studies. It is recommended that this methodology is built upon in larger scale studies integrating rock mechanics, structural geology, petrology, petrophysics, petroleum geology, and ichnology, in order to quantitatively assess the impact of trace fossils on fracture susceptibility and ultimately on reservoir quality. The impact of trace fossils on reservoir quality will change depending on an array of lithologic, tectonic, and petrophysical properties. Extensive studies incorporating different lithologies, controlling stresses and other reservoir properties are required in order to further understand the effect that trace fossils and associated pre-existing natural fractures would have on artificial fracture susceptibility and ultimately on reservoir quality.

It is suggested that in future studies, samples are subjected to controlled rock deformation experiments and experimental fracturing, and subsequently imaged using micro or nano computerized tomographic scanning as well as the serial grinding and reconstruction methodologies described by Bednarz *et al.* (2015) and herein. The serial grinding techniques and reconstruction techniques are recommended as they do not rely on lithologic density contrasts, and will allow the mapping of fractures with respect to visually determined lithotypes. A combined approach will garner more reliable results rather than only relying on X-radiograph attenuation/porosity distribution. Various tight sandstone and shale samples with ichnofabrics of varying trace fossils and intensities of bioturbation should be tested. This will allow the

quantitative assessment of the effects of bioturbation on bulk strength and grain scale mechanisms of crack propagation in various unconventional reservoir facies.

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