

**TAXONOMY, TAPHONOMY AND PALEOECOLOGY OF A NEW BURGESS
SHALE-TYPE LAGERSTÄTTE FROM THE MACKENZIE MOUNTAINS,
NORTHWEST TERRITORIES, CANADA**

A Thesis Submitted to the College of
Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy
In the Department of Geological Sciences
University of Saskatchewan
Saskatoon

By

Julien K. F. Kimmig

PERMISSION TO USE

In presenting this thesis in partial fulfilment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Geological Sciences
University of Saskatchewan
114 Science Place
Saskatoon, Saskatchewan, S7N 5E2
Canada

DEDICATION

I dedicate this thesis to my parents, Florence and Karl-Josef Kimmig, whom supported me throughout my studies.

STATEMENT OF SOURCES AND DECLARATION

I, declare that this thesis is my own work and has not been submitted in any other form for another degree or diploma at any university or other institute of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

ABSTRACT

The middle Cambrian (Drumian) Rockslide Formation is a deeper-water succession of mixed carbonates and siliciclastics. At the Ravens Throat River location it hosts a Burgess Shale-type (BST) deposit. The BST units are found in two separate 1m thick horizons of green-coloured calcareous mudstone and contain a biota similar to that of the Wheeler and Marjum formations of Utah, and to some extent the Burgess Shale itself. The biota is low in diversity and preserves mainly robust soft-tissue parts. The lithologically heterogeneous composition of the formation (shale, dolomite, lime mudstone, sandstone, mudstone) and absence of metamorphism offer an opportunity to analyze the depositional environment and taphonomy of this deeper water unit. Geochemical analysis including, trace elements, organic carbon, biomarker, and synchrotron were attempted and yielded varying results. Trace element ratios, particularly V/Sc, indicate low oxygenation of the bottom waters during the deposition of the fossil-bearing interval. These results differ from most other BST deposits, which suggest that oxygenated bottom waters were maintained throughout sedimentation. In addition, organic matter in the sediments and $\delta^{13}\text{C}_{\text{org}}$ values suggest the presence of benthic microbial mats. Silver is concentrated mostly in nm to μm -sized particles in the fossiliferous calcareous mudstone, suggesting elevated levels in the depositional environment. Organic films and the evidence for hyoliths feeding on them suggest an in situ preservation of the biota, perhaps from sudden and short anoxic events and quick burial under either microbial mats or the muddy sediment. This is also supported by the presence of only very rare trace fossils.

ACKNOWLEDGMENTS

I would like to thank B.R. Pratt for the opportunity to pursue this project and his support during the good and bad times. I also thank M.G. Mángano for help with trace fossil identification, B. Novakovski for thin section preparation, D. Besic for the carbon analyses, and R. Millar and the Saskatchewan Research Council for the trace elements analyses. V. Thiel and J.-P. Duda of the University Göttingen are thanked for the biomarker analyses. C. West is thanked for his assistance in the field. The referees D. A. Legg and J. Vannier, associate editor B. S. Lieberman, and editor S. J. Hageman for comments to the manuscript for chapter 1. Specimens have been collected under Aurora Institute Research Licenses issued to BRP. The expeditions to the Mackenzie Mountains were possible thanks to funding from Natural Sciences and Engineering Research Council of Canada Discovery Grants and a LITHOPROBE grant to BRP. A special thanks goes to Sara Worsham for her support and patience throughout my time at the University of Saskatchewan.

TABLE OF CONTENTS

	<u>page</u>
PERMISSION TO USE.....	i
DEDICATION.....	ii
STATEMENT OF SOURCES AND DECLARATION.....	iii
ABSTRACT.....	iv
ACKNOWLEDGEMENTS.....	v
LIST OF FIGURES.....	viii
LIST OF TABLES.....	xvi
STATEMENT OF AUTHORSHIP.....	xvii
INTRODUCTION.....	1
1. SOFT-BODIED BIOTA FROM THE MIDDLE CAMBRIAN (SERIES 3)	
ROCKSLIDE FORMATION, MACKENZIE MOUNTAINS, NORTHWESTERN	
CANADA.....	4
1.1 Abstract.....	4
1.2 Introduction.....	5
1.3 Geology and fossil locality.....	6
1.4 Systematic paleontology.....	8
1.5 Discussion.....	23
1.6 Conclusions.....	25
LINK BETWEEN CHAPTER 1 AND 2.....	43
2. TAPHONOMY OF THE MIDDLE CAMBRIAN (DRUMIAN) RAVENS THROAT	
RIVER LAGERSTÄTTE, ROCKSLIDE FORMATION, MACKENZIE	
MOUNTAINS, NORTHWEST TERRITORIES, CANADA.....	44
2.1 Abstract.....	44
2.2 Introduction.....	45
2.3 Geological setting.....	46
2.4 Methodology.....	47
2.5 Observations.....	49
2.5.1 Lithofacies.....	49
2.5.2 Fossil preservation.....	51
2.5.3 Ichnology.....	52
2.5.4 Geochemistry.....	52

2.5.4.1 Redox-sensitive trace elements.....	53
2.5.4.2 Carbon.....	53
2.6 Discussion.....	54
2.6.1 Rockslide Formation.....	54
2.6.2 Comparison.....	56
2.7 Conclusions.....	58
LINK BETWEEN CHAPTER 1, 2 AND 3.....	73
3. SILVER IN ORGANIC FILMS IN A MIDDLE CAMBRIAN LAGERSTÄTTE, MACKENZIE MOUNTAINS NORTHWESTERN CANADA.....	74
3.1 Abstract.....	74
3.2 Introduction.....	75
3.3 Geological setting.....	76
3.4 Materials and methods.....	78
3.5 Results.....	78
3.6 Discussion.....	79
3.6.1 Source of silver.....	80
3.6.2 Organic accumulation of silver.....	81
3.6.3 Preservation of soft tissue.....	82
3.6.4 Toxicity of silver.....	84
3.7 Conclusions.....	85
SUMMARY.....	92
LIST OF REFERENCES.....	94
APPENDIX A: ABSTRACT PALAEOONTOLOGICAL ASSOCIATION ANNUAL MEETING 2012.....	111
APPENDIX B: ABSTRACT GEOLOGICAL ASSOCIATION OF CANADA – MINERALOGICAL ASSOCIATION OF CANADA ANNUAL MEETING 2013.....	112
APPENDIX C: ABSTRACT GEOLOGICAL SOCIETY OF AMERICA ANNUAL MEETING 2013.....	113
APPENDIX D: ABSTRACT GEOLOGICAL SOCIETY OF AMERICA ANNUAL MEETING 2014.....	114

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
Chapter 1	
1.1 Location of the Ravens Throat River locality (asterix; 63°10'N, 127° 55'W), Mackenzie Mountains, Northwest Territories, Canada: 1, regional map; 2, topographic map.	26
1.2 Regional cross-section across the Mackenzie Mountains (modified from Aitken et al., 1973).	27
1.3 Generalized stratigraphy of the Rockslide Formation in the Ravens Throat river area (upper part of section and contact with overlying Avalanche Formation is not exposed). Star symbol indicates main fossil bed.	28
1.4 The outcrop area near the headwaters of the Ravens Throat River: 1, panorama looking west; 2, left side of outcrop showing the synsedimentary fault (black line; formations labeled; stratigraphic position of fossil-bearing unit shown by arrow); 3, close-up of the fossiliferous thin-bedded mudstone (hammer circled).	29
1.5 <i>Isoxys mackenziensis</i> n. sp. from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, lateral view of valve and holotype (TMP 2013.101.0038); 2, lateral view of valve (TMP 2013.101.0040); 3, lateral view of valve (TMP 2013.101.0042); 4, lateral view of valve (TMP 2013.101.0039); 5, lateral view of valve (TMP 2013.101.0041); 6, lateral view of valve (TMP 2013.101.0043; surface scratched). Scale bars are 5 mm.	30

1.6 *Perspicularis? dilatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, lateral view of valve (TMP 2013.101.0009; cut by two oblique fractures); 2, lateral view of valve (TMP 2013.101.0002; flipped horizontally); 3, lateral view of valve with burrows beneath (latex cast dusted with ammonium chloride; TMP 2013.101.0002); 4, close-up of 3 showing pustular ornament on valve exterior; 5, lateral view of valve (TMP 2013.101.0005; surface scratched); 6, lateral view of valve (TMP 2013.101.0006; cut by oblique fracture); 7, latex cast of 8 dusted with ammonium chloride; 8, lateral view of small valve (TMP 2013.101.0010); 9, lateral view of weathered partial valve (TMP 2013.101.0011). Scale bars are 5 mm.

.....31

1.7 *Perspicularis? dilatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, dorsal view of butterflyed carapace (TMP 2013.101.0001; surface scratched); 2, same as 1 (dusted with ammonium chloride); 3, lateral views of three complete and one partial valves (TMP 2013.101.0004); 4, lateral views of one complete and two partial valves (latex cast dusted with ammonium chloride; TMP 2013.101.0004; flipped horizontally); 5, lateral interior view of complete valve, with muscle scar (TMP 2013.101.0008); 6, lateral interior view of complete valve, with muscle scar (latex cast dusted with ammonium chloride; TMP 2013.101.0008; flipped horizontally). Scale bars are 5 mm.

.....32

1.8 Variation in outline of *Perspicularis? dilatus* specimens from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains. 1, TMP 2013.101.0006; 2, TMP 2013.101.0002; 3, TMP 2013.101.0005; 4, TMP 2013.101.0009; 5, TMP 2013.101.0010; 6, TMP 2013.101.0001; 7, TMP 2013.101.0008; 8, TMP 2013.101.0007; 9, TMP 2013.101.0004. Specimens are drawn to scale and anterior is oriented to the left. Scale bar is 10 mm.

.....33

1.9 Arthropods from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, *Branchiocaris? sp.*, lateral view of valve (TMP 2013.101.0045); 2 *Tuzoia* cf. *T. guntheri*, lateral view of partial valve (TMP 2013.101.0047); 3, *Tuzoia* cf. *T. guntheri*, close-up of 2 showing reticulate ornament on valve exterior surface (TMP

2013.101.0047); 4, small valve of *Perspigaris? dilatus* in lateral view (TMP 2013.101.0007); 5, *Branchiocaris?* sp., lateral view of valve (TMP 2013.101.0046); 6, *Perspigaris? dilatus*, lateral view of partial valve with broken hinge, possibly two valves overlying each other (TMP 2013.101.0048). Scale bars are 5 mm.

.....34

1.10 Bradoriids from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, bradoriid genus and species indet. 1, complete carapace in dorsal view (TMP 2013.101.0044); 2, latex cast of 1 dusted with ammonium chloride; 3, bradoriid genus and species indet. 2, valve in lateral view (TMP 2013.101.0024). Scale bar is 5 mm.

.....35

1.11 Fragmentary arthropods from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, *Branchiocaris?* sp. lateral views of two disarticulated valves (TMP 2013.101.0021); 2, *Tuzoia* sp. lateral view of partial valve with ornament of cusped ridges along margin (TMP 2013.101.0018); 3, *Perspigaris? dilatus* lateral view of valve (TMP 2013.101.0019); 4, *Perspigaris? dilatus* lateral view of valve (TMP 2013.101.0017); 5, *Branchiocaris?* sp. butterflyed carapace (TMP 2013.101.0022); 6, lateral view of valve, possibly *Perspigaris? dilatus* (TMP 2013.101.0016). Scale bars are 5 mm.

.....36

1.12 Arthropod fragments from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1,2, arthropod genus and species indet. 1: 1, posterior portion of thorax with lateral telson process consisting of two processes in dorsal view (TMP 2013.101.0036); 2, posterior portion of thorax with lateral telson process in lateral view (TMP 2013.101.0035); 3, arthropod genus and species indet. 2, isolated lateral telson process (TMP 2013.101.0034); 4, arthropod genus and species indet. 3, possible biramous appendage consisting of endopod(?) and exopod(?) (TMP 2013.101.0037). Scale bars are 5 mm.

.....37

1.13 *Haplophrentis carinatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, conch with operculum and helens (TMP 2013.101.0058); 2, conch with operculum and one helen (TMP 2013.101.0059); 3, conch

(TMP 2013.101.0063); 4, conch (TMP 2013.101.0064); 5, conch with operculum and one helen (TMP 2013.101.0065); 6, conch with operculum (TMP 2013.101.0066); 7, conch with operculum and partial helen (TMP 2013.101.0067); 8, three conches (TMP 2013.101.0068a, b, c); 9, two conches, one possible juvenile specimen (TMP 2013.101.0070a, b); 10, two juxtaposed conches (TMP 2013.101.0071a, b); 11, conch (TMP 2013.101.0072). Scale bar is 2 mm.

.....38

1.14 Priapulids from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains. Possible gut contents or residual soft tissues appear as dark patches.

1–3, priapulid genus and species indet. 1: 1, curved specimen, with partially extended proboscis to left (TMP 2013.101.0051); 2, coiled specimen, with anterior end at bottom (TMP 2013.101.0052); 3, coiled specimen, with anterior end at bottom (TMP 2013.101.0053); 4–6, priapulid genus and species indet. 2: 4, sinuous specimen, anterior to the right (TMP 2013.101.054); 5, sinuous specimen, anterior and posterior ends unknown (TMP 2013.101.0055); 6, Elongated specimen (TMP 2013.101.0056). Scale bar is 5 mm.

.....39

1.15 *Margaretia dorus* from the Rockslide formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, partial branch (TMP 2013.101.0130); 2, partial branch (TMP 2013.101.0131); 3, branching specimen (TMP 2013.101.0132); 4, partial branch (TMP 2013.101.0133); 5, partial branch (TMP 2013.101.0134); 6, partial branch (TMP 2013.101.0135); 7, two partial branches (TMP 2013.101.0136); 8, partial branch (TMP 2013.101.0137); 9, partial branch (TMP 2013.101.0138); 10, partial branch (TMP 2013.101.0139); 11, partial branch (TMP 2013.101.0140). Scale bar is 10 mm.

.....40

1.16 Relative abundance of specimens of metazoan taxa in all samples collected from the fossiliferous unit of the Rockslide formation (both in situ and from the scree slope), middle Cambrian, Ravens Throat River area, Mackenzie Mountains.

.....41

Chapter 2

- 2.1 A, Location of the Ravens Throat River locality (asterisk; 63°10'N, 127° 55'W), Mackenzie Mountains, Northwest Territories, Canada; B, topographic map of location; C, Panorama of the outcrop area near the headwaters of the Ravens Throat River looking west (arrow indicates location of geochemical samples).
.....59
- 2.2 Generalized stratigraphy of the Rockslide Formation in the Ravens Throat river area. Grey-coloured intervals contain BST fossils, mostly in the lower one.
.....60
- 2.3 Photographs of the different lithofacies of the Rockslide Formation at the Ravens Throat River Lagerstätte. A, Lime mudstone ('ribbon limestone') at +110 m. B, Calcareous mudstone with interbedded lime mudstone beds and lenses at +136 m. C, Debris-flow breccia at +73 m. D, Outcrop photograph of the lower calcareous mudstone beds at +135 m – +137 m. Scale bar is 10 cm for A–C.
.....61
- 2.4 Thin-section photomicrographs of lithofacies in the Rockslide Formation. A, Black shale at +7 m consisting of plane-laminated claystone erosively overlain by indistinctly cross- and plane-laminated silty claystone. B, Lime mudstone with planar lamination at +35 m. C, Debris-flow breccia at +102 m consisting of angular granules of peloidal grainstone (pelsparite) in lime mudstone matrix with trilobite sclerite (marked by arrow). D, Lime mudstone at 133 m, the base of the BST unit; the arrow shows the diagenetic packstone between the limestone and the mudstone. E, Dolomitic-limestone at +190 m, on top of the outcrop. Scale bars are 1 cm.
.....62
- 2.5 A-G, Photographs of the thin sections of the fossiliferous calcareous from the Rockslide Formation at the Ravens Throat River Lagerstätte. A, Calcareous mudstone facies of the fossil bed with burrow (white arrow) and trilobite fragment (black arrow) at +134.4 m. B, Close-up of A with possible burrow. C, Close-up of A with trilobite fragment. D, lime mudstone interlayer at +134.7 m. E, Calcareous mudstone facies with pyrite crystals and

potential sponge spicules (white arrows) at +134.9 m. F, Close-up of E with possible burrow. G, Calcareous mudstone facies with burrow (white arrow) at +134.5 m. H, SEM photograph of the matix of the fossilifereous calcareous mudstone. Scale bars in A, D, E, G are 1 cm, in B, C, and F are 1 mm, H is 100 μ m.

.....63

2.6 Ravens Throat River Lagerstätte fossils: A, *Perspicaris? dilatus* (TMP 2013.101.0005); B, *Margaretia dorus* (TMP 2013.101.0132); C, *Haplophrentis carinatus* (TMP 2013.101.0058); D, Arthropod Indet. (TMP 2013.101.0035); E, *Isoxys mackensiensis* (TMP 2013.101.0038). Scale bars are 10 mm.

.....64

2.7 Photographs of partially decomposed fossils of the Ravens Throat River Lagerstätte. A, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0016). B, Arthropod indet. fragment (TMP 2013.101.0020). C, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0017). D, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0018). E, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0023) F, *Branchiocaris? sp.* lateral views of two disarticulated valves (TMP 2013.101.0021). Scale bars are 5 mm.

.....65

2.8 Trace fossils of the Ravens Throat River Lagerstätte: A, *Perspicaris? dilatus*, lateral view of valve with apparent branching burrow beneath, preserved as negative relief (latex cast dusted with ammonium chloride; TMP 2013.101.0002); B, close-up of apparent branching burrow, preserved as negative relief (latex cast dusted with ammonium chloride; TMP 2013.101.0002); C, *Perspicaris? dilatus*, lateral view of valve with burrow beneath, arrow indicates burrow (TMP 2013.101.0033); D, *Rhizocorallium? sp.* (TMP 2013.101.0303). Scale bar is 10 mm.

.....66

2.9 Relationship between total organic carbon content (TOC) and the abundance of selected redox-sensitive trace elements in the lower calcareous mudstone between 134 m and 137 m of the Rockslide Formation at the Ravens Throat River outcrop (Fig. 2.1C).

.....67

2.10 Relationship of total organic carbon content to the abundance of $\delta^{13}\text{C}_{\text{org}}$ in the lower calcareous mudstone between 134 m and 137 m of the Rockslide Formation at the Ravens Throat River outcrop.
.....68

2.11 Chemostratigraphic profiles of redox-sensitive trace element ratios for the BST unit of the Rockslide Formation at the Ravens Throat River outcrop. Vertical subdivisions represent the redox zones of Jones and Manning (1994) and Kimura and Watanabe (2001). Height is above base of the lower calcareous mudstone at 134 m.
.....69

Chapter 3

3.1 Map showing the main Ag deposits close to the Ravens Throat River Lagerstätte, as well as the main tectonic features.	87
3.2 A) Photograph under reflected light of organic film hosting silver (TMP 2013.101.0084), taken under ethanol; B) Photograph under reflected light of organic film hosting silver (TMP 2013.101.0079), taken under ethanol; C) SEM photograph of the elemental silver in microbial mat, indicated by arrows (TMP 2013.101.0084); D) SEM photograph of the elemental silver in microbial mat, indicated by arrows (TMP 2013.101.0079).	88
3.3 EDX spectra of A) Silver in the organic film (TMP 2013.101.0084); B) The surrounding matrix (TMP 2013.101.0084).	89
3.4 Thin sections of the Ravens Throat River Lagerstätte fossil bed. A) Lime mudstone facies without organic remains; B) Fine laminated layer with organic structures, likely representing microbial mats (indicated by arrows); C) Fine laminated layer with fossils and organic structures, likely representing microbial mats (indicated by microbial mats), overlying a coarser layer.	90

LIST OF TABLES

<u>Table</u>	<u>page</u>
Chapter 1	
1.1 Occurrence of Ravens Throat River taxa in other western Laurentian Lagerstätten: Pioche Formation (Series 3, Stage 5); Burgess Shale (Series 3, Stage 5); Marjum Formation (Series 3, Drumian); Wheeler Formation (Series 3, Drumian); √=represented, x=not represented.	42
Chapter 2	
2.1 Trace element and organic carbon data of selected beds of the Rockslide Formation at the Ravens Throat River Lagerstätte. Height is above base of the Rockslide Formation.	70
2.2 Enrichment factors (EF) for selected trace elements in the Ravens Throat River first fossiliferous calcareous mudstone. Height is above base of the Rockslide Formation.	71
Chapter 3	
3.1 Trace element and organic carbon data of the BST unit of the Rockslide Formation at the Ravens Throat River outcrop.	91

STATEMENT OF AUTHORSHIP

Abstract

J. K. F. Kimmig authored the abstract.

Introduction

J. K. F. Kimmig authored the introduction.

Chapter 1

Chapter 1 is co-authored by J. K. F. Kimmig, and B. R. Pratt.

B. Pratt and J. Kimmig collected the samples. J. Kimmig analyzed and identified the fossils. J. Kimmig wrote the chapter with support of B. R. Pratt. The chapter was submitted to the *Journal of Paleontology* and published in volume x:x-x. David Legg (Oxford) and Jean Vannier (Lyon) reviewed the paper. The paper was edited by Bruce Lieberman (Kansas) and Steve Hageman (Appalachian State).

Chapter 2

Chapter 2 is co-authored by J. K. F. Kimmig and B. R. Pratt.

J. Kimmig collected the samples. J. Kimmig analyzed the sediments and geochemical data. J. Kimmig wrote the chapter with support of B.R. Pratt.

Chapter 3

Chapter 3 is co-authored by J. K. F. Kimmig and B. R. Pratt.

B. Pratt and J. Kimmig collected the samples. J. Kimmig analyzed the sediments and geochemical data. J. Kimmig wrote the chapter with support of B. R. Pratt.

Summary

J. K. F. Kimmig authored the summary.

INTRODUCTION

Fossils are the only direct evidence of life in the geologic past. Even though fossils from most time periods are preserved, the record is incomplete (e.g., Selden and Nudds, 2012) leading to complications in reconstructing ancient ecosystems and in gaps in the evolutionary history. While the evolutionary gaps can be filled with genetic data (e.g., Dohrmann et al., 2013), the fossil record is predominantly characterized by mineralizing body parts from marine environments. This leads to a preservation of only about 15% of organisms under normal fossilisation conditions (Selden and Nudds, 2012), and a dominance of marine taxa in the fossil record.

Every now and then, however, the fossil records holds surprises and soft-tissues are preserved. This can happen a multitude of ways, depending on the time interval. The deposits in which these fossil soft-tissues are preserved are defined as Konservat Lagerstätten (Seilacher et al., 1985). Important deposits include the Cambrian Burgess Shale of British Columbia, the Ordovician Soom Shale of South Africa, the Devonian Rhynie Chert of Scotland, the Carboniferous Bear Gulch Limestone of Montana, the Permian Kupferschiefer of Germany and Poland, the Jurassic Solnhofen Limestone of Germany, the Cretaceous Santana Formation of Brazil, the Eocene Green River Formation of the USA, the Eocene Messel shales of Germany, the Pliocene Willershausen clay pit of Germany, and the Pleistocene Rancho La Brea Tar Pits of California. The term Lagerstätte is derived from German economic geology, where it defines a rich ore seam. On the other hand, there are also Konzentrat Lagerstätten, which refer to large or exceptional accumulation of mineralized fossils, such as shell and bone beds (i.e. the Morrison Formation of the USA), or cave deposits.

Many of the findings on the fossil record have been through the study of Konservat Lagerstätten, as they offer a unique setting to understand fossil communities, their dietary behaviour, and other ecological and taphonomic aspects. The mode of preservation varies throughout the deposits and soft-tissues can be preserved in different substances such as amber, oil, chert, limestone, and shale (Selden and Nudds, 2012).

Burgess Shale-type (BST) Lagerstätten are Cambrian to Ordovician deposits containing soft-tissue preservation (e.g., Briggs et al., 1994; Edgecombe and Legg, 2013). They have been referred to as deposits of 'exceptional' fossil preservation of non-mineralized organism compressions in marine shales (Butterfield, 1995), and have a near worldwide distribution. The organisms retain their outlines, but are mostly compressed into two-dimensional

structures. The quality of preservation can vary from nervous system remains (e.g., Cong et al., 2014) to rare robust soft-tissue preservation (e.g., Lieberman, 2003; this study).

Burgess Shale biotas are famous for the preservation of a large number of stem-group arthropods as well as sponges, worms, molluscs, early vertebrates, and problematica (e.g. Briggs et al., 1994; Hou et al., 2004; Caron et al., 2014). In many cases the represented fossils appear for the first time in the fossil record. The timeframe in which these deposits are preserved is as important as the preservation of soft-tissue. The ‘Cambrian explosion’ is one of the most important episodes of rapid evolution in earth history. Thanks to these deposits, we have access to information on the evolution of soft-bodied species at the dawn of the modern body plans. Whereas the biotas themselves are well known, and new species are discovered on a regular basis (e.g. Briggs et al., 1994; Hou et al., 2004; Legg, 2013), the preservation process is still unclear (e.g. Orr et al., 1998; Butterfield et al., 2007; Gaines et al., 2012a; Wilson and Butterfield, 2014).

The Mackenzie Mountains of northwestern Canada preserve large amounts of Cambrian strata and BST deposits (e.g., Aitken et al., 1973), but only two of these BST deposits have been described. The first is in the lower Cambrian Sekwi Formation which preserves Chancelloriids exhibiting BST preservation (Randell et al., 2005), the other is the middle Cambrian Rockslide Formation described here. Rare BST fossils have also been reported from strata coeval with and older than the Rockslide Formation that crop out in the Mackenzie River Valley to the east of the Mackenzie Arch (Butterfield, 1994; Butterfield and Nicholas, 1996; Harvey and Butterfield, 2011).

Brian R. Pratt discovered the Ravens Throat River Lagerstätte in the Mackenzie Mountains, northwestern Canada, in the mid 1980s during his PhD work, and collected some of the specimens described here. More fossil and lithological material was recovered during three later trips (Pratt: 1994, 2004; Kimmig: 2012). While it was known since then that BST preservation occurred at this location, no active research began until the commencement of this project in September 2011. The Lagerstätte is of Drumian age and approximately age equivalent with the Wheeler and Marjum formations of Utah (Kimmig and Pratt, in press). It is exposed as a steep cliff and is only accessible by helicopter.

Although most research on BST deposits concentrates on the exceptional preservation (e.g. Briggs et al., 1994; Mckirdy et al., 2011; Gaines et al., 2012a; Edgecombe and Legg, 2013), the aim of this study was to analyse the information provided by a less well-preserved deposit. The poor preservation of most specimens in the Ravens Throat River Lagerstätte led to many unidentified specimens in the taxonomic review of the biota. Specimens at this

locality either exhibit poor soft-tissue preservation or are devoid of such preservation. At least 10 species have been identified, including a new species of *Isoxys* (Kimmig and Pratt, in press).

After taxonomy, the most significant information extracted from the study of the Ravens Throat River Lagerstätte includes the sedimentological and geochemical data. The depositional environment has been identified as a mainly oxic, relatively quiet, water column. Not only does this reflect and support results from previous research (e.g. Powell et al., 2003; Gabbott et al., 2008; McKirdy et al., 2011), but it also offers new insights into the depositional environment (Chapter two; Chapter three).

The purpose of this project is to describe the biota, depositional environment, and possible preservation paths of the Ravens Throat River Lagerstätte, and compare it to other BST Lagerstätten worldwide. Chapter One is dedicated to the description of the biota including a complete taxonomic review of the specimens collected from the Ravens Throat River Lagerstätte and offering a comparison with other BST deposits from North America, Greenland, and China. Chapter one has been accepted for publication in the Journal of Paleontology (Kimmig and Pratt, in press).

Chapter Two covers the sedimentological and geochemical analyses and the interpretation of the depositional environment. It compares the environment and possible depositional processes with other BST deposits.

Chapter Three covers the enrichment of silver in the fossiliferous calcareous mudstones of the fossil bed and the possible correlations with the preservation quality and diversity in Ravens Throat River Lagerstätte.

CHAPTER 1

SOFT-BODIED BIOTA FROM THE MIDDLE CAMBRIAN (SERIES 3; DRUMIAN) ROCKSLIDE FORMATION, MACKENZIE MOUNTAINS, NORTHWESTERN CANADA

This Chapter has been accepted for publication as:

Kimmig, J. and Pratt, in press. Soft-bodied biota from the middle Cambrian (Drumian) Rockslide Formation, Mackenzie Mountains, northwestern Canada. *Journal of Paleontology*.

1.1 Abstract

A new Burgess Shale-type Lagerstätte is described from the middle Cambrian (Series 3, Drumian) Rockslide Formation of the Mackenzie Mountains, Northwest Territories, Canada. The Rockslide Formation is a unit of deeper water ramp to slope, mixed carbonate and siliciclastic facies deposited on the northwestern margin of Laurentia. At the fossil-bearing locality, the lower part abuts a fault scarp cutting lower Cambrian sandstones. There it consists of a succession of shale and thick-laminated to thin-bedded lime mudstone, calcareous sandstone, and greenish-colored calcareous mudstone, overlain by shallower water dolostones, which is indicative of an overall progradational sequence. The Rockslide Formation is of similar age to the Wheeler and Marjum formations of Utah, belonging to the *Bolaspidella* Biozone. Only two 1 m thick units of greenish mudstone exhibit soft-bodied preservation, with most specimens coming from the lower interval. However, the biota is fairly common but not as diverse as that of other Lagerstätten like the Burgess Shale in its type area. The shelly fauna is dominated by the hyolith *Haplophrentis carinatus* Matthew, 1899 along with sparse linguliformean brachiopods, agnostoid arthropods, and ptychoparioid trilobites. The non-mineralized biota includes the macrophytic alga *Margaretia dorus* Walcott, 1911, priapulid worms, and the carapaces of a number of arthropods. The arthropods belong to *Isoxys mackenziensis* n. sp., *Tuzoia* cf. *T. guntheri* Robison and Richards, 1981, *Branchiocaris?* sp., *Perspiscaris?* *dilatatus* Robison and Richards, 1981, and bradoriids, along with fragments of arthropods of indeterminate affinities. The style of preservation indicates that most soft parts

underwent complete biodegradation, leaving just the more resistant materials such as chitinous arthropod cuticles. The range of preservation and similarity to the coeval biotas preserved in Utah suggests that the composition of this Lagerstätte is probably representative of the community living on the relatively deep-water ramp or slope during middle Cambrian time in Laurentia. This would argue that the extraordinary diversity of the Burgess Shale at Mount Field is anomalous.

1.2 Introduction

BIOTAS EXHIBITING Burgess Shale-type (BST) preservation have been reported from the Cambrian and Ordovician of most continents and are critical for the understanding of the early evolution of life, because they conserve a greater diversity beyond typical shelly biotas (e.g., Briggs et al., 1994; Edgecombe and Legg, 2013; Caron et al., 2014). Not only do these important deposits open a window that does not exist under normal fossilization conditions, but the degree of complexity of the fossil lineages also suggests that evolution of several main branches of life was extremely rapid, but there is debate as to whether it began prior to or during the earliest Cambrian (e.g., Dohrmann et al., 2013; Erwin and Valentine, 2013; Landing et al., 2013; Lee et al., 2013).

BST deposits pose several fundamental questions, as soft body preservation is exceptional in earth history but does seem to be more common in the early Paleozoic. The nature of the BST taphonomic phenomenon is still controversial and several ideas have been suggested (e.g., Allison, 1988; Butterfield, 1995; Butterfield et al., 2007; Gaines et al., 2012). Another question is to what degree the different BST Lagerstätten represent a typical benthos of the early Paleozoic. Depending on the deposit the biota varies in composition, with only the Burgess Shale in the vicinity of Mount Field, its type area, exhibiting a truly high diversity (e.g., Briggs et al., 1994; Lieberman, 2003; Caron and Jackson, 2008; Edgecombe and Legg, 2013).

Here we present a new Lagerstätte in the Rockslide Formation of the Mackenzie Mountains of northwestern Canada. It is approximately the same age as the Wheeler and Marjum formations of Utah (Drumian stage, *Bolaspidella* Biozone) and, occurring in greenish mudstone, is similar in lithology to the ‘phyllopod bed’ of the Burgess Shale (Gabbott et al., 2010).

In addition to the hyoliths, linguliformean brachiopods, agnostoids and ptychoparioid trilobites, the soft-bodied fauna is dominated by bivalved arthropods along with priapulids and macrophytic algae, representing a biota similar to that of the Wheeler and Marjum formations. The purpose of this paper is to describe the hyoliths and soft-bodied components of the Rockslide Formation fauna and offer a comparison with similar Lagerstätten.

1.3 Geology and fossil locality

The Rockslide Formation is a regionally extensive, relatively deep-water middle Cambrian unit in the Mackenzie Mountains (Fig. 1.1; Fritz, 1979; Pratt, 1989). It ranges in age from the *Plagiura–Poliella* Biozone to late *Bolaspidella* or *Lejopyge laevigata* Biozone (Gabrielse et al., 1973). It was deposited on the west-facing continental slope flanking the Selwyn Basin and ultimately the Panthalassic Ocean (Fig. 1.2; Fritz et al., 1991). The slope was probably seaward of a carbonate platform that has since been planed off. On the other side of the Mackenzie Arch, in the eastern Mackenzie Mountains and Mackenzie River valley, the lower part of the Rockslide Formation is correlative with intrabasinal shales of the upper Mount Cap Formation. To the north it grades into the Hess River Formation, a thick, deep-water package deposited in the Misty Creek embayment (Cecile, 1982; Chevrier and Turner, 2013).

The new Lagerstätte is located near the headwaters of the Ravens Throat River and was discovered by BRP in 1983, and further collections were made in 1998 and 2004, and by JK in 2012. The Rockslide Formation in this area is about 175 m thick and is a succession of shales that grade upwards into interbedded shale and lime mudstone, and thence to thin-bedded lime mudstone (Fig. 1.3). It overlies a thin unit of shallow-subtidal limestone and dolomite belonging to the lower Cambrian Sekwi Formation, which in turn rests abruptly on shallow-marine sandstones of the Ediacaran to lower Cambrian (Terreneuvian) Backbone Ranges Formation. At this locality the Rockslide Formation is gradationally overlain by shallower water sandy dolostones and dolomitic sandstones, that would be now considered to belong to the Avalanche Formation, which are succeeded by shallow-water limestones and dolostones of the upper Cambrian Broken Skull Formation (Gabrielse et al., 1973; Gordey and Anderson, 1993). To the west the Rockslide Formation is overlain by deep water limestones of the Rabbitkettle Formation (Pratt, 1992; Gordey and

Anderson, 1993).

At the Ravens Throat River locality, the Rockslide Formation abuts a syndepositional fault scarp cutting the Backbone Ranges Formation (Fig. 1.4.1). The Sekwi Formation and lowermost part of the Rockslide Formation have dropped down and rotated on this normal fault. A change in dip at 19 m above the base of the Rockslide Formation suggests another phase of movement on the fault. The fault scarp is about 750 m north of the ridge that comprises section 19 of Gabrielse et al. (1973) which is unfaulted (Pratt, pers. obs.). Faulting is also absent at the type section 50 km to the east (section 16 of Gabrielse et al., 1973). The fault can be traced to the mountainside across the valley to the north of the Lagerstätte locality. It is likely listric in nature (cf. Collom et al., 2009; Johnston et al., 2009a) and it probably a localized feature, forming an inclined surface cut into the gentle slope and broadly U-shaped in plan view.

There are two intervals that exhibit the distinctive lithology containing soft-bodied preservation, 134–139 m and 162–166 m above the top of the Sekwi Formation respectively, with an approximately 1 m thick portion of the lower one yielding virtually all of the fossils that were recovered during excavation of the outcrop. Agnostoids and trilobites indicate this interval belongs to the *Bolaspidea* Biozone (Series 3, Drumian). It is therefore younger than the Burgess Shale but approximately correlative with the Marjum and Wheeler formations of the Great Basin of Utah. The Burgess Shale is of middle Cambrian (Series 3, Stage 5) age, within the *Bathyriscus–Elrathina* Biozone. Robison and Babcock (2011) placed *Elrathina* Resser, 1937 in synonymy with *Ptychoparella* Poulsen, 1927 but for the time being the traditional biozone name is retained.

Because the exposure is located on a steep cliff (Fig. 1.4.2), most specimens were collected systematically from the scree slope below it, comprising an area that covers about 1500 m². The host facies is a laminated, light-greenish colored, slightly calcareous mudstone. XRD analysis indicates that is composed of quartz, chlorite, calcite and dolomite. There are interbedded lenses of lime mudstone; scour surfaces and cross-lamination are absent. This lithology has not been encountered at the type section of the Rockslide Formation to the east (Gabrielse et al., 1973; Pratt, pers. obs.) or in sections to the west and north (Pratt, pers. obs.). It appears to be localized perhaps in a depression that persisted long after movement of the synsedimentary fault.

1.4 Systematic paleontology

The fossils were photographed under water using a Nikon D80 camera with a 60 mm Nikkor macro lens. Latex casts were made of molds and dusted with ammonium chloride. Because the original specimens are mostly dark greenish-gray in color and similar to the host mudstone, photographic images were manipulated in Adobe Photoshop for optimal tone and contrast.

Specimens are housed in the paleontological collection of the Royal Tyrrell Museum, Drumheller, Alberta, Canada (TMP).

Kingdom ANIMALIA Linnaeus, 1758

Phylum ARTHROPODA von Siebold, 1848

Remarks.—The name Arthropoda is correctly attributed to von Siebold (Hegna et al., 2013). The higher level taxonomy of Cambrian bivalved arthropods is problematic. Early views considered most species to be crustaceans, whereas more recent studies indicate that many belong to the most basal arthropod taxa (Stein, 2010; Legg et al., 2012, 2013; Legg and Caron, 2014). For this reason the higher-level affiliations of the arthropod genera in the Rockslide Formation are left open.

Class, Order and Family uncertain

Genus ISOXYS Walcott, 1890

Type species.—*Isoxys chilhoweanus* Walcott, 1890, by original designation.

Other species.—*Isoxys acutangulus* Walcott, 1908; *I. carbonelli* Richter and Richter, 1927; *I. longissimus* Simonetta and Delle Cave, 1975; *I. communis* Glaessner, 1979; *I. auritus* Jiang, 1982 (in Luo et al. 1982); *I. paradoxus* Hou, 1987; *I. bispinatus* Cui, 1991 (in Huo et al. 1991); *I. zhurensis* Ivantsov, 1990; *I. volucris* Williams, Siveter and Peel, 1996; *I. elongatus* Luo and Hu, 1999 (in Luo et al. 1999); *I. curvirostratus* Vannier and Chen, 2000; *I. wudingensis* Luo and Hu, 2006 (in Luo et al. 2006); *I. minor* Luo et al., 2008; *I. glaessneri* García-Bellido et al. 2009; *I. shandongensis* Wang et al. 2010; *I. granulus* Yuan, Peng and Zhao, 2011; *I.*

mackenziensis n. sp.

Diagnosis.—See García-Bellido et al. (2009)

Occurrence.—China, Australia, Siberia, Europe, Laurentia (including Greenland), lower and middle Cambrian, Series 2 and 3, Stages 3–5 and Drumian.

Remarks.—*Isoxys* species are known from all major BST deposits of late early and early middle Cambrian age and some are known from their soft tissues in addition to the carapace (García-Bellido et al., 2009). The different species have usually been distinguished based on carapace shape although in general individual valves are sub-oval in outline, tapering anteriorly, and vary in the relative widths of the posterior and anterior ends of the valve and in the length of the anterolateral and posterolateral spines. Intraspecific variation and sexual dimorphism, however, may be present (Fu et al., 2013). Despite widespread occurrence and soft tissue detail, higher level taxonomic relationships are still unclear (Legg and Vannier, 2013).

ISOXYS MACKENZIENSIS new species

Figure 1.5.1–1.5.6

Holotype.—One complete laterally compressed valve (TMP 2013.101.0038).

Material.—Two complete and five partial valves in lateral view (TMP 2013.101.0030, 2013.101.0038–2013.101.0043).

Diagnosis.—*Isoxys* with elongated carapace, anterior wider than posterior; ratio of length to maximum width about 1:4. Dorsal line with dorsally directed flexure; anterolateral and posterolateral spines short with respective spine to carapace length ratios of 1:7 and 1:10.5 .

Description.—The valve is elongate ovate in outline, the anterior wider than the posterior. The ratio of length to width about is 1:4. The largest specimen is 85 mm long and 22 mm wide, whereas the smallest is 30 mm long and 8 mm wide; maximum width occurs at about one-third the total length from the anterior end as measured

along the dorsal hinge. The dorsal hinge is nearly straight but has a gentle, dorsally directed flexure at about one-third the length from the anterior end. Each valve has an anterolateral and posterolateral spine. The anterior spine is shorter, with the longest 10 mm in length and a maximum thickness of about 2 mm at the base. The posterior spine is longer, with the longest 15 mm in length and a maximum thickness of about 1.5 mm. The dorsal surface is smooth.

Etymology.—After the Mackenzie Mountains.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The valve of *Isoxys mackenziensis* n. sp. differs from those of *I. chilhoweanus*, *I. acutangulus*, *I. zhurensis*, *I. auritus*, *I. glaessneri*, *I. carbonelli*, *I. curvirostratus*, *I. communis*, *I. wudingaspis*, *I. minor*, *I. volucris* and *I. bispinatus* by being more slender, in that it is narrower and more elongated. In contrast to these species the posterior end is also narrower and the dorsal hinge has a dorsally directed flexure which is lacking in other species. It differs from *I. longissimus* and *I. paradoxus* by having shorter anterolateral and posterolateral spines. The valves of the new species is larger in comparison with the other described species but this is not taken as diagnostic at present. A fragmentary specimen belonging to *Isoxys* was recovered from older strata in the Mount Cap Formation exposed on the east side of the Mackenzie Arch (Butterfield and Nicholas, 1996). It has a longer and stouter posterolateral spine.

Order CANADASPIDIDA Novozhilov *in* Orlov, 1960

Family PERSPICARIDAE Briggs, 1978

Genus PERSPICARIS Briggs, 1977

Type species.—*Canadaspis dictynna* Simonetta and Delle Cave, 1975, by original designation.

Other species.—*Perspicaris recondita* Briggs, 1977; *P.?* *dilatatus* Robison and

Richards, 1981; *P.?* *ellipsopelta* Robison and Richards, 1981.

Diagnosis.—See Briggs (1977).

Occurrence.—Laurentia, middle Cambrian, Series 3, Stage 5 and Drumian.

Remarks.—Most of the taxonomically important features used to differentiate *Canadaspis* and *Perspiscaris* and their species are based on the soft tissues (Briggs, 1977; Lieberman, 2003). Therefore, *Perspiscaris?* *dilatus* and *P.?* *ellipsopelta* are questionably assigned to the genus because these species are based only on isolated carapaces. *Perspiscaris* differs by possessing true, elongate lateral telson process bearing spines, whereas *Canadaspis* has a pair of spinose projections on the ventrolateral margin of the telson. Also the eyes of *Perspiscaris* are larger. However, the valves are closely similar and may well be indistinguishable. Lieberman (2003), however, suggested that in *Perspiscaris* the maximum width is further posteriorward, the anterior and posterior processes are larger, the muscle scar is more ventrally located, and the height-to-length ratio is smaller. Consequently we assign most valves in the Rockslide Formation to *Perspiscaris?* rather than *Canadaspis*.

PERSPICARIS? DILATUS Robison and Richards, 1981

Figures 1.6.1–1.6.9, 1.7.1–1.7.6, 1.9.4, 1.9.6, 1.11.3, 1.11.4, 1.11.6

1981 *Perspiscaris?* *dilatus* ROBISON AND RICHARDS, p. 4, pl. 1, fig. 4, pl. 2, figs. 5–7.

2003 ?*Perspiscaris dilatus*; LIEBERMAN, p. 677, fig. 1.2.

Material.—24 valves in lateral view and one complete carapace in dorsal view (TMP 2013.101.0001–2013.101.0015).

Diagnosis.—*Perspiscaris?* with valve sub-ovate in outline, posterior process larger than anterior process.

Description.—Valve is sub-ovate in outline; posterior portion moderately wider than anterior, with maximum width is about two-thirds along the length of the hinge

line from the anterior margin. Maximum length is 65 mm and maximum width is 45 mm, with the smallest 11 mm in length and 8 mm in width. The posterior process is slightly larger than the anterior process, and exhibits an angle of about 100°. Hinge line is straight. The circular muscle scar is inconspicuous in larger valves; on one smaller specimen (Fig. 1.7.5, 1.7.6) it is located close to the anterior margin and three times its diameter from the hinge line.

Occurrence.—Comet Shale Member, Pioche Formation, Nevada, middle Cambrian, Series 3, Stage 5, *Eokochaspis nodosa* Biozone; Wheeler Formation, Utah, middle Cambrian, Series 3, Drumian, *Ptychagnostus atavus* Biozone; Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The specimens from the Ravens Throat River area are conspecific with *P.?* *dilatatus* and not *P.?* *ellipsopelta* based on the outline of the valves (Fig. 1.8) with the maximum width being more posterior, the relatively larger posterior process, and the more anterior location of the muscle scar. However, these are rather small differences and it is possible that larger collections may show that *P.?* *ellipsopelta* is a junior synonym. Some isolated soft-tissue fragments (Fig. 1.8.2, 1.8.3) might represent *P.?* *dilatatus*.

One specimen (Fig. 1.6.3) shows some simple, seemingly non-branching burrows under the valve. These are preserved as grooves, indicating that they were originally empty tubes, probably from post-mortem bioturbation. They are similar to those described by Mángano et al. (2012; see also Robison and Richards, 1981, pl. 1, fig. 4; Chlupáč and Kordule, 2002).

Order and Family uncertain

Genus BRANCHIOCARIS Briggs, 1976

Type species.—*Protocaris pretiosa* Resser, 1929, by original designation.

Diagnosis.—See Briggs (1976).

Occurrence.— Laurentia and China, middle Cambrian, Series 3, Stage 5 and Drumian; possibly China, Series 2, Stage 4.

Remarks.—*Branchiocaris* contains four species and an additional one with question: the type species from the Burgess Shale, three species from the Malong and Guanshan biotas (Honjingshao and Wulongqing formations respectively, lower Cambrian, Series 2, Stage 4), and *B.?* *yunnanensis* Hou, 1987 from the Chengjiang biota (Yu'an-shan Member, Helinpu Formation, China, lower Cambrian, Series 2, Stage 3). The last is known from the carapace only, hence the questionable assignment.

BRANCHIOCARIS? sp.

Figure 1.9.1, 1.9.5, 1.11.1, 1.11.5

Material.—One carapace in dorsal view (TMP 2013.101.0022) and four valves in lateral view (TMP 2013.101.21a, b, TMP 2013.101.0045, TMP 2013.101.0046).

Description.—The valve is semicircular in outline; maximum length is 25 mm and maximum width is 13 mm. The anterior process is slightly smaller than the posterior process, and both are relatively small. The anterior muscle scar is indistinct in one specimen (Fig. 1.9.1) and is located close to anterior margin.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—Six valves are placed in *Branchiocaris?* because of their semicircular outline, but the absence of soft-tissue attributes necessitates open nomenclature. In the better preserved valves, the anterior and posterior processes are smaller than in previously described specimens of *B. pretiosa* which occurs in strata of about the same age (Briggs, 1976; Briggs and Robison, 1984, fig. 1.9.1–1.9.4).

Order TUZOIDA Simonetta and Delle Cave, 1975

Family TUZOIDAE Raymond, 1935

Genus TUZOIA Walcott, 1912

Type species.—*Tuzoia retifera* Walcott, 1912, by original designation.

Other species.—*Tuzoia burgessensis* Reeser, 1929; *T. canadensis* Reeser, 1929; *T. polleni* Reeser, 1929; *T. dunbari* Reeser, 1929; *T. praemorsa* Reeser, 1929; *T. manchuriensis* Reeser and Endo in Endo and Reeser, 1937; *T. nitida* Reeser and Howell, 1938; *T. australis* Glaessner, 1979; *T. guntheri* Robison and Richards, 1981; *T. bispinosa* Yuan and Zhao, 1999; and questionably *T. ? parva* Walcott, 1912; *T. ? peterseni* Robison and Richards, 1981.

Diagnosis.—See Vannier et al. (2007).

Occurrence.—Laurentia, China and South Australia, lower and middle Cambrian, Series 2 and 3, Stages 3–5 and Drumian.

Remarks.—Species belonging or possibly belonging to *Tuzoia* are reported from all major BST deposits and *T.* is the largest bivalved arthropod known from the Cambrian, with a length up to 180 mm. Only a few specimens with soft-body preservation are known (Vannier et al., 2007) and the carapace outline, the arrangement of the spines and spacing in between them, and the valve convexity are used to differentiate species.

TUZOIA cf. *T. GUNTHERI* Robison and Richards, 1981

Figure 1.9.2, 1.9.3

cf. 1981 *Tuzoia guntheri* ROBISON AND RICHARDS, p. 13, pl. 7, figs. 1, 2; pl. 8, figs. 4, 5; pl. 9, fig. 2.

cf. 1991 *Tuzoia guntheri*; ROBISON, p. 84, fig. 7.1.

cf. 2003 *Tuzoia guntheri*; LIEBERMAN, p. 679, fig. 1.3.

cf. 2007 *Tuzoia guntheri*; VANNIER ET AL., p. 462, figs. 16, 25.4, 26, 31.

Material.—One partial valve in lateral view (TMP 2013.101.0047).

Diagnosis.—See Vannier et al. (2007).

Description.—The specimen is 60 mm long, representing a fragment of an ovate valve about 75 mm long. It has four spines on the posterior margin; the most dorsal is 4 mm long, the mid-posterior spine is 6 mm long, the posteroventral spine is 17 mm long, and the ventral spine is 2 mm long. Exterior surface is covered by somewhat irregular reticulate pattern of fine grooves surrounding slightly convex interiors. The diameter of the cells is between 0.5 to 2 mm, with the smaller ones towards the periphery.

Occurrence.—Comet Shale Member, Pioche Formation, *Eokochaspis nodosa* Biozone, middle Cambrian, Series 3, Stage 5, Nevada; Marjum Formation, Utah, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone; Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—*Tuzoia* cf. *T. guntheri* from the Ravens Throat River area has a posterior arrangement of four spines of short to moderate length, which fits the holotype from the Marjum Formation. As the fragment does not preserve the hinge, dorsal spine, and anterior or posterior processes, the assignment is tentative.

Order BRADORIIDA Raymond, 1935

Family uncertain

bradoriid genus and species indet. 1

Figure 1.10.1, 1.10.2

Material.—One carapace (TMP 2013.101.0044).

Description.—Carapace postplete; valve elongate ovate in outline, 16 mm long and 10 mm wide. Possible anterodorsal node present. The anterior margin is transverse. Narrow marginal ridge extends from anterior end of hinge around at least to postero-lateral margin and possibly to posterior end of hinge. Exterior surface probably smooth.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The specimen is flattened and the left valve is slightly dorso-ventrally compressed. The outline, presence of narrow marginal ridge, simple convexity and large size of the valve show similarities with species of *Anabaroichilina* Abushik, 1960, such as material from the Marjum and Week formations of Utah assigned to *A. cf. A. australis* Hinz-Schallreuter, 1993 (Siveter and Williams, 1997). It is possible that the Rockslide specimen has a similar anterodorsal node but this cannot be determined with certainty.

bradoriid genus and species indet. 2

Figure 1.10.3

Material.—One valve (TMP 2013.101.0024).

Description.—Valve almost semi-circular in outline, 10 mm long and 8 mm wide. Hinge is probably short. Anterior process is short; posterior process unknown. Narrow marginal ridge extends from anterior end of hinge around posterolateral margin and possibly to posterior end of hinge. Exterior surface probably smooth.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The semi-circular outline, absence of antero-dorsal node, and narrow marginal ridge are similar to *Liangshanella burgessensis* Siveter and Williams, 1997 from the Burgess Shale, but the Rockslide valve is some three times larger.

Class, Order and Family uncertain
arthropod genus and species indet. 1

Figure 1.12.1, 1.12.2

Material.—Two telsons, one preserved in dorso-ventral view (TMP 2013.101.0036) and the other in lateral view with abdominal segments (TMP 2013.101.0035).

Description.—In dorso-ventral view (Fig. 1.12.1), telson (and possible short abdominal somite) is 26 mm long and 9 mm wide. It consists of a pair of posteriorly directed, nearly straight to slightly inward-curving pair of lateral telson processes 20 mm in length, Base of the lateral telson process narrow then expanding abruptly, becoming elongated blade-like in outline.

In lateral view (Fig. 1.12.2), telson and nine abdominal segments is 37 mm long and 13 mm wide. Abdominal segments are uniformly about 1 mm in length, transverse in outline, and terminate laterally to short, backward-curving spines. Lateral telson process projects from rounded surface and is 13 mm in length and slightly curved.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The two specimens are considered to belong to the same taxon but represent different views. The telson of *Perspicaris dictynna* from the Burgess Shale has two wider lateral telson processes and there is a row of short marginal secondary spines (Briggs, 1977). By contrast, the telson of *Canadaspis perfecta* consists of a fringe of spines (Briggs, 1978, fig. 162; Lieberman, 2003). No telson belonging to *Tuzoia* has been described (Vannier et al., 2007). One small specimen from the Burgess Shale possesses a pair of narrow spines (Briggs, 1977, pl. 72, fig. 8). However, it is not clear if that specimen is a juvenile or belongs to a different arthropod group such as the Bradoriidae (Vannier et al., 2007). No soft tissues are known for *P? dilatatus* but it is also possible that these specimens could belong to that species. On the other hand, the lateral telson processes are distinctly narrower than the lateral telson process of arthropod genus and species indet. 2 (Fig. 1.12.3). Another possibility is that it belongs to *Branchiocaris*, *B. pretiosa* from the Wheeler

Formation is similar (Briggs et al., 2008), as are some specimens from the Burgess Shale (D. A. Legg, pers. obs.).

arthropod genus and species indet. 2

Figure 1.12.3

Material.—One fragmentary telson preserving one lateral telson process (TMP 2013.101.0034).

Description.—The lateral telson process is a 20 mm long and 5 mm wide at its maximum. For most of its length it tapers gently posteriorly, until close to its terminus where it tapers sharply to a blunt point.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—This lateral telson process differs from the narrower forms that have been assigned to *Canadaspis perfecta*, but it resembles those of *Perspicaris dictynna* Briggs, 1977 while lacking the marginal spines present in that species. Given the co-occurring carapaces, this lateral telson process could belong to either *P.?* *dilatatus* or *Branchiocaris?* sp.

arthropod genus and species indet. 3

Figure 1.12.4

Material.—One fragment of a possible biramous appendage (TMP 2013.101.0037).

Description.—A slender ‘anterior ramus’ (exopod?) appears to be joined to a wider ‘posterior ramus’ (endopod?) forming an angle of about 30°. The former is straight and uniform in thickness, possibly segmented, terminating in a slightly wider, backward-curving ‘claw’; it is 11 mm long and 1.5 mm at its widest point. The latter

consists of a wide backward-curving 'claw', 10 mm long and 3 mm at its widest point. Broken lateral margin of the specimen is more or less transverse.

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—The isolated specimen appears to be biramous but this could be coincidental overlapping of two separate objects. It resembles biramous appendages lacking the gills of trilobites, for example.

Phylum MOLLUSCA Cuvier, 1797

Class HYOLITHA Marek, 1963

Order HYOLITHIDA Matthew, 1899

Family HYOLITHIDAE Nicholson, 1872

Genus HAPLOPHRENTIS Matthew, 1899

Type species.—*Haplophrentis carinatus* Matthew, 1899, by original designation.

Other species.—*Haplophrentis reesei* Babcock and Robison, 1988.

Diagnosis.—Hyolithid with weak, longitudinal, dorso-medial septum in conch. Lateral longitudinal sulci singly paired on dorsum and venter. One pair of curved helens. (Modified from Babcock and Robison, 1981).

Occurrence.—Laurentia, middle Cambrian, Series 3, Stage 5 and Drumian.

Remarks.—*Haplophrentis* broadly resembles *Hyolithes* d'Eichwald, 1840 and *Linevitus* Syssoiev, 1958, but differs from these and other hyolithids in having an inner dorso-medial septum and longitudinal sulci on the dorsum and venter (Babcock and Robison, 1988).

HAPLOPHRENTIS CARINATUS Matthew, 1899

Figures 1.13.1–1.13.11

1899 *Hyolithes carinatus* MATTHEW, p. 42, pl. 1, figs. 5a, b.

1988 *Haplophrentis carinatus*; BABCOCK AND ROBISON, p. 15, fig. 7. [see for synonymy]

1994 *Haplophrentis carinatus*; BRIGGS ET AL., p. 113, fig. 62.

cf. 2011 *Haplophrentis cf. carinatus*; ZHAO ET AL., p. 112, figs. 114–118.

cf. 2014 *Haplophrentis cf. carinatus*; CARON ET AL., p. 4, fig. 3.

Material.—66 specimens, some with associated operculum and helens (TMP 2013.101.0056–TMP 2013.101.0121).

Description.—Conch conical exhibits an apical angle about 25°. Average length without the ligula is 12.4 mm, the smallest being 6 mm and the longest 20 mm. Average width is 4.8 mm, the smallest being 2.5 mm and the largest 7 mm. The conical shield of the opercula has an apical angle of about 125°. Cardinal processes are 0.5–0.8 mm in length. Conch with fine, straight transverse growth lines; these are arcuate in the ligula and opercula. Line spacing varies: they are closer together near the apex, and the distance becomes uniform after about one-third the length of the conch. Helens are curved.

Occurrence.—Burgess Shale, southern British Columbia, middle Cambrian, Series 3, Stage 5, *Bathyriscus–Elrathina* Biozone; Marjum and Wheeler formations, Utah, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone; Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—Hyoliths are the most abundant elements in the fossiliferous beds, but most specimens are preserved as isolated conches. The specimens are assigned to *H. carinatus* based on the apical angle of the conch and the conical shield of the operculum. This species differs from *H. reesei* by its wider conch, larger apical angle, presence of faint longitudinal grooves on the dorsum, and stronger rugae on the operculum (Babcock and Robison, 1988).

Phylum PRIAPULIDA Théel, 1906
priapulid genus and species indet. 1

Fig. 1.14.1–1.14.3

Material.—3 specimens (TMP 2013.101.0051– TMP 2013.101.0053).

Description.—Shape is curved or coiled into a single whorl; anterior portion is narrower than posterior. The longest specimen is 65 mm long and 6 mm at its widest point. Poorly preserved proboscis is partially extended in one specimen (Fig. 1.14.1).

Occurrence.—Burgess Shale, southern British Columbia, middle Cambrian, Series 3, Stage 5, *Bathyriscus–Elrathina* Biozone; Marjum and Wheeler formations, Utah, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone; Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—These specimens resemble *Ottoia prolifica* because they show the enlarged posterior region and the curved to coiled shape which is characteristic of this species when contracted. However, the preservation is such that other features are not discernible, especially the trunk annulation and details of the proboscis. Black carbonaceous films in the specimens may be remains of gut contents or residues from the soft tissues. The fossiliferous beds yield many poorly preserved, elongate objects visible as patchy dark films. These most likely belong to *Margaretia dorus* or worms, but identification is impossible.

priapulid genus and species indet. 2

Figures 1.14.4–1.14.6

Material.—3 specimens in lateral view (TMP 2013.101.0054–TMP 2013.101.0056).

Occurrence.—Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—Poorly preserved specimens vary in width along the length of the trunk somewhat as in *Ottoia prolifica*, but although they are similar in size and two are sinuous in attitude, they are not coiled.

Kingdom PLANTAE Haeckel, 1866

Division CHLOROPHYTA Reichenbach, 1834

Class CHLOROPHYCEAE Wille *in* Warming, 1884

Family CAULERPACEAE Kützing, 1843

Genus MARGARETIA Walcott, 1931

Type species.—*Margaretia dorus* Walcott, 1931, by original designation.

Other species.—*Margaretia chamblessi* Waggoner and Hagadorn, 2004.

Diagnosis.—See Waggoner and Hagadorn (2004).

Occurrence.—Laurentia, middle Cambrian Series 3, stage 5 and Drumian.

Remarks.—*Margaretia dorus* and *M. chamblessi* differ in that the former exhibits more frequent anastomosis of the longitudinal fibers in the cortex, and the papillae are sparser in *M. chamblessi*.

MARGARETIA DORUS Walcott, 1931

Figure 1.15.1–1.15.11

1931 *Margaretia dorus* WALCOTT, p. 2, pl. 1, figs. 1–6.

1988 *Margaretia dorus*; CONWAY MORRIS AND ROBISON, p. 6, figs. 3, 4. [see for synonymy]

1994 *Margaretia dorus*; BRIGGS ET AL., p. 55, fig. 3.

2010 *Margaretia dorus*; GAINES AND DROSER, p. 653, fig. 5H

2012 *Margaretia dorus*; HANDLE AND POWELL, p. 306, fig. 2H, 4C–E, 6B–C.

Material.—74 partial specimens (TMP 2013.101.0130–TMP 2013.101.0203).

Diagnosis.—See Conway Morris and Robison (1988).

Description.—Thallus is large, branching, and more or less uniform in branch width. Average width is 7.8 mm, the smallest being 4 mm and the largest 15 mm. Branches extend from the trunk at right angles; branch shape varies from straight to tightly curved (equivalent to one branch width). Papillae are parallel to the axis in rows; they vary from elongate to oval to nearly circular. Most specimens are carbonaceous films but some preserve marked relief.

Occurrence.—Burgess Shale, southern British Columbia, middle Cambrian, Series 3, Stage 5, *Bathyriscus–Elrathina* Biozone; Spence Shale member of the Langston Formation, Utah, middle Cambrian, Series 3, Stage 5, *Ptychagnostus praecurrens* Biozone; Marjum and Wheeler formations, Utah, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone; Rockslide Formation, Ravens Throat River area, Mackenzie Mountains, Northwest Territories, middle Cambrian, Series 3, Drumian, *Bolaspidella* Biozone.

Remarks.—*Margaretia dorus* is the only macrophytic alga present. It occurs in the lower fossiliferous unit and in thin beds up to 0.5 m above it, as well as being the only fossil recovered from the upper bed with soft-bodied preservation. The many poorly preserved elongate objects in the fossiliferous beds, if they belong to *Margaretia*, would indicate a greater abundance of these algae.

1.5 Discussion

The BST fossil-bearing greenish mudstones of the Rockslide Formation is interpreted to have been deposited below storm wavebase, because of their fine-grained composition and absence of erosional features and cross-lamination. The restriction of the fossils to two thin units in a succession of shales and lime mudstones suggests special, localized geochemical and sedimentological circumstances on the sea floor and maybe also in the water column at the time of deposition. It is at present uncertain if the taphonomic factors that led to soft-bodied preservation are comparable to those proposed for other Lagerstätten (e.g., Butterfield, 1995; Gaines et

al., 2012). However, the quality of preservation does not match that in the Burgess Shale and some of the other Cambrian Lagerstätten. The soft tissues of the arthropods are not preserved and the priapulids show advanced decay. This suggests that biodegradation proceeded more or less normally on the sea floor or under shallow burial before ceasing.

The environmental setting of the Rockslide Formation at the Ravens Throat River locality bears some similarities to that of the Burgess Shale (e.g., Johnston et al., 2009a), the lower Cambrian (Series 2, Stage 4) Sirius Passet locality in northern Greenland (Peel and Ineson, 2011) and the Wheeler and Marjum formations of Utah (Rees, 1986) because all are associated with syndepositional block faulting. The significance of this relationship is unclear in terms of its effect on the benthic ecology or the taphonomy of the soft-bodied components. Rare BST fossils have also been reported from strata coeval with and older than the Rockslide Formation that crop out in the Mackenzie River Valley to the east of the Mackenzie Arch (Butterfield, 1994; Butterfield and Nicholas, 1996; Harvey and Butterfield, 2011). These rocks were deposited in a shallow, intra-shelf basin (Dixon and Stasiuk, 1998). Chancelloriids exhibiting BST preservation also occur in the lower Cambrian Sekwi Formation (Randell et al., 2005).

Arthropods, namely carapace-bearing taxa, are represented by the highest diversity of forms. The most common species is *Perspicularis? dilatatus*. So far, the carapaces have not been associated with soft-bodied parts, but isolated fragments likely belong to that species. Priapulids and macrophytic algae are also present, along with typical members of the shelly fauna of this age. Simple burrows are observed under some of the arthropod valves. In terms of simple relative abundance, the fauna is dominated by hyoliths (Fig. 1.16). These early molluscs often occur with their operculum and helens. The biota may represent a fairly typical benthic community of middle Cambrian age in the deeper water ramp or slope region of marginal Laurentia. However, there is an apparent absence of siliceous sponges, which are variably common elsewhere.

The Ravens Throat River Lagerstätte is similar to the BST deposits from the Great Basin. Not only is it of about the same age as the Wheeler and Marjum formations, but it also has several taxa in common with these units, as well as with the older Burgess Shale and Pioche Shale Lagerstätten (Table 1; e.g., Robison and Richards, 1981; Robison, 1991; Briggs et al., 1994, 2008; Lieberman, 2003). The

dominance of arthropods over other groups is also observed in the Burgess Shale (e.g., Briggs et al., 1994; Caron and Jackson, 2008), the Chengjiang biota (Hou et al., 2004), and the Kaili biota (Zhao et al., 2005; 2011).

1.6 Conclusions

The new middle Cambrian Lagerstätte in the Rockslide Formation of the Mackenzie Mountains of northwestern Canada carries a shelly fauna consisting of common hyoliths, agnostoid arthropods and polymeroid trilobites, and scarce linguliformean brachiopods. It yields a soft-bodied fauna that includes a number of bivalved and other arthropods, especially species belonging to *Isoxys*, *Perspicularis*?, *Tuzoia*, *Branchiocaris*? and bradoriids, along with the macrophytic alga *Margaretia* and rare priapulids. Overall, the biota is similar in composition to the known Laurentian Burgess Shale-type deposits of similar age in the Great Basin of southwestern U.S.A. Like the Burgess Shale and some other comparable Cambrian Lagerstätten, it is similarly associated with synsedimentary faulting in a deeper water depositional setting. One difference lies in the heterogeneity of the facies that comprise the Ravens Throat River section and the preservation of only the more robust components of its biotic elements restricted to two thin units. This locality affirms that the propensity for Burgess Shale-type preservation was more widespread in Laurentia than hitherto understood.

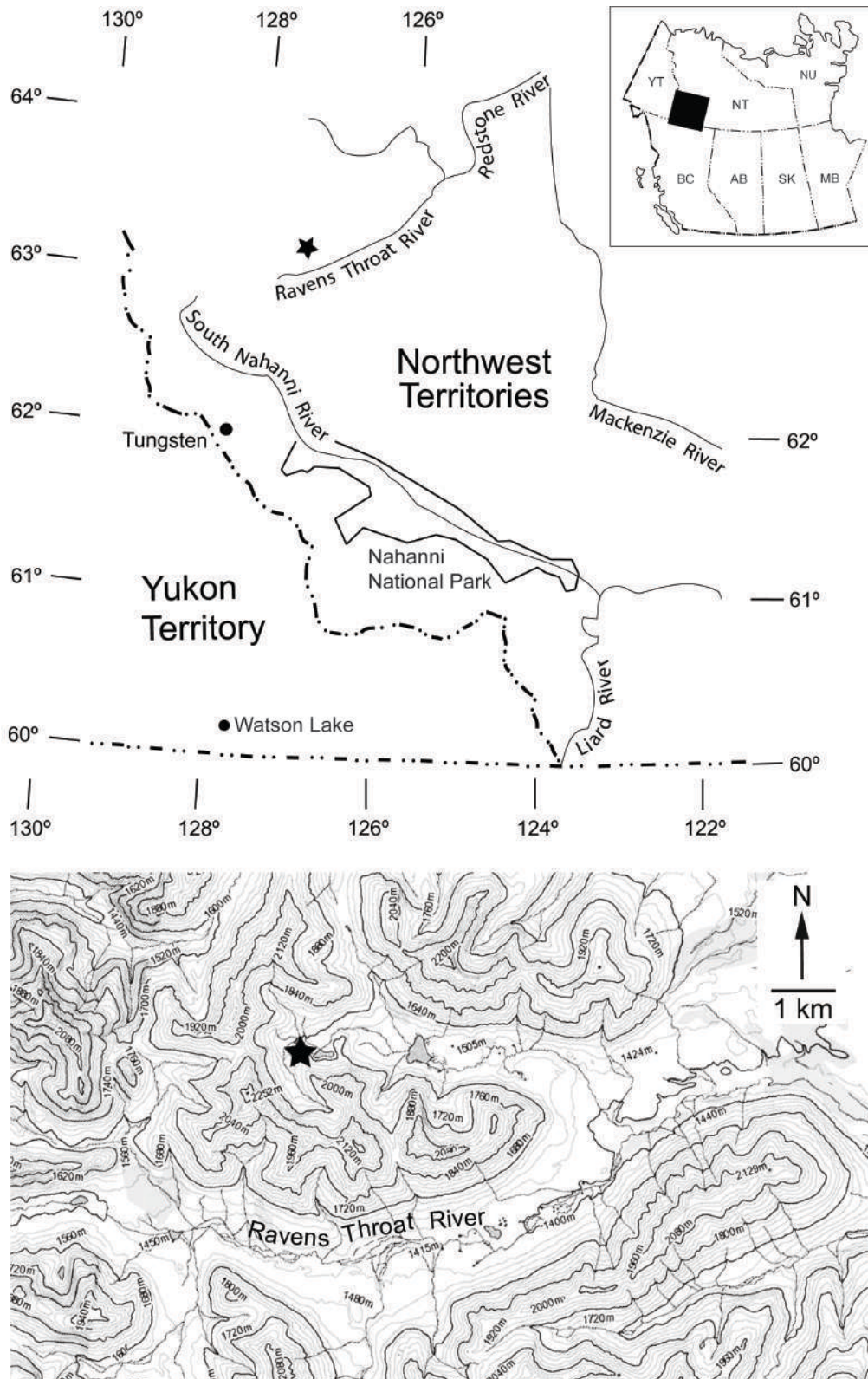


FIGURE 1.1—Location of the Ravens Throat River locality (asterix; 63°10'N, 127°55'W), Mackenzie Mountains, Northwest Territories, Canada: 1, regional map; 2, topographic map.

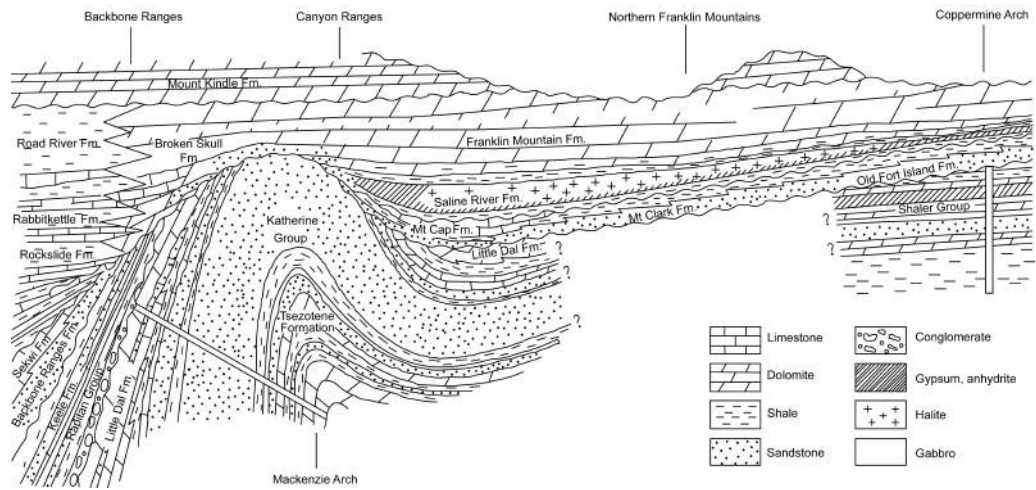


FIGURE 1.2—Regional cross-section across the Mackenzie Mountains (modified from Aitken et al., 1973).

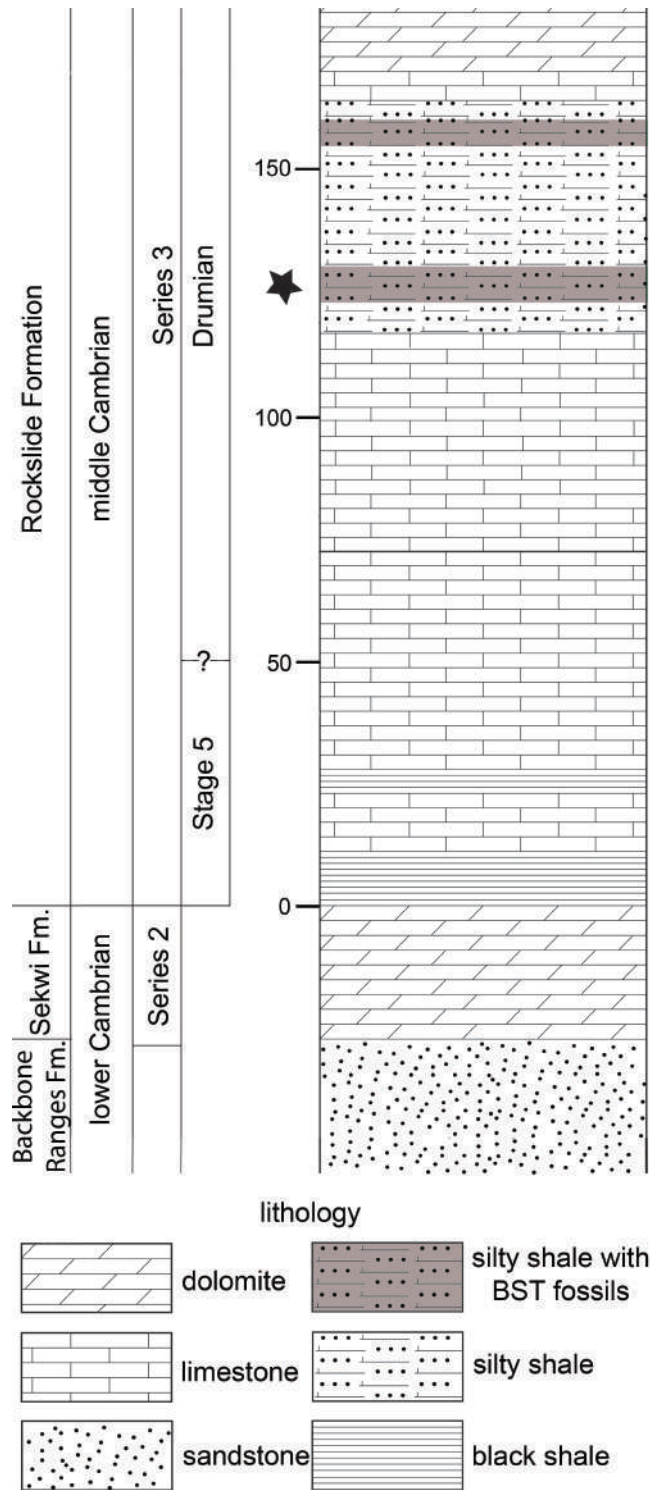


FIGURE 1.3—Generalized stratigraphy of the Rockslide Formation in the Ravens Throat river area (upper part of section and contact with overlying Avalanche Formation is not exposed). Star symbol indicates main fossil bed.

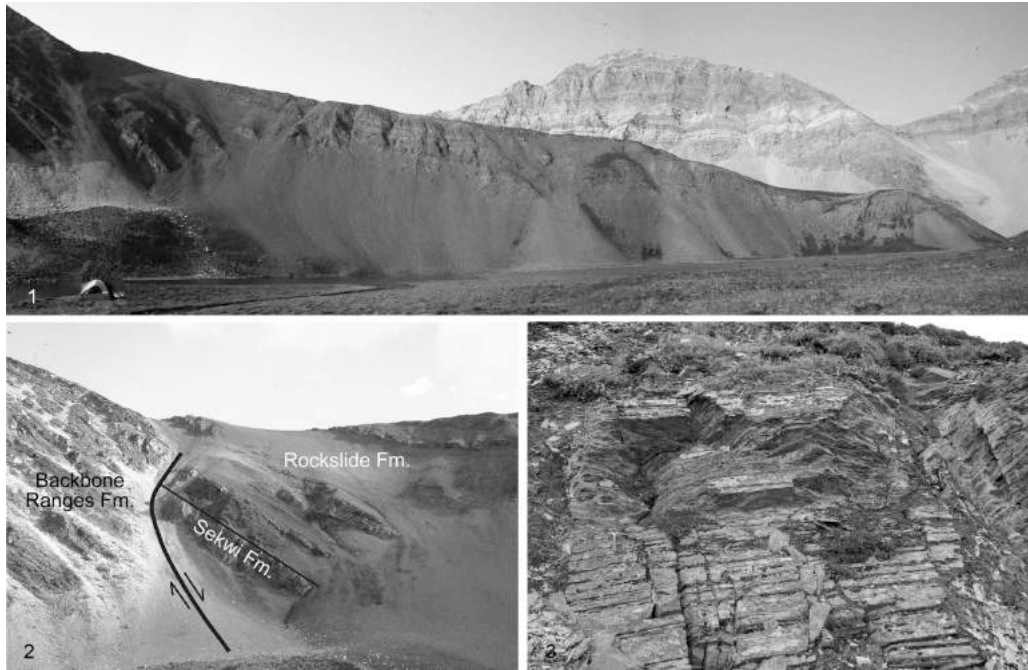


FIGURE 1.4—The outcrop area near the headwaters of the Ravens Throat River: 1, panorama looking west; 2, left side of outcrop showing the synsedimentary fault (black line; formations labeled; stratigraphic position of fossil-bearing unit shown by arrow); 3, close-up of the fossiliferous thin-bedded mudstone (hammer circled).

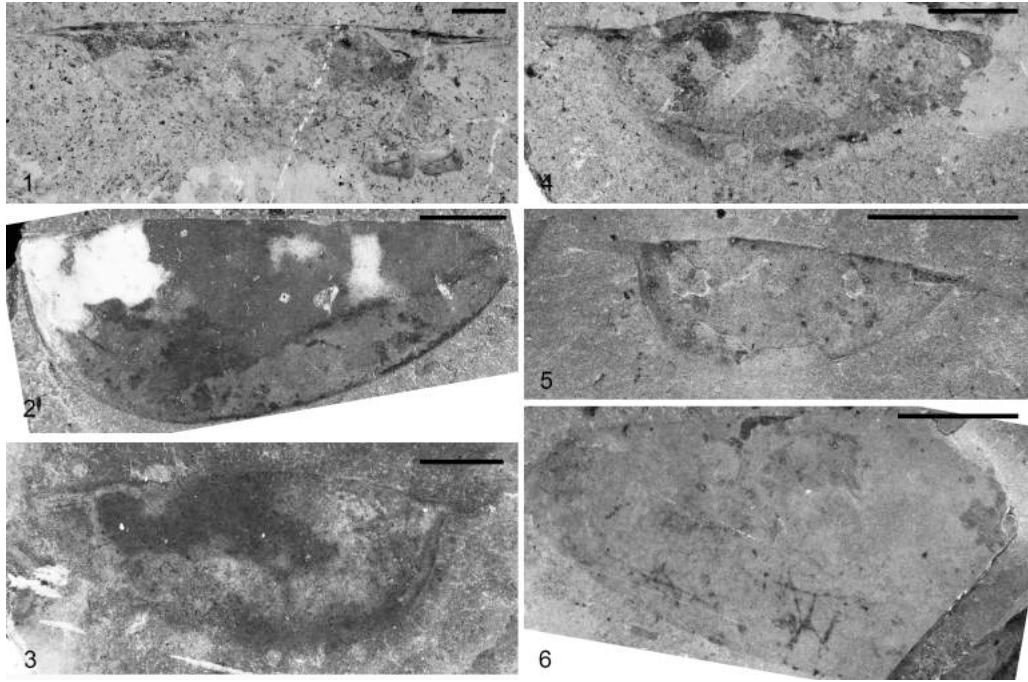


FIGURE 1.5—*Isoxys mackenziensis* n. sp. from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, lateral view of valve and holotype (TMP 2013.101.0038); 2, lateral view of valve (TMP 2013.101.0040); 3, lateral view of valve (TMP 2013.101.0042); 4, lateral view of valve (TMP 2013.101.0039); 5, lateral view of valve (TMP 2013.101.0041); 6, lateral view of valve (TMP 2013.101.0043; surface scratched). Scale bars are 5 mm.

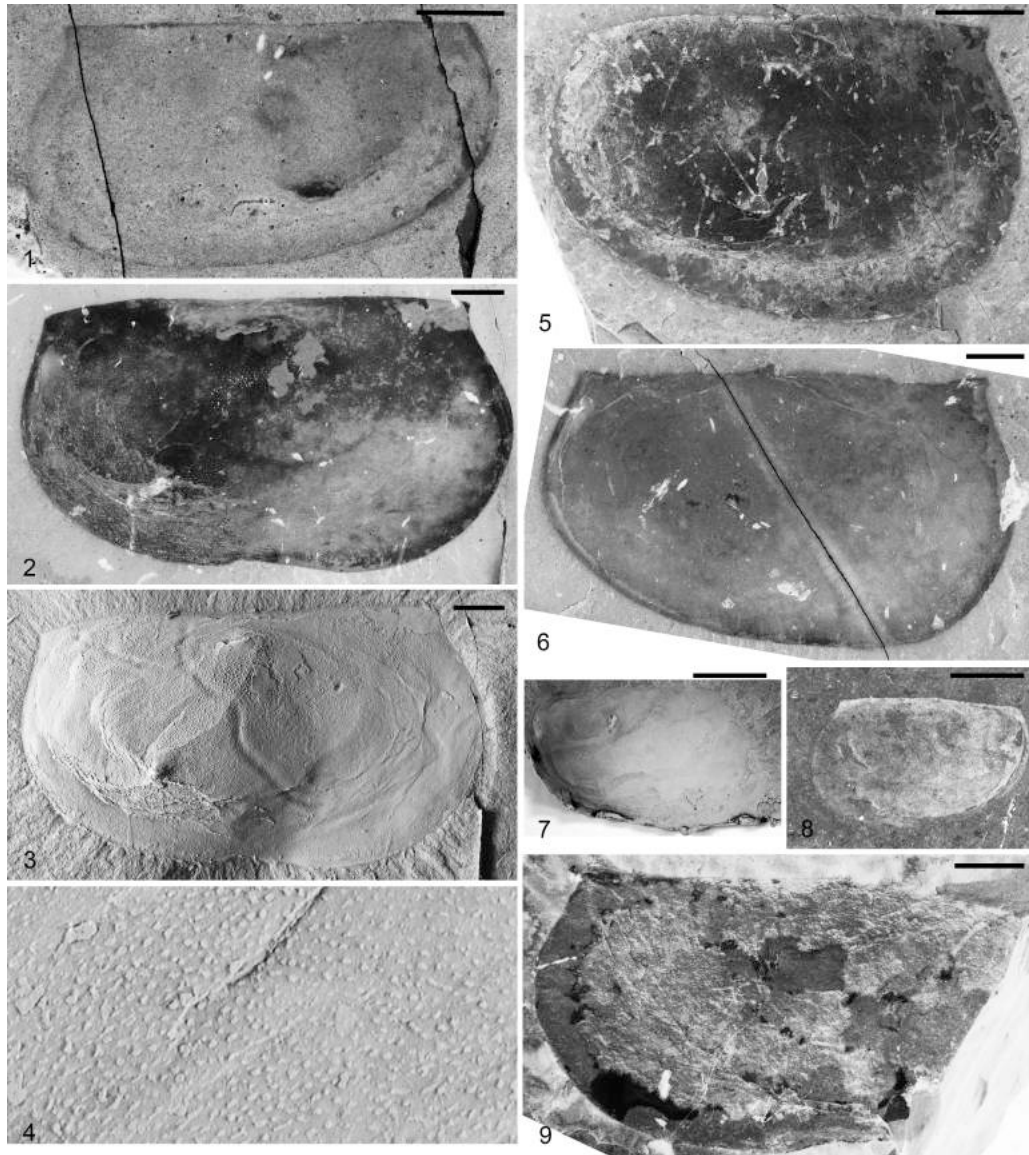


FIGURE 1.6—*Perspicaris? dilatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, lateral view of valve (TMP 2013.101.0009; cut by two oblique fractures); 2, lateral view of valve (TMP 2013.101.0002; flipped horizontally); 3, lateral view of valve with burrows beneath (latex cast dusted with ammonium chloride; TMP 2013.101.0002); 4, close-up of 3 showing pustular ornament on valve exterior; 5, lateral view of valve (TMP 2013.101.0005; surface scratched); 6, lateral view of valve (TMP 2013.101.0006; cut by oblique fracture); 7, latex cast of 8 dusted with ammonium chloride; 8, lateral view of small valve (TMP 2013.101.0010); 9, lateral view of weathered partial valve (TMP 2013.101.0011). Scale bars are 5 mm.

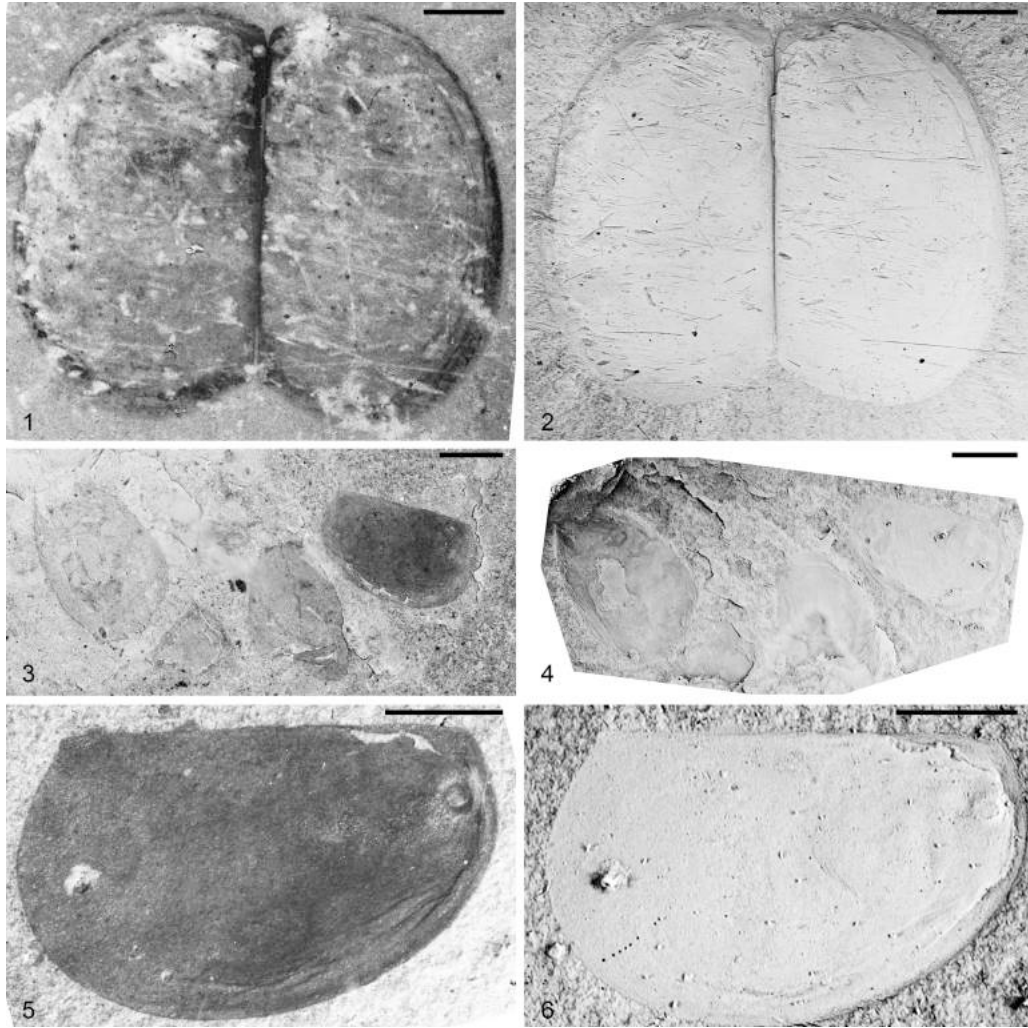


FIGURE 1.7—*Perspicaris? dilatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, dorsal view of butterflyed carapace (TMP 2013.101.0001; surface scratched); 2, same as 1 (dusted with ammonium chloride); 3, lateral views of three complete and one partial valves (TMP 2013.101.0004); 4, lateral views of one complete and two partial valves (latex cast dusted with ammonium chloride; TMP 2013.101.0004; flipped horizontally); 5, lateral interior view of complete valve, with muscle scar (TMP 2013.101.0008); 6, lateral interior view of complete valve, with muscle scar (latex cast dusted with ammonium chloride; TMP 2013.101.0008; flipped horizontally). Scale bars are 5 mm.

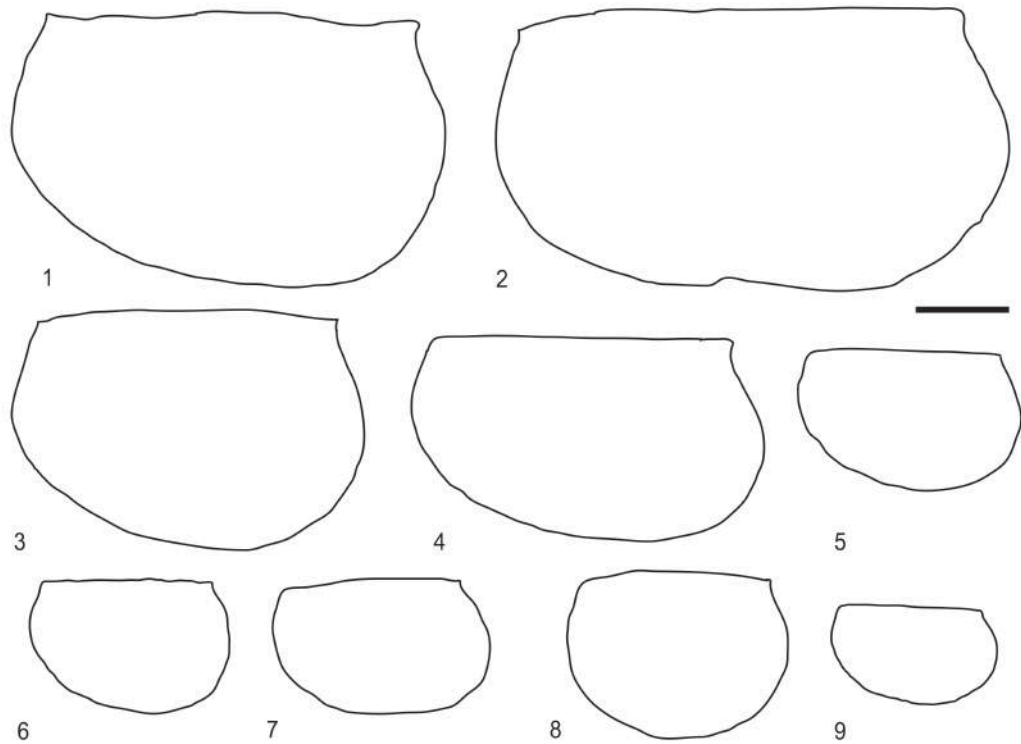


FIGURE 1.8—Variation in outline of *Perspicaris? dilatus* specimens from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains. 1, TMP 2013.101.0006; 2, TMP 2013.101.0002; 3, TMP 2013.101.0005; 4, TMP 2013.101.0009; 5, TMP 2013.101.0010; 6, TMP 2013.101.0001; 7, TMP 2013.101.0008; 8, TMP 2013.101.0007; 9, TMP 2013.101.0004. Specimens are drawn to scale and anterior is oriented to the left. Scale bar is 10 mm.

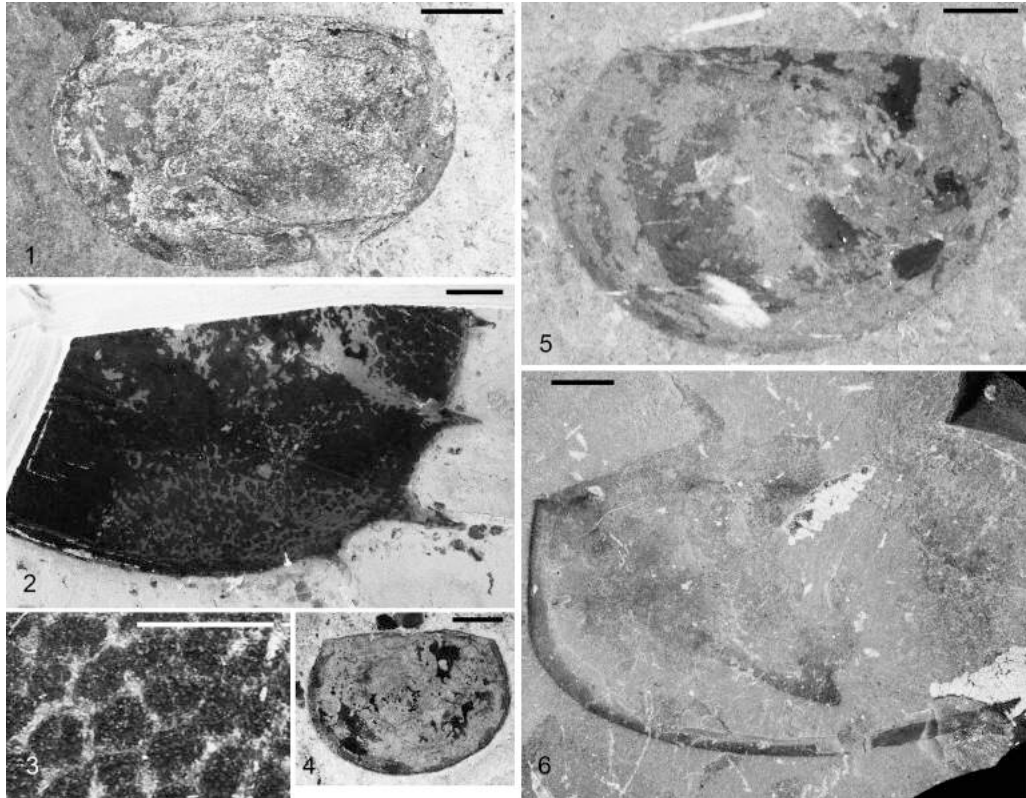


FIGURE 1.9—Arthropods from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, *Branchiocaris?* sp., lateral view of valve (TMP 2013.101.0045); 2 *Tuzoia* cf. *T. guntheri*, lateral view of partial valve (TMP 2013.101.0047); 3, *Tuzoia* cf. *T. guntheri*, close-up of 2 showing reticulate ornament on valve exterior surface (TMP 2013.101.0047); 4, small valve of *Perspicares?* *dilatatus* in lateral view (TMP 2013.101.0007); 5, *Branchiocaris?* sp., lateral view of valve (TMP 2013.101.0046); 6, *Perspicares?* *dilatatus*, lateral view of partial valve with broken hinge, possibly two valves overlying each other (TMP 2013.101.0048). Scale bars are 5 mm.



FIGURE 1.10—Bradoriids from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, bradoriid genus and species indet. 1, complete carapace in dorsal view (TMP 2013.101.0044); 2, latex cast of 1 dusted with ammonium chloride; 3, bradoriid genus and species indet. 2, valve in lateral view (TMP 2013.101.0024). Scale bar is 5 mm.

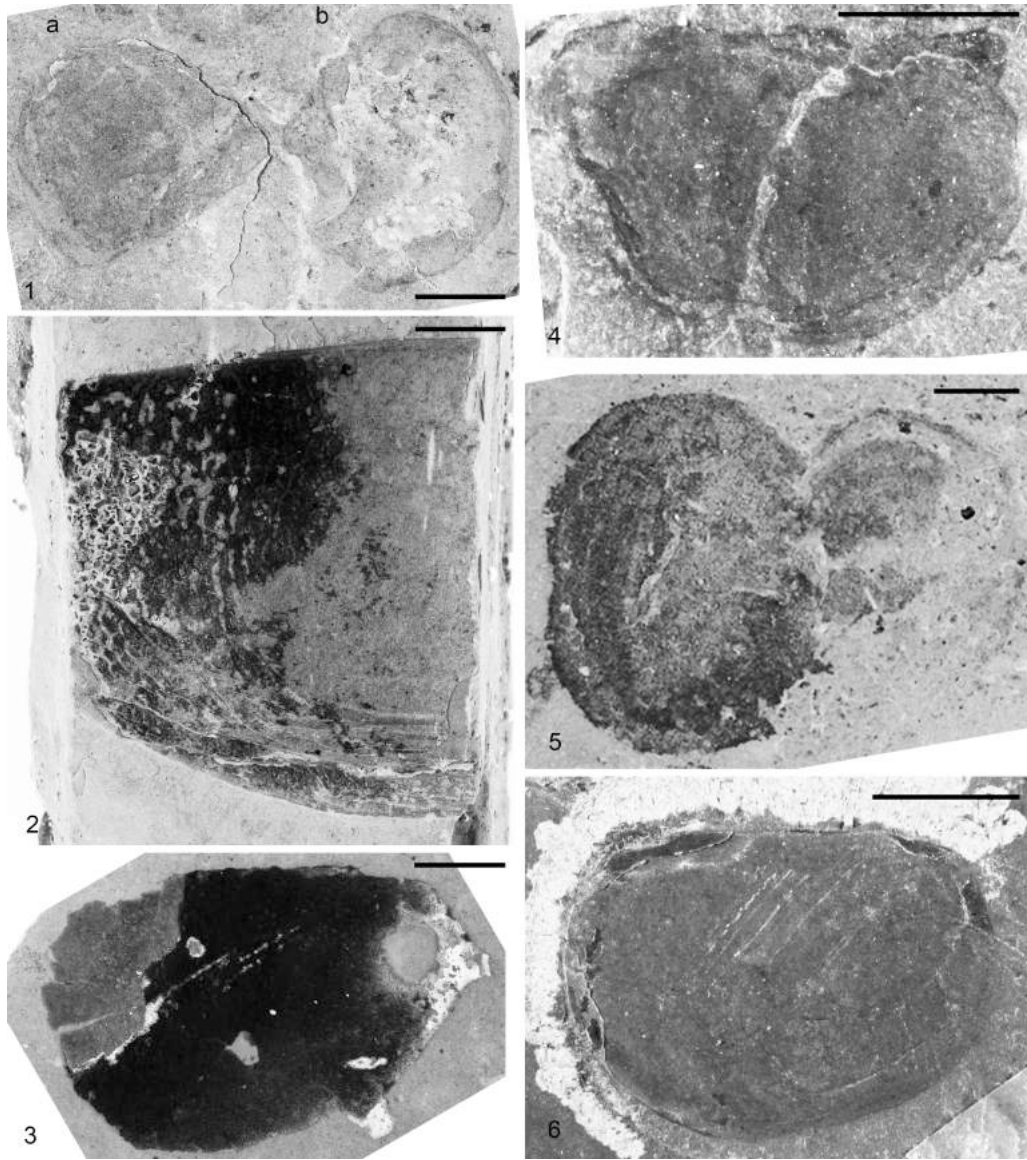


FIGURE 1.11—Fragmentary arthropods from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, *Branchiocaris?* sp. lateral views of two disarticulated valves (TMP 2013.101.0021); 2, *Tuzoia* sp. lateral view of partial valve with ornament of cusped ridges along margin (TMP 2013.101.0018); 3, *Perspicaris? dilatatus* lateral view of valve (TMP 2013.101.0019); 4, *Perspicaris? dilatatus* lateral view of valve (TMP 2013.101.0017); 5, *Branchiocaris?* sp. butterflyed carapace (TMP 2013.101.0022); 6, lateral view of valve, possibly *Perspicaris? dilatatus* (TMP 2013.101.0016). Scale bars are 5 mm.

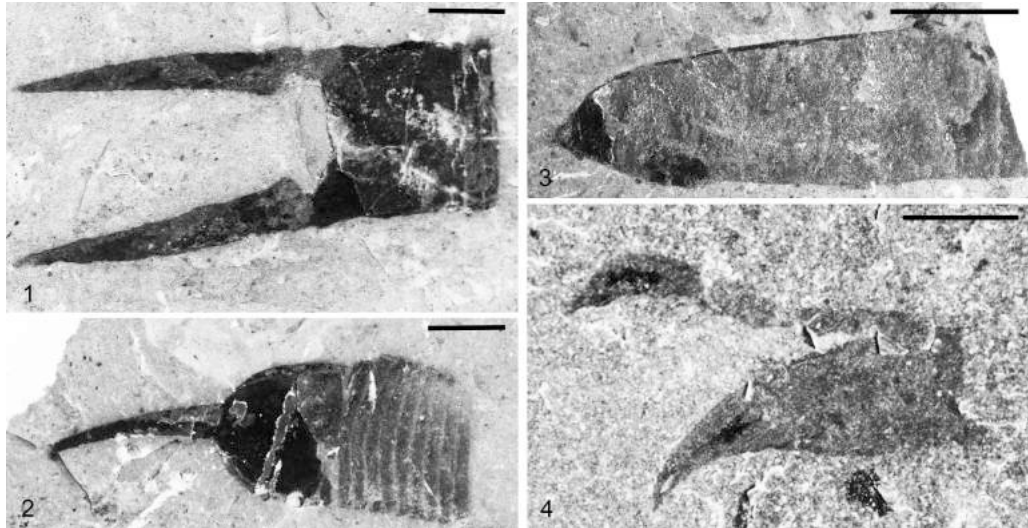


FIGURE 1.12—Arthropod fragments from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1,2, arthropod genus and species indet. 1: 1, posterior portion of thorax with lateral telson process consisting of two processes in dorsal view (TMP 2013.101.0036); 2, posterior portion of thorax with lateral telson process in lateral view (TMP 2013.101.0035); 3, arthropod genus and species indet. 2, isolated lateral telson process (TMP 2013.101.0034); 4, arthropod genus and species indet. 3, possible biramous appendage consisting of endopod(?) and exopod(?) (TMP 2013.101.0037). Scale bars are 5 mm.

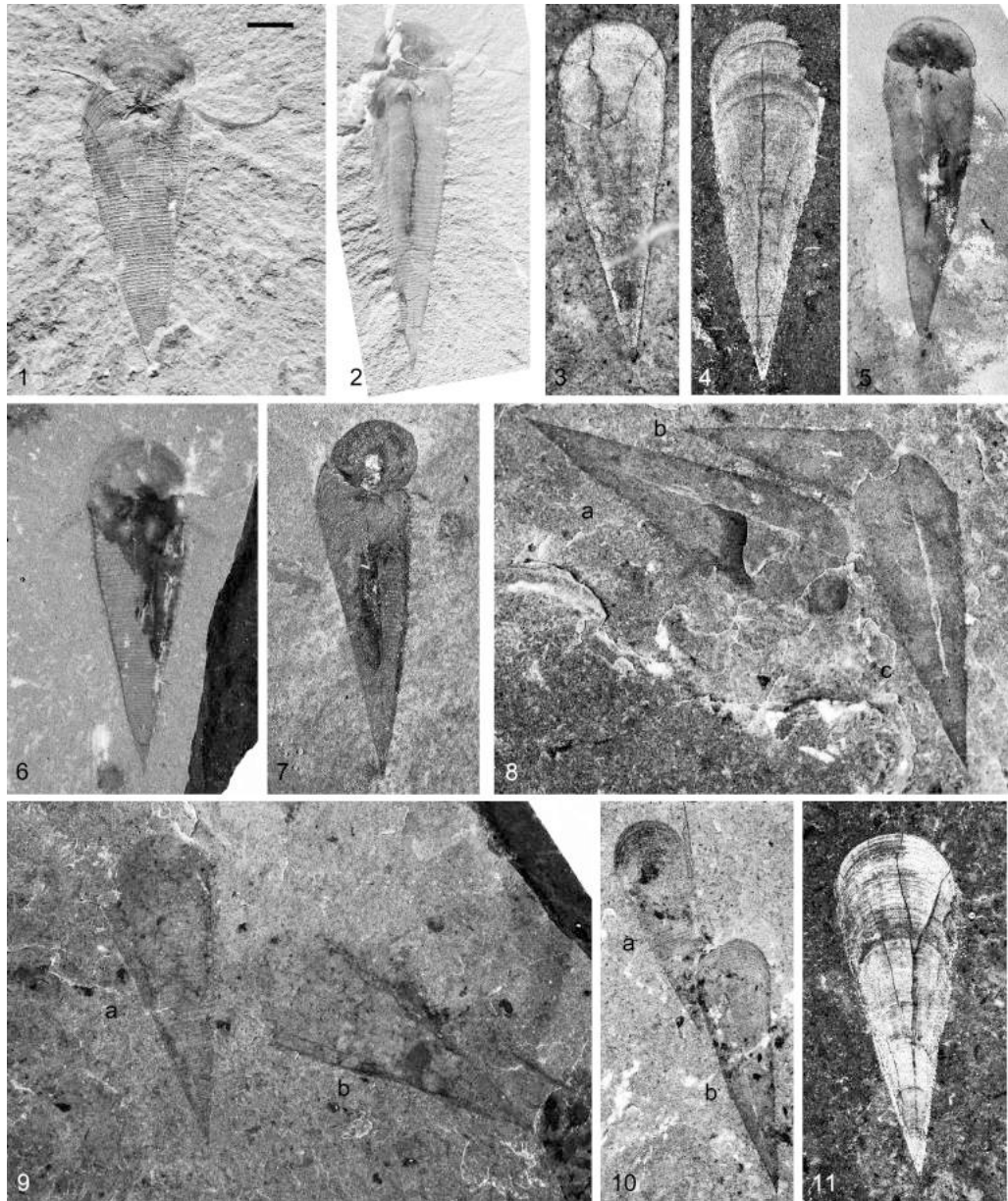


FIGURE 1.13—*Haplophrentis carinatus* from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, conch with operculum and helens (TMP 2013.101.0058); 2, conch with operculum and one helen (TMP 2013.101.0059); 3, conch (TMP 2013.101.0063); 4, conch (TMP 2013.101.0064); 5, conch with operculum and one helen (TMP 2013.101.0065); 6, conch with operculum (TMP 2013.101.0066); 7, conch with operculum and partial helen (TMP 2013.101.0067); 8, three conches (TMP 2013.101.0068a, b, c); 9, two conches, one possible juvenile specimen (TMP 2013.101.0070a, b); 10, two juxtaposed conches (TMP 2013.101.0071a, b); 11, conch (TMP 2013.101.0072). Scale bar is 2 mm.

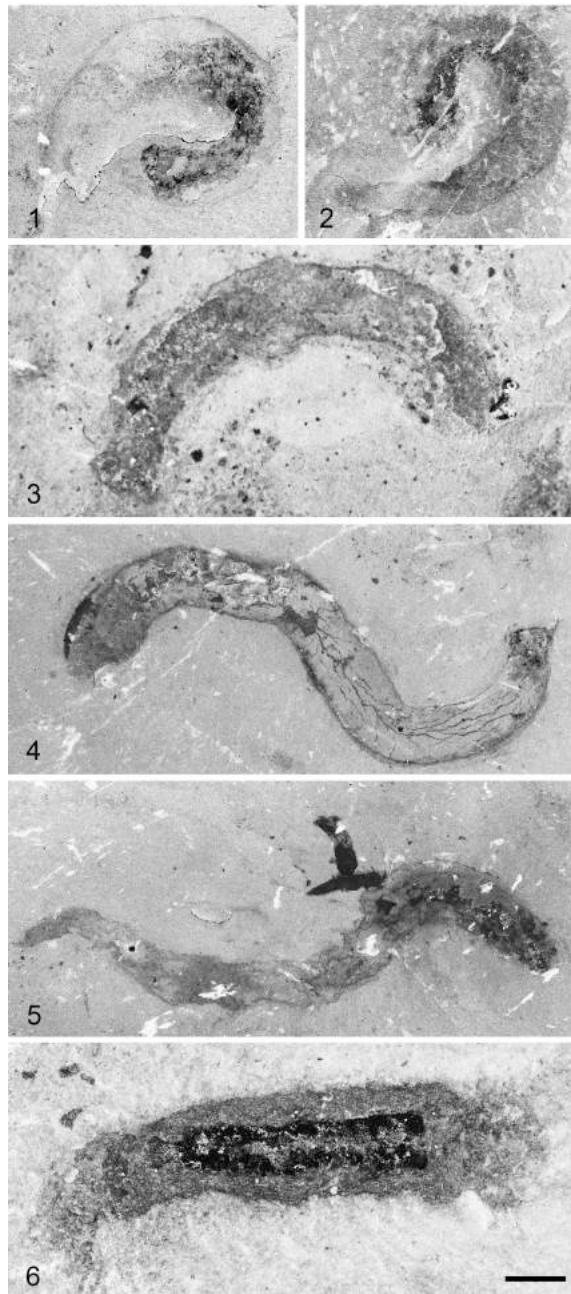


FIGURE 1.14—Priapulids from the Rockslide Formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains. Possible gut contents or residual soft tissues appear as dark patches. 1–3, priapulid genus and species indet. 1: 1, curved specimen, with partially extended proboscis to left (TMP 2013.101.0051); 2, coiled specimen, with anterior end at bottom (TMP 2013.101.0052); 3, coiled specimen, with anterior end at bottom (TMP 2013.101.0053); 4–6, priapulid genus and species indet. 2: 4, sinuous specimen, anterior to the right (TMP 2013.101.0054); 5, sinuous specimen, anterior and posterior ends unknown (TMP 2013.101.0055); 6, Elongated specimen (TMP 2013.101.0056). Scale bar is 5 mm.

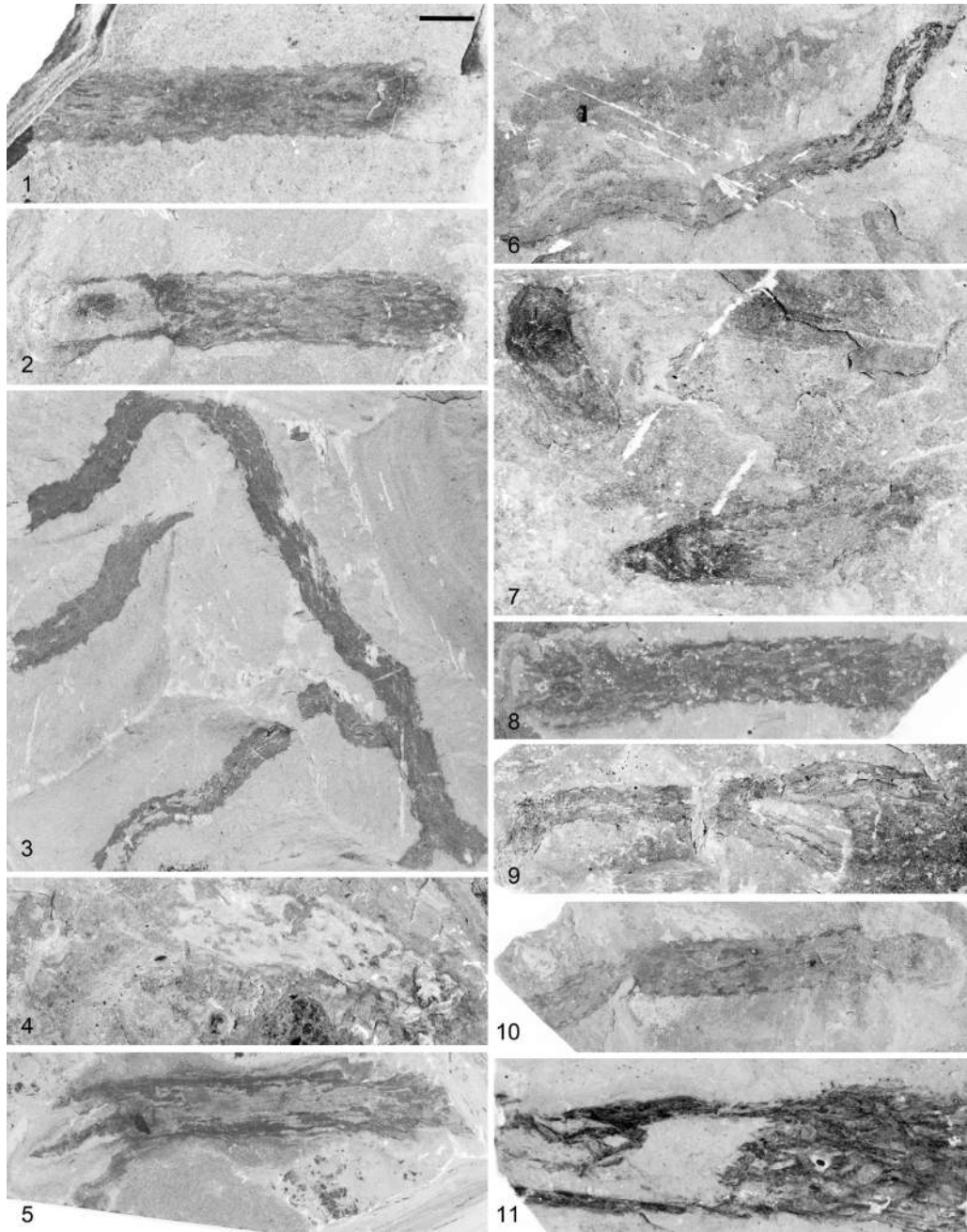


FIGURE 1.15—*Margaretia dorus* from the Rockslide formation, middle Cambrian, Ravens Throat River area, Mackenzie Mountains: 1, partial branch (TMP 2013.101.0130); 2, partial branch (TMP 2013.101.0131); 3, branching specimen (TMP 2013.101.0132); 4, partial branch (TMP 2013.101.0133); 5, partial branch (TMP 2013.101.0134); 6, partial branch (TMP 2013.101.0135); 7, two partial branches (TMP 2013.101.0136); 8, partial branch (TMP 2013.101.0137); 9, partial branch (TMP 2013.101.0138); 10, partial branch (TMP 2013.101.0139); 11, partial branch (TMP 2013.101.0140). Scale bar is 10 mm.

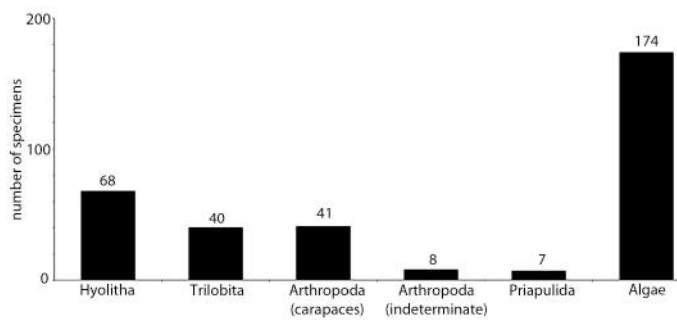


FIGURE 1.16—Relative abundance of specimens of metazoan taxa in all samples collected from the fossiliferous unit of the Rockslide formation (both in situ and from the scree slope), middle Cambrian, Ravens Throat River area, Mackenzie Mountains.

Species of the Ravens Throat River Lagerstätte	Pioche Formation		Burgess Shale		Wheeler Shale and Marjum Formation	
	Genus	Species	Genus	Species	Genus	Species
<i>Isoxys mackenziensis</i>	x	x	√	x	√	x
<i>Branchiocaris? Sp.</i>	x	x	√	x	√	x
<i>Perspicularis? dilatatus</i>	√	√	√	x	√	√
<i>Tuzoia</i> cf. <i>T. guntheri</i>	√	√	√	x	√	√
<i>Haplophrentis carinatus</i>	x	x	√	√	√	√
<i>Lingulella waptensis</i>	x	x	√	√	x	x
<i>Ottoia</i> cf. <i>O. prolifica</i>	x	x	√	√	√	√
<i>Margaretia dorus</i>	x	x	√	√	√	√

Table 1.1—Occurrence of Ravens Throat River taxa in other western Laurentian Lagerstätten: Pioche Formation (Series 3, Stage 5); Burgess Shale (Series 3, Stage 5); Marjum Formation (Series 3, Drumian); Wheeler Formation (Series 3, Drumian); √=represented, x=not represented.

LINK BETWEEN CHAPTER 1 AND 2

While understanding the diversity of the Ravens Throat River Lagerstätte is important for knowledge of Cambrian biodiversity and global distribution of species at the time, the big question for BST deposits is how they were deposited. In the following chapter, sedimentological and geochemical methods are used to understand the depositional environment and its influence on Burgess Shale-type deposits. Furthermore it considers the correlation of the sediments of several BST deposits throughout North America, and how far they play a role in the preservation of BST fossils.

CHAPTER 2

TAPHONOMY OF THE MIDDLE CAMBRIAN (DRUMIAN) RAVENS THROAT RIVER LAGERSTÄTTE, ROCKSLIDE FORMATION, MACKENZIE MOUNTAINS, NORTHWEST TERRITORIES, CANADA

2.1 Abstract

The middle Cambrian (series 3, Drumian, *Bolaspidella* Biozone) Ravens Throat River Lagerstätte in the Rockslide Formation of the Mackenzie Mountains, northwestern Canada, contains a Burgess Shale-type biota of similar age as the Wheeler and Marjum formations of Utah. The Rockslide Formation is a unit of deep-water, mixed carbonate and siliciclastic facies deposited in a slope setting on the northwestern margin of Laurentia. At the fossil-bearing locality, the unit is about 175 m thick and the lower part onlaps a fault scarp cutting lower Cambrian sandstones. It consists of a succession of shale, laminated to thin-bedded lime mudstone, debris-flow breccias, calcareous sandstone, greenish-coloured calcareous mudstone and dolomitic siltstone, overlain by shallow-water dolostones of the Broken Skull Formation, which indicates of an overall progradational sequence. Two 1 m-thick units of greenish calcareous mudstone in the upper part exhibit soft-bodied preservation, yielding a biota dominated by bivalved arthropods and macrophytic algae, along with hyoliths and trilobites. Most of the biota is in the lower interval, and only the more robust components are preserved. Branching burrows are present under the carapaces of some arthropods, and common millimeter-sized disruptions of laminae are interpreted as bioturbation.

The planar-laminated calcareous mudstone consists of quartz silt, calcite, dolomite, illite and chlorite, and is an anomalous facies in the succession. It was deposited by hemipelagic fallout. Geochemical analysis and trace-element proxies indicate oxic bottom waters that only occasionally might have become dysoxic. Productivity in the water column was dominated by cyanobacteria. Fragments of microbial mats are common as carbon seams. The biota records a low-diversity *in situ* community. Complete decay of soft tissues was interrupted due to the specific sediment composition, providing support for the role of certain clay minerals in the taphonomic process.

2.2 Introduction

Burgess Shale-type (BST) deposits are exceptional windows that reveal early Palaeozoic biodiversity because they preserve rare soft-body parts. These are preserved as two-dimensional compressed fossils that can contain interior structures. In addition to continued study of the taxonomy and the composition of these fossils (e.g., Briggs et al. 1994; Butterfield, 1995; Edgecombe and Legg, 2013), the environmental and taphonomic aspects remain controversial. Most analyses support oxygenated bottom waters in BST deposits (Powell et al., 2003; McKirdy et al., 2011), but the preservation of soft tissue is usually ascribed to anaerobic conditions, at least within the sediments (e.g., Allison, 1988; Sagemann et al., 1999). These seemingly opposing factors must be reconciled (Gaines et al., 2008; Butterfield, 2012). Sedimentological studies confirm that BST environments are low-energy settings in deep water (Gabbott et al., 2008; Webster et al., 2008; Brett et al., 2009; Gaines et al., 2011). Several mechanisms have been suggested to explain a presumed sharp redox boundary between the oxygenated water column and the sediment, including rapid burial, clay mineral precipitation, organic matter enrichment and microbial mats (Butterfield, 1995; Butterfield et al., 2007; Hall et al., 2011; Garson et al., 2012; Gaines et al., 2012a). The details of water-column productivity and benthic microbial activity are difficult to determine by biomarker analysis because the signals are lost in most BST deposits because of diagenetic alteration and incipient metamorphism. However, the presence of benthic microbial mats has been interpreted based on organic seams (i.e., Butterfield, 1990; McKirdy et al., 2011).

The Ravens Throat River Lagerstätte of Drumian (middle Cambrian) age (Kimmig and Pratt, in press) offers an opportunity to examine the environmental and taphonomic factors relating to BST preservation, or the lack of preservation, in a deeper water slope or ramp setting. Occurring in non-metamorphic strata, this is a low-diversity biota comparable to the coeval Wheeler and Marjum formations of Utah. Besides analysis of the sedimentary facies in the field, a variety of laboratory methods were used, including petrography, X-ray diffractometry, back-scattered scanning electron microscopy and synchrotron X-ray fluorescence, and determination of trace-element composition, total organic carbon content, biomarkers, and organic carbon stable isotopes.

2.3 Geological Setting

The Rockslide Formation is a regionally extensive, mixed carbonate–siliciclastic unit of middle Cambrian (series 3, *Plagiura-Poliella* to late *Bolaspidella* or *Lejopyge laevigata* Biozone) age in the Mackenzie Mountains (Fig. 2.1; Gabrielse et al., 1973; Fritz, 1979; Pratt, 1989). Thicknesses can exceed 500 m and the rocks consist of fossiliferous argillaceous and silty lime mudstone, calcareous siltstone and both siliciclastic and carbonate debris-flow conglomerates. Previous investigations indicate deposition in deep water on a west-facing slope towards the Selwyn Basin, that appears to have been seaward of a mixed carbonate–siliciclastic platform on or rimming the Mackenzie Arch that has since been planed off (Pyle et al., 2007). Mudmound reefs are locally present (Pratt, 1989). BST fossils are known only from the location named Ravens Throat River Lagerstätte (Kimmig and Pratt, in press). Further east along the Mackenzie River valley, the lower Rockslide Formation correlates with intrabasinal shales of the Mount Cap Formation (Dixon and Stasiuk, 1998; MacNaughton et al., 2013). These sediments yield rare examples of BST preservation (Butterfield, 1994; Butterfield and Nicholas, 1996). To the north the Rockslide Formation grades into a thick succession of deep-water sediments belonging the Hess River Formation in the Misty Creek embayment (Cecile, 1982; Chevrier and Turner, 2013). To the west the Rockslide Formation is overlain by deep-water limestones of the Rabbitkettle Formation (Pratt, 1992; Gordey and Anderson, 1993).

The Lagerstätte is located near the headwaters of the Ravens Throat River (127° 55'W, 63°10'N). About 175 m of the lower Rockslide Formation are exposed on a mountainside above an unnamed lake. It consists of a succession of shales that grade upwards into interbedded shale and lime mudstone, and then into thin-bedded lime mudstone (Fig. 2.2). The Rockslide Formation overlies a thin limestone and dolomite unit of the lower Cambrian Sekwi Formation, which itself rests abruptly on shallow-marine sandstones of the Ediacaran to lower Cambrian Backbone Ranges Formation. The base of the Rockslide Formation yields trilobites probably belonging to the *Albertella* Biozone (pers. obs.). About 750 m to the south, the upper Rockslide Formation continues with about 50 m of thin-bedded dolomitic limestones overlain by 50 m of medium-bedded dolostone. Shallow-water dolomites belonging to the Broken Skull Formation overlie the Rockslide Formation at this location (section 19 of

Gabrielse et al., 1973). The lower 50 m of the Broken Skull Formation consist of sandstone and sandy dolomite that more recent stratigraphic studies in the region would assign to the Avalanche Formation (Gordey and Anderson, 1993).

The Sekwi Formation and lower 60 m of the Rockslide Formation at the Ravens Throat River locality are in fault contact against the upper Backbone Ranges Formation. This is the southern margin of a syndepositional fault scarp that can be traced northwards across the valley to the next ridge. In plan view the fault appears to be broadly U-shaped; the fault plane was relatively gently inclined but steepened markedly at the southern margin. A change in dip between the Sekwi–lowermost Rockslide Formation interval (140°/56W°) and the rest of the Rockslide Formation (125°/64°W) implies a second phase of movement. The fault is likely listric in nature and probably a local feature, less steep than the Cathedral and Eldon escarpments of the southern Rocky Mountains (cf. Collom et al., 2009; Johnston et al., 2009b).

Two 1 m thick units contain soft-bodied preservation in distinctive greenish lime mudstone at 134–139 m and 162–166 m above the Sekwi Formation. The lower unit, at 135 m, contains almost all the fossils, whereas the upper one, at about +164 m, contains only rare fragments of *Margaretia dorus*. Trilobites and agnostoids indicate that the fossil-bearing interval belongs to the *Bolaspidella* Biozone, and is therefore of similar age as the Wheeler and Marjum formations of Utah. The Burgess Shale in contrast is slightly older (*Bathyriscus–Elrathina* Biozone), but shares some taxa with the Ravens Throat River Lagerstätte (Kimmig and Pratt, 2014). Because the outcrop is a cliff, most fossil specimens were collected from the scree.

2.4 Methodology

The fossil specimens are housed in the collections of the Royal Tyrrell Museum (TMP) in Drumheller, Alberta.

A suite of 55 polished thin-sections of the various Rockslide lithofacies and the lowest 39 layers of the lower fossil-bearing unit were examined with a Nikon Optiphot-Pol microscope for grain size, sedimentary structures and organic residues. Mineralogy was determined using a JEOL JXA-8600 Superprobe with Backscatter Scanning Electron Microscope. Mineralogical composition was determined by X-ray diffractometer (XRD) analysis of whole-rock powder using a PANalytical Powder

XRD operating at 40 kV and 45 mA with monochromated Co K_{alpha} radiation (100.9650 secs/ 0.0170° step).

Samples for trace element analysis were powdered using a Siebtechnik disc mill, then stored in 50 ml centrifuge tubes. The samples were analysed by the Saskatchewan Research Council, Saskatoon, using PerkinElmer Optima 4300DV or Optima 5300DV ICP-MS instruments. An aliquot of pulp was digested to dryness in a hot block digestion system using a mixture of ultra-pure concentrated acids HF, HNO₃, HClO₄. The residue was dissolved and made up to volume using deionized water prior to analysis. Total digestion and analysis were performed on samples to determine the dilution required prior to analysis.

Enrichment factors (EF) were determined by normalizing selected trace elements to Al, which represents a proxy for the detrital fraction, and comparing those ratios to “average shale”. The EF is equal to $(\text{Element}/\text{Al})_{\text{sample}}/(\text{Element}/\text{Al})_{\text{shale}}$, where the ratio in the numerator is that for the shale in question, and the ratio in the denominator is that for a ‘typical’ shale (Tribovillard et al., 2006; using data from Turekian and Wedepohl, 1961; Wedepohl, 1971).

Total organic carbon (TOC) and $\delta^{13}\text{C}$ analyses of carbonate-bearing samples were measured on samples that were first acidified to remove carbonate material. The residue was then homogenized and loaded into tin capsules. Stable isotope values were obtained using a Thermo Finnigan Flash 1112 EA coupled to a Thermo Finnigan Delta Plus XL through a Conflo III. Samples were dropped under helium into an oxidation furnace packed with chromium (VI) oxide and silvered cobaltic/cobaltous oxide (to remove any halogens) at 1000°C. Organic material was oxidized to CO₂, various nitrogen-bearing gases, and water. This gas was then passed through a reduction furnace packed with elemental copper at 680°C to reduce all nitrogen-bearing compounds to pure gaseous nitrogen. The resulting gases were then passed through a water trap to eliminate moisture. A GC column at 50°C then followed to unmix the carbon dioxide and nitrogen gases for analysis in the mass spectrometer. Data were blank-corrected. Carbon isotope ratios were corrected for ¹⁷O contribution using the Craig correction, and reported in per mil notation relative to the V-PDB scale. Carbon data were calibrated against the international standards L-SVEC ($\delta^{13}\text{C} = -46.6\text{‰ VPDB}$) and IAEA-CH6 ($\delta^{13}\text{C} = -10.45\text{‰ VPDB}$). IAEA-CH7, an intermediate international standard, gave the following result during

calibration of the in-house standards: $\delta^{13}\text{C} = -32.15 \pm 0.04\text{‰}$ VPDB ($n = 11$), compared to the accepted value of $\delta^{13}\text{C} = -32.15 \pm 0.10\text{‰}$ VPDB. The precision of $\delta^{13}\text{C}$ measurements is 0.12‰ ($n = 18$). The %C measurements have a precision of $\pm 10\%$ of the reported percentage. Percentage data are reported by mass.

2.5 Observations

2.5.1 Lithofacies

The Rockslide Formation at the Ravens Throat River location is subdivided into five facies: (1) black shale; (2) lime mudstone; (3) debris-flow breccia; (4) calcareous mudstone (containing the BST preservation); and (5) dolomitic lime mudstone. The Rockslide Formation is thinner than the type section at this location (175 m), but is the only location known where BST preservation occurs.

Facies 1: Black shale.—The base of the Rockslide Formation consists of a 20 m thick, thin-bedded, dark grey to black calcareous shale, which overlies the Sekwi Formation abruptly. Planar laminae are variably rich in silt and rounded very fine sand (Fig. 2.4A). The shale (one sample) is composed of calcite (49%), quartz (22%), clinocllore (22%), and illite (7%). The basal beds are rich in disarticulated trilobite sclerites belonging to *Ogygopsis klotzi* and other ptychoparioid and eodiscoid trilobites along with lingulate brachiopods.

The facies is interpreted to have been deposited in a deep-water environment, involving suspension settling of clay, silt and lime mud. The trilobite and brachiopod fauna indicates sporadic benthic colonization. However, the trace-element composition indicates anoxic bottom waters (see ‘Geochemistry’ below).

Facies 2: Lime mudstone.—Thin- to medium-bedded, wavy and lenticular beds of silty lime mudstone comprise the bulk of the Rockslide Formation. They are intercalated with layers of laminated silty micrite and uniform micrite without lamination or gradation (Fig. 2.4B, D). Trilobite and agnostoid sclerites and lingulate brachiopod valves occur rarely, mostly in a convex-upward orientation. A highly fossiliferous horizon is present 133 m above the base, just below the lowest interval of

facies 4. In places, the lime mudstone is interlayered with dolomitic mudstone laminae, producing the 'ribbon limestone' fabric commonly encountered in Cambrian carbonate units. Lime mudstone (two samples from the middle interval) is composed of calcite (73%) and quartz (17%), with minor dolomite (7%) and illite (3%); 133 m above base, a bed containing neomorphic bladed calcite is composed of calcite (60%) and quartz (32%), with minor amounts of clinocllore, illite and pyrite. The lime mudstone is variably interbedded with black shale between about 20 to 40 m above base. Intervals of lime mudstone are separated by a number of debris-flow breccia beds (facies 3).

This facies reflects deep-water conditions, involving suspension fall-out of lime mud, silt and clay. Fossils represent sparse in situ populations that established themselves from time to time; low-velocity bottom currents oriented the sclerites into the stable position. Dysoxic to anoxic conditions are indicated by trace element composition (see 'Geochemistry' below).

Facies 3: Debris-flow breccia.—Erosive based, thick-bedded breccias range from 0.5 to 3 m thick and punctuate intervals of lime mudstone (facies 2). Clasts range from millimetres to about 10 centimetres across, and are subangular, tabular to equant to irregular in shape (Fig. 2.4C). Clasts include lime mudstone and sandy peloidal and oolitic grainstone. Both clast- and matrix-supported fabrics are present; the matrix is silty and sandy lime mudstone with rare trilobite bioclasts.

These beds represent sporadic debris-flows caused by collapse of beds of lime mud and weakly cemented sediments further upslope. Because most clasts are lime mudstone, similar to the host intervals, transport distance was probably small. These events might have been caused by storms and/or tectonic activity. The latter is favoured by the deeper water setting.

Facies 4: Calcareous mudstone.—This facies is greenish and hosts the BST preservation. It consists of planar-laminated, variably silty claystone containing scattered pyrite crystals up to several millimetres across, and rare lenses up to 100 μm wide containing small framboids. In thin section, mudstone laminae are variably distinct, commonly graded, and locally show deformation in the form of tiny folds or sheared domains a few millimetres in size; it is possible that some of these are millimetre-sized burrows (2.5B; see below). Discontinuous planar seams and flakes of

organic matter are common. Lenticular very thin laminae and dispersed silt-sized calcite crystals and angular silt grains are locally present. The laminae vary in their proportion of clay, organic matter and calcite. The mudstone is composed of quartz (~35%), illite (~30%) and clinochlore (~20%), plus calcite and dolomite (~10%) and pyrite. Interbedded are lighter grey-coloured laminae, thin beds and concretionary lenses of lime mudstone (facies 2) containing more quartz (~50%) and carbonate minerals (~20%). The calcite is microspar from recrystallization. Large pyrite crystals commonly replace larger calcite spar crystals.

Ptychoparioid trilobites and agnostoids are present and preserved in three dimensions, whereas the soft-bodied fossils show little to no relief. Most of the latter ones only preserve more robust parts (Kimmig and Pratt, in press).

This facies is interbedded with facies 2 and 3 and was therefore likely deposited under similar deep-water conditions.

Facies 5: Dolomitic siltstone.—Overlying the BST deposits at the top of the exposed section is a >10 m-thick unit of thin-bedded reddish-stained, buff-weathering dolomitic siltstone (Fig. 2.4E) composed of quartz (35%), calcite (27%), dolomite (15%), sanidine (10%), illite (8%), clinochlore (5%) and local pyrite cubes. The beds show flaggy weathering with irregular surfaces preferentially dolomitized. The beds are internally non-laminated, argillaceous and contain scattered trilobite sclerites and lingulate brachiopod valves.

2.5.2 Fossil preservation

The biota in the lower fossiliferous calcareous mudstone consists of bivalved arthropods, trilobites, agnostoids, worms, hyoliths and macrophytic algae (Fig. 2.6). The arthropods are the most diverse component of the biota, while most specimens recovered from the Lagerstätte belong to the hyolith *Haplophrentis carinatus* and the macrophytic alga *Margaretia dorus*. The bivalved arthropods, worms and algae are preserved mostly as dark-grey to black carbonaceous films. Most bivalved arthropods are represented by single valves, The margins of some of these (twelve specimens) are not smooth but are cusped, which may be scavenging traces, while others are only partially preserved (Fig. 7 A–F). Most specimens are flattened (~85%), which generated concentric wrinkles. Some hyoliths are complete, but about 80% are

missing the helens and about 40% are represented only by the conch without the operculum. Most worms are decomposed and cannot be identified to phylum level. Most trilobites and agnostoids are articulated and most are uncompact. *Margaretia dorus* thallus fragments in the upper fossiliferous calcareous mudstone at about +165 m, where they comprise most of the biota, are preserved with some positive relief showing the characteristic network of lozenge-shaped indentations.

5.5.3 Ichnology

The lime mudstone facies lacks burrows and other evidence of bioturbation. The dolomitic siltstone overlying the Lagerstätte-bearing interval contains fine sand- and silt-filled simple burrows 2 mm in diameter that meander horizontally and vertically. They are assigned to *Palaeophycus*.

The fossiliferous calcareous mudstone yields only a few larger feeding and burrowing traces, including very rare *Rhizocorallium*-like burrows about 3 cm long and 1.5 cm wide (Fig. 2.8D). These burrows are about 0.5 mm wide and the Spreiten are marked by fine arcuate organic lines.

Under two of the more than 50 non-biomineralized arthropod valves collected are groove-shaped, simple burrows between 0.5 and 1 mm wide and several centimetres long (Fig. 2.8 A, B). Possible bifurcation is likely due to intersection rather than true branching. They resemble the structures described from below arthropod valves in other BST deposits (Zhang et al., 2007; Mángano, 2011; Mángano et al., 2012), but they are wider and longer. The groove-shape indicates that the burrows remained open and the carapace was compacted and deformed downwards.

Laminae deformed at the millimetre scale are fairly common in the calcareous mudstone. Some examples are elliptical to lenticular in cross-section, while others show domains where the laminae are overthrust and pulled apart (Fig. 2.5F). Most appear to be from bioturbation, but some may represent small soft-sediment deformation features triggered by seismic activity under shallow burial before significant compaction.

2.5.4 Geochemistry

2.5.4.1 Redox-sensitive trace elements.—Aluminium falls between 5 and 9% and is similar to “average shale” composite standards (Turekian and Wedepohl, 1961). The trace-element data for the fossil beds and the other lithofacies (Table 2.1), in the context of the Enrichment Factor (EF) in order to account for the detrital bias (Table 2.2), show variable enrichment of most elements, but neither of the major redox-sensitive metals (U and V) shows a correlation with Al, suggesting that they are not of detrital origin. The shales of the calcareous mudstone are slightly enriched in Co (average EF=3.4), but two beds above the lower fossiliferous unit at +136.06 m and +136.76 m show higher enrichment (EF of 7.39 and 6.94, respectively). On the other hand the calcareous mudstone overall is variably depleted in Mo (avg. EF=0.27), Cu (avg. EF=0.41), Ni (avg. EF=0.53), Pb (avg. EF=0.14) and Zn (avg. EF=0.85). Cr, Sc, U and V are at “average shale” level (Wedepohl, 1971). Uranium enrichment generally happens during redox conditions typical of sulfate reduction in marine environments, while V enrichment occurs under conditions of nitrate reduction (Jones and Manning, 1994; Piper and Isaacs, 1995; Maloof et al., 2010). No obvious co-variation with organic matter is exhibited (Fig. 2.9), but this might be due to the narrow spread of the observed TOC values (McKirdy et al., 2011). The bed at +136.06 m is enriched in all trace elements compared to other beds (Table 2.1). These enrichments are minor, but do not necessarily indicate a dysoxic water column, because most trace elements are depleted compared to “average shale”.

2.5.4.2 Carbon.—The amount of C_{carb} in the fossiliferous beds is low (0.2–0.4%; Table 2.1), with slightly higher values in the interbedded lenses of lime mudstone. Dolomite is the dominant carbonate in the fossiliferous unit. TOC values are low with a mean of 0.16% (0.10–0.22%; Table 2.1).

TOC values are similar to the Burgess Shale (0.11–0.42%; Butterfield, 1990; Powell et al., 2003; Powell, 2009) and the age-equivalent Marjum Formation (~0.14%; Smith, 2007). The thermal alteration of the Ravens Throat River Lagerstätte appears to be lower than that of the Burgess Shale, suggesting that the primary TOC value was around 1.5% (Powell, 2003; McKirdy et al., 2011). That TOC content is too low to have accumulated under stable anoxic or dysoxic conditions, even after accounting for a primary TOC level of 1.5% (e.g., Algeo and Maynard, 2004). Sedimentary organic matter is preferentially preserved in oxygen-depleted bottom waters (Demaison and Moore, 1980), although increased organic matter can also be

related to enhanced productivity in the photic zone (Calvert, 1987), and suitable sedimentation rates.

Samples from the fossiliferous unit show no correlation between $\delta^{13}\text{C}_{\text{org}}$ and TOC (Fig. 2.10) suggesting that porosity- and permeability-dependent contamination associated with migrating hydrocarbons (Maloof et al., 2010) was not a factor in this case.

The organic carbon preserved in the fossiliferous unit has a bulk stable isotopic composition of ($\delta^{13}\text{C}_{\text{org}} = -24.6$ to -22.3‰ , mean = -23.2‰ ; Table 2.1). This is slightly higher than the lower Cambrian (Series 2) Emu Bay Shale of Australia and the Series 2–3 Kaili Formation of China (Guo et al., 2005; McKirdy et al., 2011), but the results fit within the range of middle Cambrian average values (Hayes et al., 1999). The associated facies have lower values, between -24.91‰ and -25.25‰ .

2.6 Discussion

Redox status reconstructions of BST Lagerstätten permit estimates of the oxidation state of the water column (e.g., Powell et al., 2003; Rimmer, 2004; McKirdy et al., 2011; Garson et al., 2012; Guo et al., 2014; Farrell et al., 2013; Le Boudec et al., 2014). The redox-sensitive trace element ratios, U/Th, V/Cr and V/Sc, suggest that the Burgess Shale and the Emu Bay Shale were deposited under oxic conditions, questioning the widely held notion that soft-bodied preservation required anoxic bottom waters.

2.6.1 Rockslide Formation

The depositional environment of the Rockslide Formation at the Ravens Throat River Lagerstätte was a relatively deep-water, low-energy setting. The presence of debris flows indicates that the depositional environment was a slope, and stratigraphic relationships suggest that the shallow-water platform lay to the east. The lack of evidence for oscillatory currents indicates that the slope was below storm wave base. The lower part of the Rockslide Formation is characterized by black shale and lime mudstone, recording clay and carbonate mud derived from the platform. Detrital zircons in Cambrian sandstones in the Mackenzie Mountains imply local derivation

from Neoproterozoic strata exposed in the Mackenzie Arch (Hadlari et al., 2012). Clay input eventually declined, leading to deposition of variably silty lime mudstones from sediment plumes washed off the platform triggered by storms (Coniglio and James, 1990; Lubeseder et al., 2009). Episodic down-to-basin movement along the listric fault appears to have ceased when the fossiliferous calcareous mudstones were deposited in the upper part of the Lagerstätte exposure. The two greenish fossiliferous calcareous mudstone intervals represent an anomalous facies in this lime mudstone-dominated succession, and are localized to this locality. It is uncertain, however, if this was due to the persistence of a depression caused by movement along the fault. Lime mud-depositing events, however, continued during these intervals because they recorded by thin interbeds and nodules of lime mudstone. The *in situ* nature of the fauna is indicated by articulated hyoliths, agnostoids and trilobites.

Sedimentation was discontinuous, as shown by the lamination, varying lithology and the evidence for scavenging of arthropod carapaces while they were exposed on the seafloor. The planar-laminated mixtures of clay, silt and lime mud, comprising the fossil-bearing host beds, indicates low-energy depositional events, from either hemipelagic fall-out from sediment plumes, turbidity currents or contour currents. If the laminae represent Bouma E divisions, there should be evidence for more complete turbidites in the succession. However, none has yet been observed. Contour currents might have existed in the Selwyn Basin. The silty and muddy contourite types (Stow et al., 2002) are similar to the calcareous mudstone facies. However, contour currents represent long-lived conditions of oceanic circulation, and therefore do not explain the limited extent of this facies.

The variable amounts of organic matter, especially as discontinuous carbonaceous seams and flakes, imply a combination of water-column productivity and benthic microbial mats. The lack of bioturbation in the lime mudstone interbeds likely reflects rapid sedimentation rates or possible dysoxic conditions.

Trace elements in the fossiliferous calcareous mudstone of the Ravens Throat River Lagerstätte are mostly depleted or close to “average shale” values (e.g., Rudnick and Gao, 2005; Tribovillard et al., 2006). The element ratios for U/Th and V/Cr both imply continuously oxygenated bottom waters, whereas V/Sc indicates suboxic conditions (Fig. 2.11). This suggests that the bottom waters were mostly oxygenated with periods of dysoxia. Assuming that the V/Sc ratio was not disturbed by rapid sedimentation events (Tribovillard et al., 2006), it is possible that episodic

dysoxia led to a lower faunal diversity in the Ravens Throat River Lagerstätte, compared to most other Cambrian BST examples. The oxic/anoxic boundary must have been at, or just beneath, the sediment–water interface.

2.6.2 Comparison

The fossils in the Burgess Shale were interpreted to represent a fauna that was transported from shallower water (e.g., Whittington, 1985). However, subsequent taphonomic analysis suggests that the biota is *in situ* and represents a primary community (Jackson and Caron, 2006; O’Brien and Caron, 2012). Investigations of other BST deposits suggest that they also host *in situ* biotas: Emu Bay (Gehling et al., 2011); Wheeler and Marjum formations (Briggs et al., 2008); Sirius Passet (Babcock and Peel, 2007); and Chengjiang (Zhang et al., 2001).

Earlier interpretations of the Burgess Shale concluded that the sediments consist of turbidites (e.g., Piper, 1972), thus supporting the hypothesis of rapid burial which led to exceptional preservation (Piper, 1972; Allison and Brett, 1995). This interpretation has been challenged. Gabbott et al. (2008) proposed that rapid sediment deposition was from mud-rich semi-continuous density currents. Similar to the Burgess Shale, most BST deposits have been deposited as laminated mudstones that do not show indicators of turbidites, especially ripples and distinct graded bedding. The Emu Bay shale has some evidence of syndepositional deformation, but is considered to have been deposited under continuous sediment supply without significant influence of bottom currents (Gehling et al., 2011). Similar to the Burgess Shale, the fossils in the Marjum and Wheeler formations are preserved in mostly non-bioturbated fine-laminated shales and were likely deposited by turbidites (Gaines et al., 2005; Brett et al., 2009). The host sediments of the Chengjiang biota are greenish-grey mudstones in unweathered samples that have been interpreted variously as episodic turbidity currents (Lindström, 1995), storm beds (Babcock et al., 2001), or sediments from rapid deposition of suspended mud (Zhu et al., 2001).

It has long been assumed that bioturbation is inimical to soft-bodied BST preservation (Allison and Briggs, 1991). It is now recognized that burrows are present in such units, including for example the Chengjiang and Sirius Passet Lagerstätten (Zhang et al., 2007; Mángano, 2011; Gaines et al., 2012b; Mángano et al., 2012). Two arthropod valves from the Ravens Throat River Lagerstätte preserve burrows below

the carapaces. However, the fossiliferous calcareous mudstone appears to show common millimetre-sized burrows, whereas the unfossiliferous lime mudstone beds are unburrowed. Thus, the presence or absence of bioturbation does not necessarily correspond to anoxic conditions in the water column or in the sediment, as previously suggested (e.g., Caron and Jackson, 2006), but may reflect local sedimentation rate, food availability and other factors (Buatois and Mángano, 2011).

The fossiliferous calcareous mudstone of the Ravens Throat River Lagerstätte is similar to the Burgess Shale in that it is composed of graded, planar laminated, illite, chlorite, silt and carbonate, along with characteristic pyrite lenses as in the 'phyllopod bed'. The fossils imply a similar degree of compaction (~85%; Whittington, 1985). The sediments present an unusual medium that was conducive to BST-style preservation (Wilson and Butterfield, 2014).

Gaines et al. (2012a) suggested that early carbonate cementation was part of the process of soft-bodied preservation because they believed it sealed the sediment and fossils from decay. However, in the Ravens Throat River Lagerstätte the laminae are compacted, indicating that near-surface lithification did not occur. The exception is calcium carbonate cementation in concretionary lime mudstone layers, but these do not host soft tissue preservation. In the Burgess Shale, slump folds at The Monarch, and small-scale synsedimentary deformation on Mount Field (BRP, unpub. obs.) refute this interpretation.

In common with other middle Cambrian mudstones (Hayes et al., 1999; Guo et al., 2005; Kouchinsky et al., 2012) the $\delta^{13}\text{C}_{\text{org}}$ values are around -20‰ and show only minor variation between the calcareous mudstone and other facies in the succession (Table 2.1). McKirdy et al. (2011) interpreted the $\delta^{13}\text{C}_{\text{org}}$ signature in the Emu Bay Shale and other Australian Lagerstätten as an indicator of cyanobacterial origin, with values similar to those of modern cyanobacteria (Brady et al., 2013). The minor difference in values likely are due to the up to ~10% dolomite in the calcareous mudstones (Hayes et al., 1999). Thus, the majority of the C_{org} remaining the calcareous mudstone is interpreted to be of cyanobacterial origin, mostly from water-column productivity. No biomarkers or aromatic hydrocarbons remain preserved, however, which would be able to elucidate the contributions of various groups, especially additional elements such as sponges.

Clays might have played a role in preservation of fossils (Butterfield et al., 2007; Wilson and Butterfield, 2014), as the host rock contains about 50% illite and chlorite. Butterfield (1995) argued that Fe-rich clays might be involved in deactivating degradative enzymes, but they might represent evidence for enhanced Fe²⁺ availability in early Paleozoic seas, that stabilized the substrates and increased the preservation potential (Wilson and Butterfield, 2014). The lack of most soft tissue preservation in the Ravens Throat River Lagerstätte indicates that this mechanism, if viable, did not halt decay to the same degree as seen in the Burgess Shale.

The high proportion of chlorite in the calcareous mudstone, as well as the Burgess Shale, in contrast to some other Cambrian shales that do not exhibit BST preservation, is still suggestive of a taphonomic influence of this clay mineral. Powell (2003) assumed that the origin of the chlorite in the Burgess Shale was due to metamorphic overprinting. On the other hand, illite and chlorite can also be formed by hydrothermal fluids (e.g., Hermann and Hill, 2001; Meunier and Berne, 2004) or can be derived from older strata. However, the high illite content (~30%) of the Ravens Throat River Lagerstätte BST sediments, as well as a lack of mica, indicate that lower greenschist metamorphism was not achieved. There is no evidence for hydrothermal fluid entry into this locality, even though there was synsedimentary fault activity. Thus, the chlorite in the calcareous mudstone is likely sedimentary. Considering that volcanic deposits of Cambrian age have been reported in the Selwyn Basin region (Gordey and Anderson, 1993; Moynihan, 2013), chlorite could have originated from weathering of basalts in those areas. It is also possible that much of it could be from erosion of Neoproterozoic igneous rocks belonging to the Franklin sills, well to the north of the Ravens Throat River Lagerstätte. The illite component was likely derived from erosion of underlying Proterozoic sedimentary successions comprising the Mackenzie Mountains Supergroup and older units, as well as the exposed Precambrian Shield (cf. Weaver, 1989, p. 563).

2.7 Conclusions

The middle Cambrian (Drumian) Rockslide Formation in the Mackenzie Mountains of northwestern Canada is a deep water succession of shales, mudstones and limestones deposited on a slope seaward of a mixed siliciclastic-carbonate platform. In a single locality overlying a submarine listric fault scarp, two metre-thick

units of greenish, laminated calcareous mudstone yield a low-diversity biota that includes bivalved arthropods, trilobites, agnostoids, worms, hyoliths and macrophytic algae. Preservation of non-mineralized components places these beds into the family of Burgess Shale-type Lagerstätten, and the fossil-bearing facies is closely similar. Trace-element data indicate that the bottom waters were oxygenated during the Burgess Shale-type deposition, but there may have been occasional dysoxic episodes. Despite the presence of bioturbation, the more robust components of the soft tissues were preserved. Thus, burrowing, by itself, likely did not have a primary effect on Burgess Shale-type preservation.

Consequently, it is the anomalous nature of the host sediment that holds the key to Burgess Shale-type preservation. The specific mixture of lime mud, quartz silt and clay minerals—chlorite and illite—presented a unique medium that slowed decay of buried carcasses. Exactly how it operated is still unclear. Nevertheless, early carbonate cementation was not observed associated with the fossils and therefore cannot be invoked as a means to seal the sediment and prevent further decay, at least at this location.

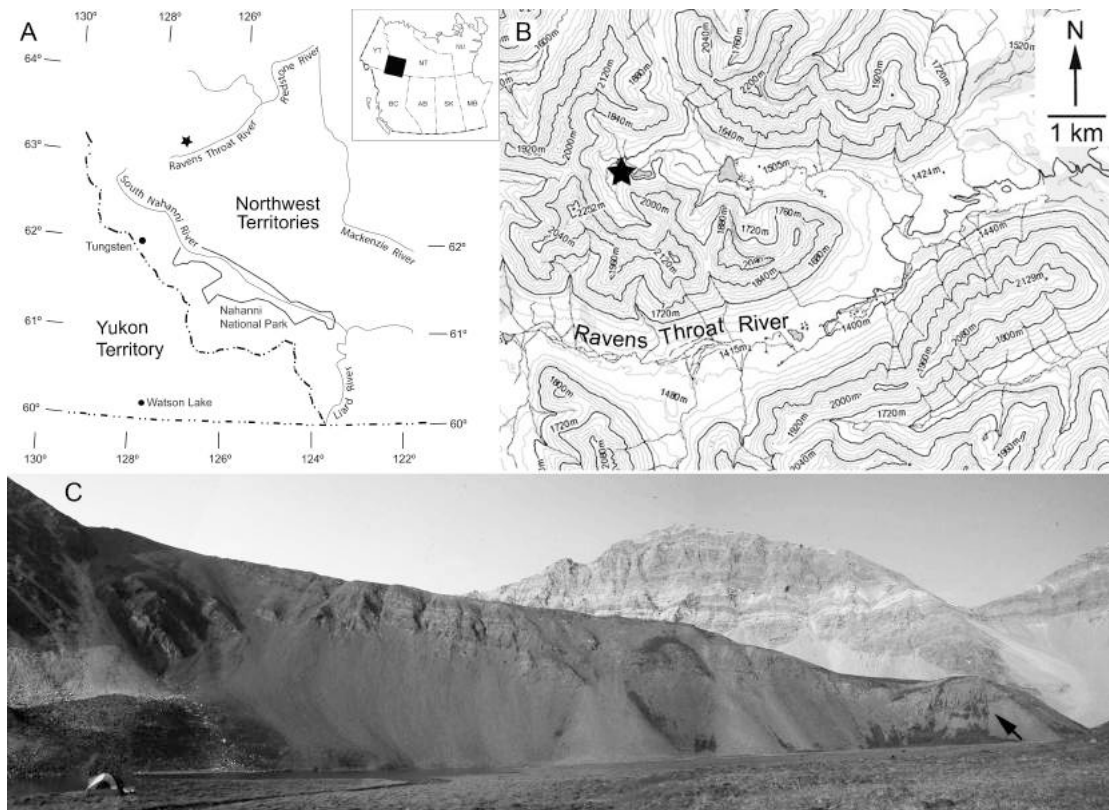


FIGURE 2.1—A, Location of the Ravens Throat River locality (asterisk; $63^{\circ}10'N$, $127^{\circ}55'W$), Mackenzie Mountains, Northwest Territories, Canada; B, topographic map of location; C, Panorama of the outcrop area near the headwaters of the Ravens Throat River looking west (arrow indicates location of geochemical samples).

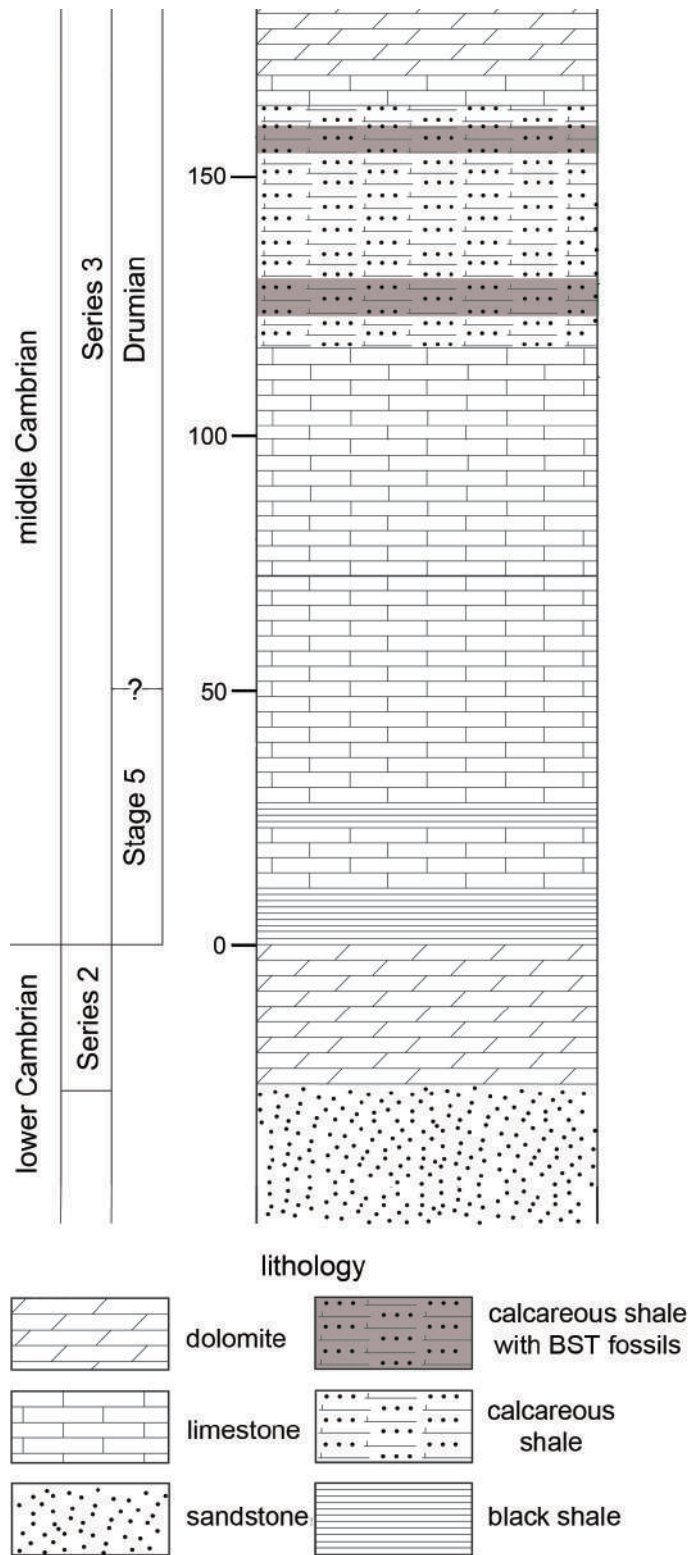


FIGURE 2.2—Generalized stratigraphy of the Rockslide Formation in the Ravens Throat river area. Grey-coloured intervals contain BST fossils, mostly in the lower one.

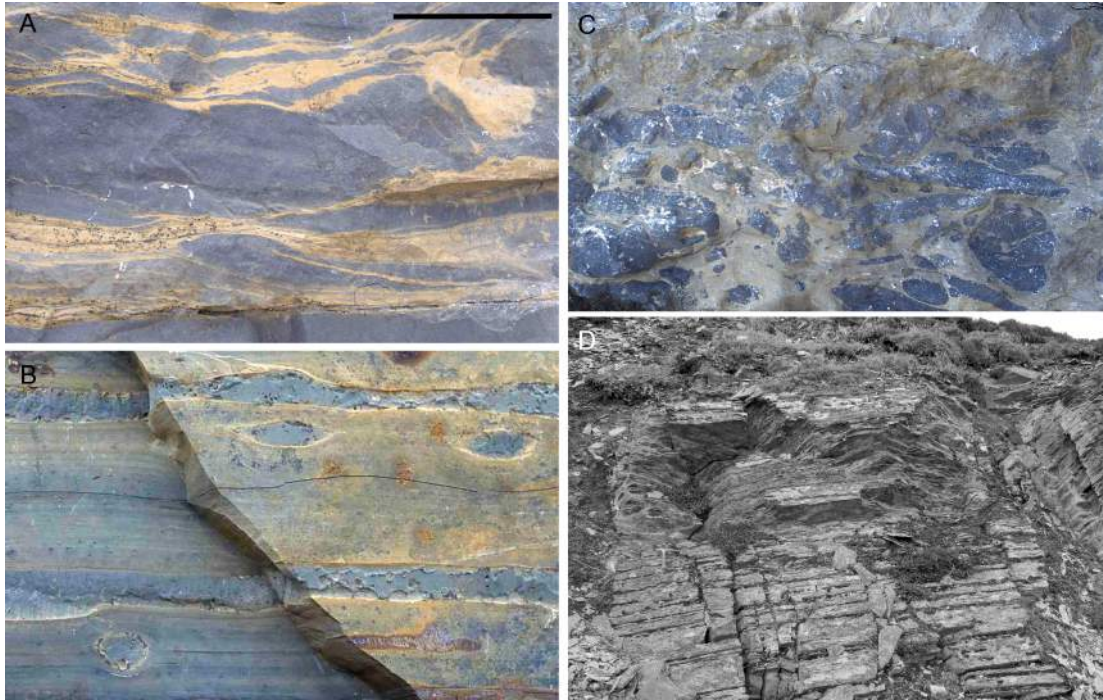


FIGURE 2.3—Photographs of the different lithofacies of the Rockslide Formation at the Ravens Throat River Lagerstätte. A, Lime mudstone (‘ribbon limestone’) at +110 m. B, Calcareous mudstone with interbedded lime mudstone beds and lenses at +136 m. C, Debris-flow breccia at +73 m. D, Outcrop photograph of the lower calcareous mudstone beds at +135 m – +137 m. Scale bar is 10 cm for A–C.

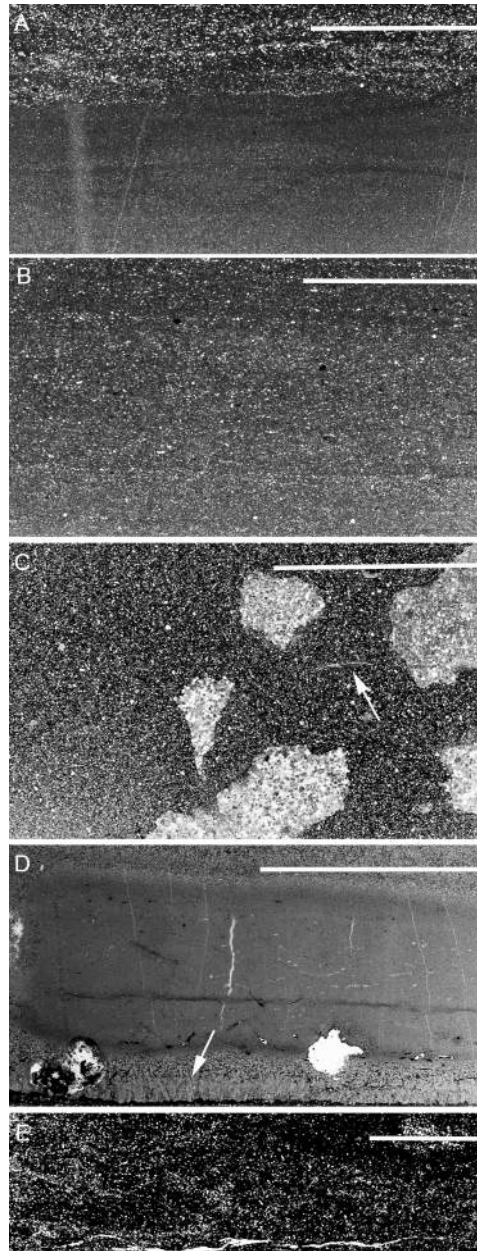


FIGURE 2.4—Thin-section photomicrographs of lithofacies in the Rockslide Formation. A, Black shale at +7 m consisting of plane-laminated claystone erosively overlain by indistinctly cross- and plane-laminated silty claystone. B, Lime mudstone with planar lamination at +35 m. C, Debris-flow breccia at +102 m consisting of angular granules of peloidal grainstone (pelsparite) in lime mudstone matrix with trilobite sclerite (marked by arrow). D, Lime mudstone at 133 m, the base of the BST unit; the arrow shows the diagenetic packstone between the limestone and the mudstone. E, Dolomitic-limestone at +190 m, on top of the outcrop. Scale bars are 1 cm.

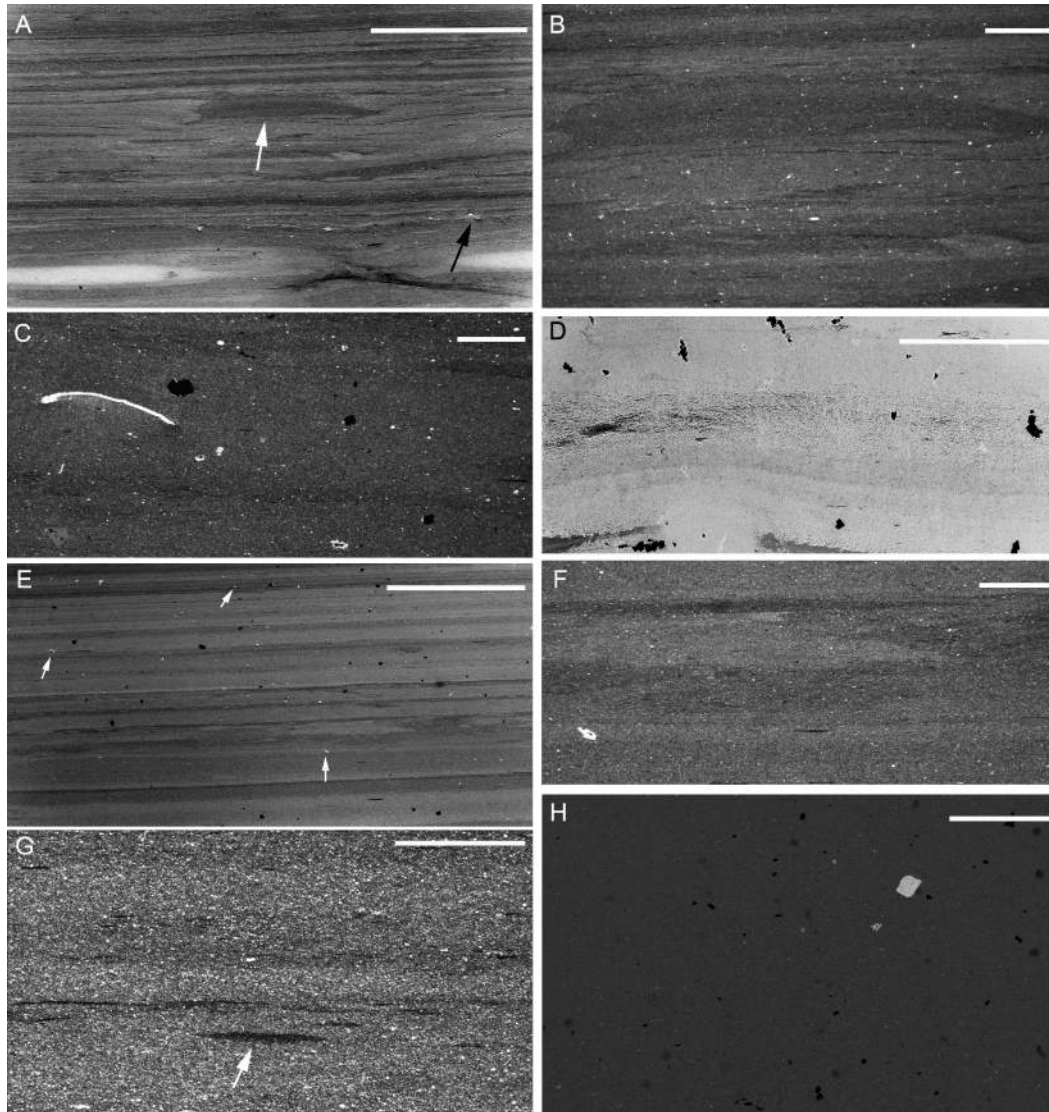


FIGURE 2.5—A-G, Photographs of the thin sections of the fossiliferous calcareous from the Rockslide Formation at the Ravens Throat River Lagerstätte. A, Calcareous mudstone facies of the fossil bed with burrow (white arrow) and trilobite fragment (black arrow) at +134.4 m. B, Close-up of A with possible burrow. C, Close-up of A with trilobite fragment. D, lime mudstone interlayer at +134.7 m. E, Calcareous mudstone facies with pyrite crystals and potential sponge spicules (white arrows) at +134.9 m. F, Close-up of E with possible burrow. G, Calcareous mudstone facies with burrow (white arrow) at +134.5 m. H, SEM photograph of the matrix of the fossiliferous calcareous mudstone. Scale bars in A, D, E, G are 1 cm, in B, C, and F are 1 mm, H is 100 μm .

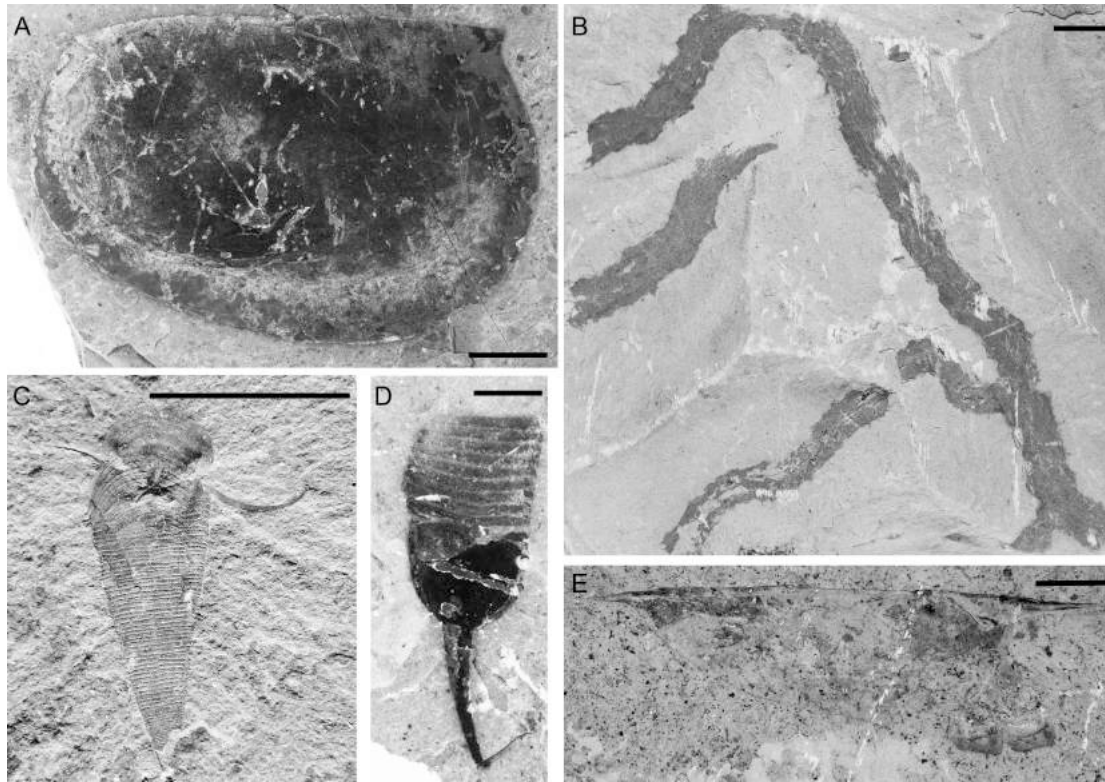


FIGURE 2.6—Ravens Throat River Lagerstätte fossils: A, *Perspicas? dilatus* (TMP 2013.101.0005); B, *Margaretia dorus* (TMP 2013.101.0132); C, *Haplophrentis carinatus* (TMP 2013.101.0058); D, Arthropod Indet. (TMP 2013.101.0035); E, *Isoxys mackensiensis* (TMP 2013.101.0038). Scale bars are 10 mm.

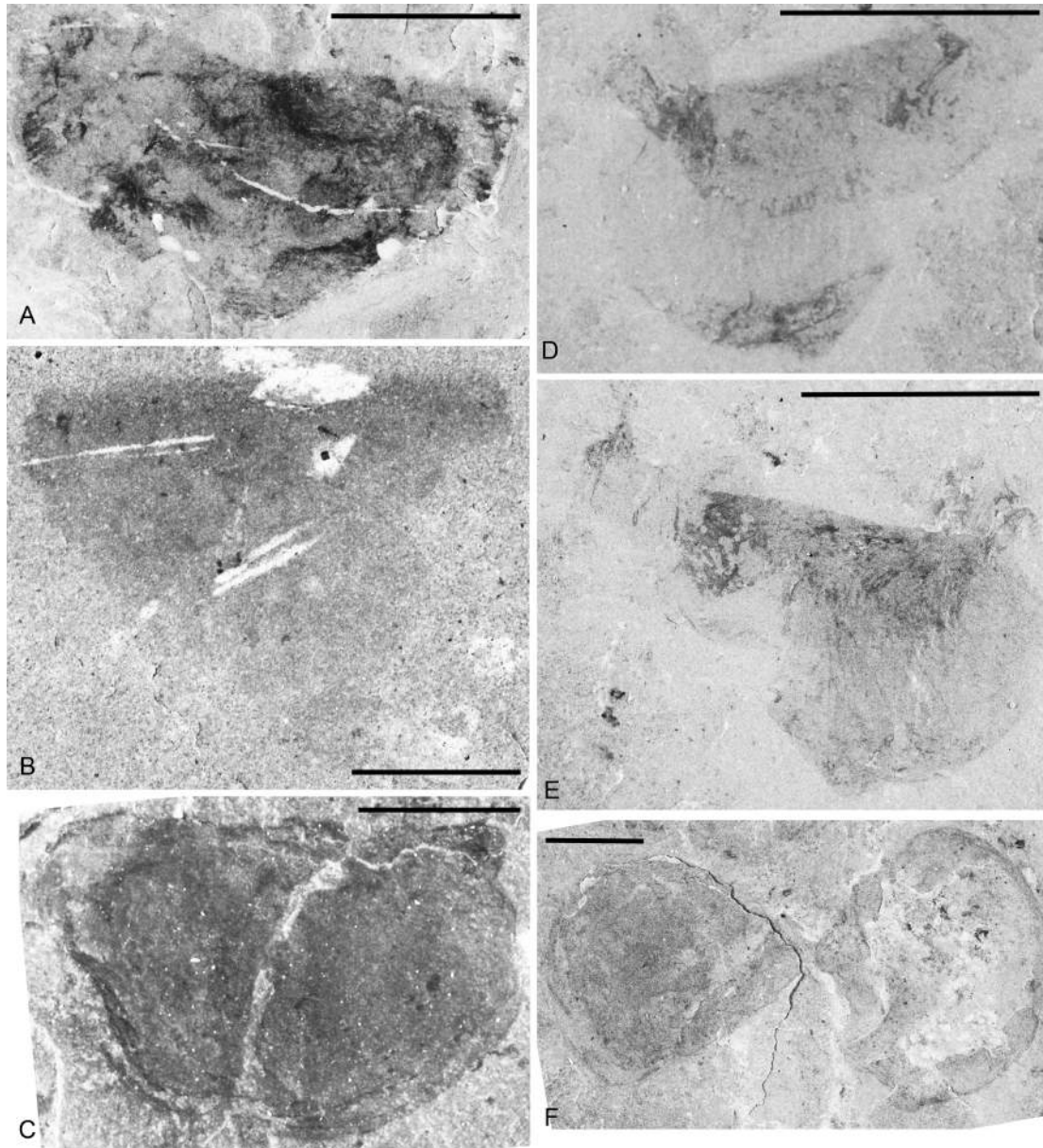


FIGURE 2.7—Photographs of partially decomposed fossils of the Ravens Throat River Lagerstätte. A, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0016). B, Arthropod indet. fragment (TMP 2013.101.0020). C, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0017). D, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0018). E, *Perspicaris? dilatus* lateral view of valve (TMP 2013.101.0023) F, *Branchiocaris? sp.* lateral views of two disarticulated valves (TMP 2013.101.0021). Scale bars are 5 mm.

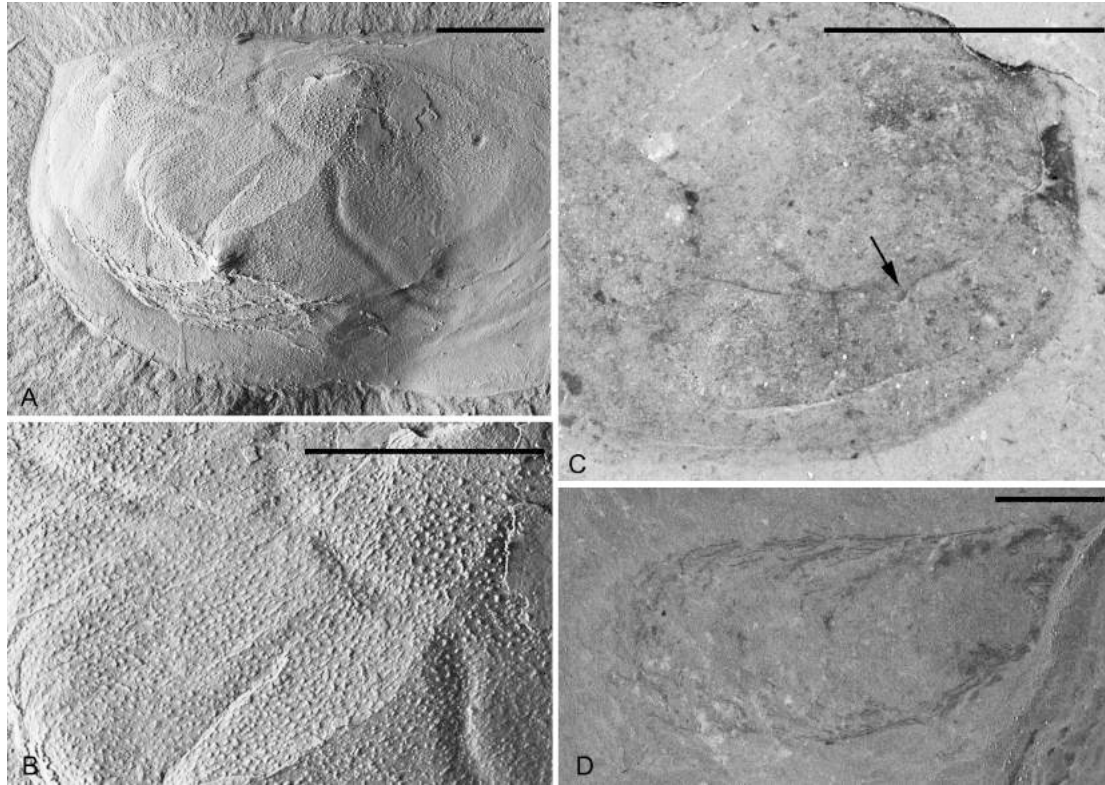


FIGURE 2.8—Trace fossils of the Ravens Throat River Lagerstätte: A, *Perspicularis? dilatus*, lateral view of valve with apparent branching burrow beneath, preserved as negative relief (latex cast dusted with ammonium chloride; TMP 2013.101.0002); B, close-up of apparent branching burrow, preserved as negative relief (latex cast dusted with ammonium chloride; TMP 2013.101.0002); C, *Perspicularis? dilatus*, lateral view of valve with burrow beneath, arrow indicates burrow (TMP 2013.101.0033); D, *Rhizocorallium? sp.* (TMP 2013.101.0303). Scale bar is 10 mm.

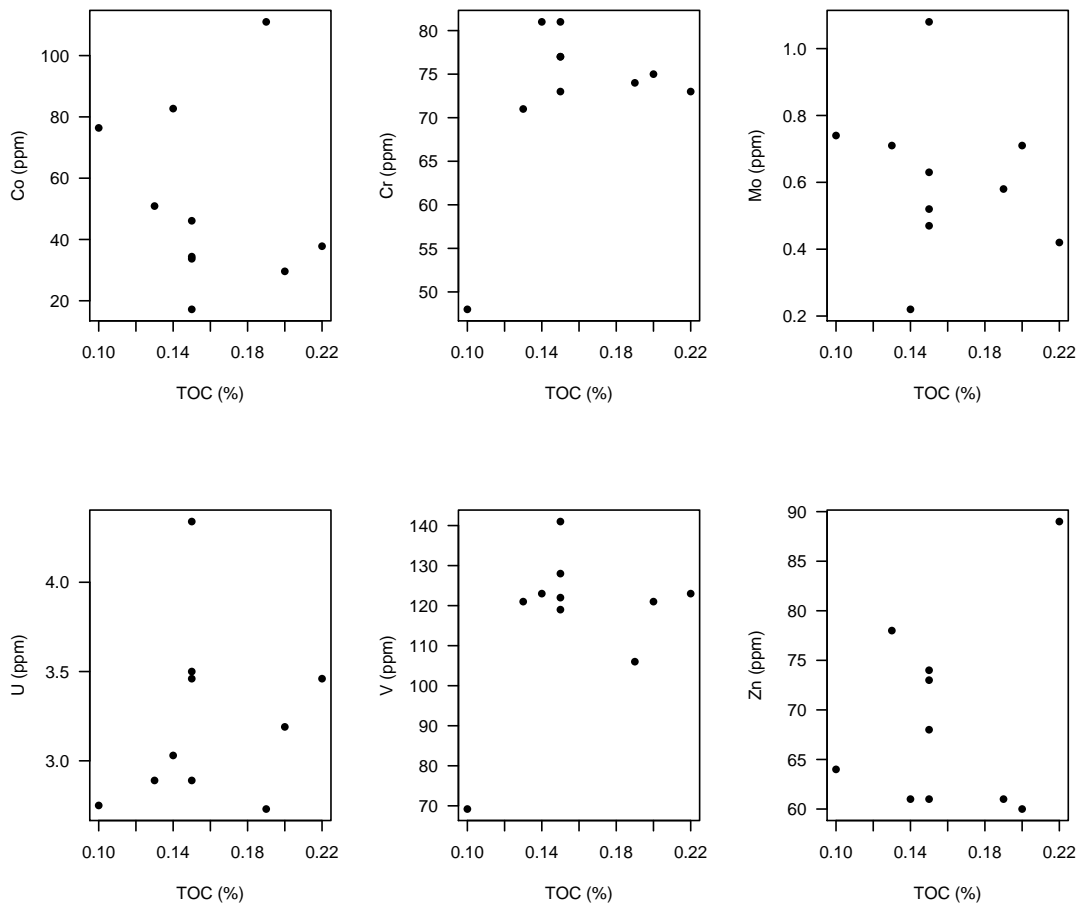


FIGURE 2.9—Relationship between total organic carbon content (TOC) and the abundance of selected redox-sensitive trace elements in the lower calcareous mudstone between 134 m and 137 m of the Rockslide Formation at the Ravens Throat River outcrop (Fig. 2.1C).

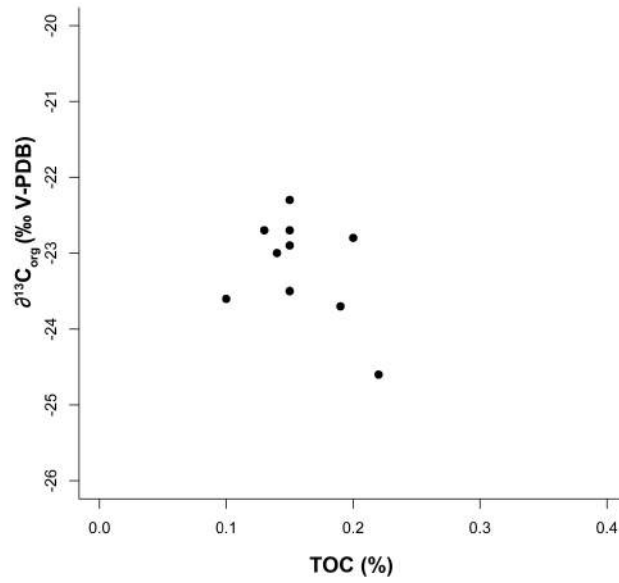


FIGURE 2.10—Relationship of total organic carbon content to the abundance of $\delta^{13}\text{C}_{\text{org}}$ in the lower calcareous mudstone between 134 m and 137 m of the Rockslide Formation at the Ravens Throat River outcrop.

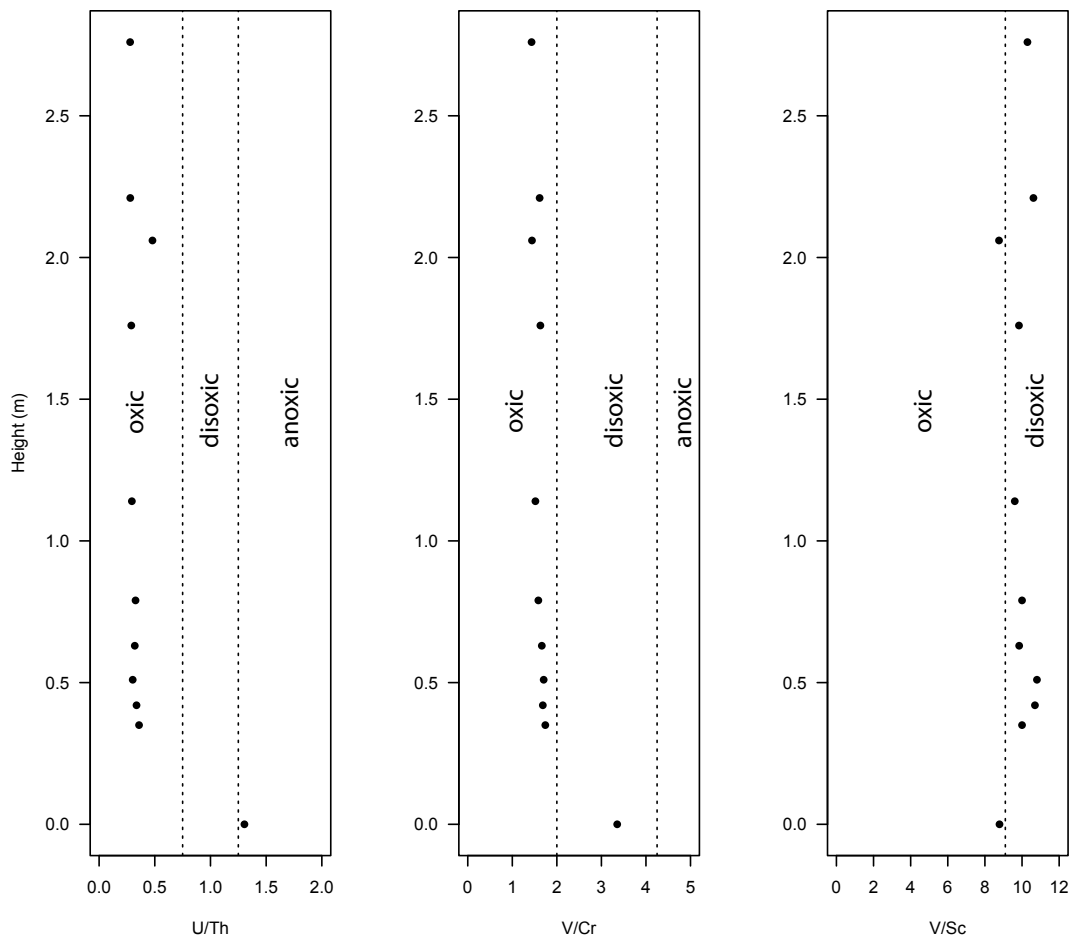


FIGURE 2.11—Chemostratigraphic profiles of redox-sensitive trace element ratios for the BST unit of the Rockslide Formation at the Ravens Throat River outcrop. Vertical subdivisions represent the redox zones of Jones and Manning (1994) and Kimura and Watanabe (2001). Height is above base of the lower calcareous mudstone at 134 m.

Unit	Height m	TOC %	$\delta^{13}C_{org}$ ‰ (V-PDB)	Sc ppm	V ppm	U ppm	Th ppm	Pb ppm	Mo ppm	Cu ppm	Co ppm	Ni ppm	Zn ppm	Cr ppm	V/Cr	V/Sc	U/Th
Black Shale	5	0.54	-24.84	7.2	234	6.32	4.24	13	6.07	16.3	22	33.6	141	44	5.32	32.50	1.49
Lime mudstone	60	0.44	-24.84	2.8	169	2.03	2.05	5.69	1.85	17.2	18.1	19.8	36	15	11.27	60.36	0.99
Debris Flow	79	0.26	-24.84	5.2	67.2	2.44	4.3	11.6	2.16	10	34.8	18.5	70	27	2.49	12.92	0.57
Lime mudstone	133	0.09	-24.25	4.2	36.9	2.14	1.64	5.39	0.88	14.4	68.4	19.8	19	11	3.35	8.79	1.30
Calcareous mudstone	134.35	0.15	-23.5	14.1	141	4.34	12.1	3.74	1.08	4.5	17.2	26.9	61	81	1.74	10.00	0.36
Calcareous mudstone	134.42	0.22	-24.6	11.5	123	3.46	10.3	3.01	0.42	15.2	37.8	35.2	89	73	1.68	10.70	0.34
Calcareous mudstone	134.51	0.13	-22.7	11.2	121	2.89	9.58	2.32	0.71	5.9	50.9	30	78	71	1.70	10.80	0.30
Calcareous mudstone	134.63	0.15	-22.7	13	128	3.46	10.8	2.5	0.47	12	33.7	29.5	74	77	1.66	9.85	0.32
Calcareous mudstone	134.79	0.15	-22.3	12.2	122	3.5	10.7	2.36	0.52	11.5	46.1	23.1	68	77	1.58	10.00	0.33
Calcareous mudstone	135.14	0.14	-23.0	12.8	123	3.03	10.3	1.85	0.22	21.3	82.7	25.4	61	81	1.52	9.61	0.29
Calcareous mudstone	135.76	0.15	-22.9	12.1	119	2.89	10	1.93	0.63	6.6	34.4	25.5	73	73	1.63	9.83	0.29
Calcareous mudstone	136.06	0.10	-23.6	7.9	69.2	2.75	5.74	2.69	0.74	50.1	76.4	53.2	64	48	8.76	0.48	1.44
Calcareous mudstone	136.21	0.20	-22.8	11.4	121	3.19	11.4	2.25	0.71	4.3	29.6	21.6	60	75	10.61	0.28	1.61
Calcareous mudstone _{2nd}	136.76	0.19	-23.7	10.3	106	2.73	9.8	2.41	0.58	5.2	111	23.3	61	74	10.29	0.28	1.43
Calcareous mudstone	164	0.24	-23.14	12.5	107	2.27	9.12	4.6	0.43	8.2	31.9	25.3	64	62	8.56	0.25	1.73
Dolomitic limestone	190	0.21	-24.91	7.2	72.8	4.38	6.63	14.8	1.56	18.2	64.2	26.5	43	40	1.82	10.11	0.66

TABLE 2.1—Trace element and organic carbon data of selected beds of the Rockslide Formation at the Ravens Throat River Lagerstätte. Height is above base of the Rockslide Formation.

Height (m)	Al (ppm)	(Co/Al) *10 ⁴	EF	(Cr/Al) *10 ⁴	EF	(Cu/Al) *10 ⁴	EF	(Mo/Al) *10 ⁴	EF	(Ni/Al) *10 ⁴	EF
134.35	86267.75	1.99	0.95	9.39	0.92	0.52	0.10	0.13	0.42	3.12	0.40
134.42	79916.75	4.73	2.25	9.13	0.90	1.90	0.37	0.05	0.18	4.40	0.57
134.51	80446.00	6.33	3.01	8.83	0.87	0.73	0.14	0.09	0.29	3.73	0.48
134.63	82563.00	4.08	1.94	9.33	0.91	1.45	0.28	0.06	0.19	3.57	0.46
134.79	78329.00	5.89	2.80	9.83	0.96	1.47	0.29	0.07	0.22	2.95	0.38
135.14	81504.50	10.15	4.83	9.94	0.97	2.61	0.51	0.03	0.09	3.12	0.40
135.76	79387.50	4.33	2.06	9.20	0.90	0.83	0.16	0.08	0.26	3.21	0.42
136.06	49220.25	15.52	7.39	9.75	0.96	10.18	2.00	0.15	0.50	10.81	1.40
136.21	78329.00	3.78	1.80	9.57	0.94	0.55	0.11	0.09	0.30	2.76	0.36
136.76	76212.00	14.56	6.94	9.71	0.95	0.68	0.13	0.08	0.25	3.06	0.40

Height (m)	Al (ppm)	(Pb/Al) *10 ⁴	EF	(Sc/Al)*10 ⁴	EF	(U/Al)*10 ⁴	EF	(V/Al) *10 ⁴	EF	(Zn/Al) *10 ⁴	EF
134.35	86267.75	0.43	0.19	1.63	1.11	0.50	1.20	16.34	1.11	7.07	0.66
134.42	79916.75	0.38	0.16	1.44	0.98	0.43	1.03	15.39	1.05	11.14	1.04
134.51	80446.00	0.29	0.13	1.39	0.95	0.36	0.86	15.04	1.02	9.70	0.91
134.63	82563.00	0.30	0.13	1.57	1.07	0.42	1.00	15.50	1.05	8.96	0.84
134.79	78329.00	0.30	0.13	1.56	1.06	0.45	1.06	15.58	1.06	8.68	0.81
135.14	81504.50	0.23	0.10	1.57	1.07	0.37	0.89	15.09	1.03	7.48	0.70
135.76	79387.50	0.24	0.11	1.52	1.04	0.36	0.87	14.99	1.02	9.20	0.86
136.06	49220.25	0.55	0.24	1.61	1.09	0.56	1.33	14.06	0.96	13.00	1.22
136.21	78329.00	0.29	0.12	1.46	0.99	0.41	0.97	15.45	1.05	7.66	0.72
136.76	76212.00	0.32	0.14	1.35	0.92	0.36	0.85	13.91	0.95	8.00	0.75

TABLE 2.2—Enrichment factors (EF) for selected trace elements in the Ravens Throat River first fossiliferous calcareous mudstone. Height is above base of the Rockslide Formation.

LINK BETWEEN CHAPTERS 1, 2 AND 3

While analysing organic films under the microprobe it became obvious, that several samples contain large amounts of elemental silver. Considering that this silver is highly enriched in these organic films, which occur only in the first fossil bed of the calcareous mudstone, it became obvious that there might be a link between these films and the accumulation of this silver. With further investigation, the possible link between the BST preservation and silver became plausible.

CHAPTER 3

SILVER IN ORGANIC FILMS IN A MIDDLE CAMBRIAN LAGERSTÄTTE, MACKENZIE MOUNTAINS, NORTHWESTERN CANADA

3.1 Abstract

Burgess Shale-type (BST) Lagerstätten are early Paleozoic deposits with extraordinary preservation. While the fossils are well known and extensively studied, the mode of preservation of these fossils is still controversial. The Ravens Throat River Lagerstätte, of Drumian age in the Mackenzie Mountains, is suitable for investigation of the ecological factors that contributed to the exceptional preservation, as it has no metamorphism. The deposit is specimen-rich, but species-poor and likely represents an ecologically somewhat inimical or stressed environment. In contrast to the well-known BST deposits, this Lagerstätte conserves mainly robust parts, even so it was deposited under an oxic to dysoxic water column similar to the Burgess Shale or the Emu Bay deposits. The sediments though conserve comparatively large amounts of organic matter, likely representing microbial mats as well as the remains of cyanobacteria that were living in the water column. On the bedding plane the visible organic remains are circular patches up to 5 cm in diameter. They occur throughout the main fossil bed of the deposit, and are found in association with trilobites and hyoliths. In many cases the associated fossils are completely preserved and appear to be in feeding position centred on the patch. The fossil bed contains a high concentration of silver (up to 0.45 ppm), and an even higher concentration in the organic patches. Elemental silver particles range in size from a few micrometres up to 300 μm . By contrast, the underlying lime mudstones are poorly fossiliferous and contain only a fraction of the silver amount (0.07 ppm). Microorganisms can play a

role in the reduction and accumulation of noble metals. and algae, bacteria and Archaea have the potential to accumulate nanoparticles from the water column. Considering the unusual, preferential accumulation of silver in organic films in the Ravens Throat River Lagerstätte, bioaccumulation can be invoked. The source of the silver is uncertain, but it may have been from penecontemporaneous metallogeny in Selwyn Basin.

Keywords: Silver, Microbial Mats, bioaccumulation, Mackenzie Mountains, Burgess Shale

3.2 Introduction

Burgess Shale-type (BST) Lagerstätten are early Paleozoic deposits with extraordinary soft-tissue preservation (e.g., Briggs et al., 1994; Edgecombe and Legg, 2013). While the fossils are well known and extensively studied, the mode of their preservation is still controversial (e.g., Butterfield, 1995; Gaines et al., 2005; Butterfield et al., 2007; Gaines et al., 2012; Wilson and Butterfield, 2014).

Most research on BST deposits has concentrated naturally on the exceptionally preserved Lagerstätten and fossils (Briggs et al., 1994; Hou et al., 2003; McKirdy et al., 2011; Vinther et al., 2011; Gaines et al., 2012a; Conway Morris and Caron, 2014). In the middle Cambrian (Drumian) Ravens Throat River Lagerstätte, by contrast, the preservation is not as good and the diversity of the biota is less (Kimmig and Pratt, in press). In this way it is more similar to the lower Cambrian Pioche Shale of Nevada and the Marjum Formation of Utah (Lieberman, 2003; Gaines et al., 2005).

Nevertheless, these differences present an opportunity to explore the paleoecology and mode of preservation.

As part of our study of the Ravens Throat River Lagerstätte, we analyzed the fossiliferous calcareous mudstone for its mineralogy, stable isotope composition of the organic carbon, and trace element geochemistry, especially to deduce the roles played by sedimentary organic matter. Indirect evidence for benthic microbial mats has been reported from other BST deposits and it has been suggested that these mats have played a key role in the preservation of the soft tissues (Briggs, 2003; Hall et al., 2011). The Ravens Throat River Lagerstätte yields different geochemical and mineralogical evidence for the presence benthic microbial mats and cyanobacteria. Some evidence for these microbial mats is found on top of coprolites found in the fossil bed. Similar microbial structures have been reported from the Lower Cambrian Indian Springs Lagerstätte in western Nevada, but in case of the Ravens Throat River Lagerstätte they also preserve elemental silver. This silver suggests a biological accumulation of this silver especially as it is very abundant in several of these microbial mats. The aim of this paper is to understand the origin, accumulation and possible environmental aspects related to the silver in the microbial structures.

3.3 Geological setting

The Rockslide Formation of the Mackenzie Mountains is a middle Cambrian (*Plagiura-Poliella* to late *Bolaspidella* or *Lejopyge laevigata* Biozone), deeper water succession of shale, lime mudstone, calcareous mudstone, and dolomitic limestone. It was deposited on the slope along the eastern flank of the Selwyn basin over a

geographic area several hundred kilometres wide (Gabrielse et al., 1973; Fritz, 1979; Pratt, 1989).

The lower part of the Rockslide Formation is correlative with intrabasinal shales of the Mount Cap Formation located farther east along the Mackenzie River valley (Dixon & Stasiuk, 1998; MacNaughton et al., 2014). These sediments yield rare examples of BST preservation (Butterfield, 1994; Butterfield & Nicholas, 1996). To the north in the Misty Creek embayment the Rockslide grades into a thick succession of deep-water sediments belonging to the Hess River Formation (Cecile, 1982; Chevrier & Turner, 2013). Towards the west the Rockslide Formation is overlain by deeper water limestones of the Rabbitkettle Formation (Pratt 1992; Gordey & Anderson 1993).

The Ravens Throat River Lagerstätte (Fig. 3.1) is the only known outcrop in the Rockslide Formation containing BST fossils. It is located near the headwaters of the Ravens Throat River, about 50 km west of the type section. The 175 m thick exposure is composed of black shale, lime mudstone, calcareous mudstone, and dolomitic limestone, along with debris flows of lime mudstone clasts with variable amounts of quartz sand. Ediacaran to lower Cambrian sandstones of the Backbone Ranges Formation and thin-bedded dolomites of the Sekwi Formation underlie the Rockslide Formation at this location. The Rockslide Formation is overlain by sandy dolomites belonging to the Avalanche Formation.

At the Ravens Throat River locality, the lower half of the Rockslide Formation onlaps a synsedimentary listric fault scarp cutting the Backbone Ranges Formation. The fossiliferous beds consist of two 1 m thick units of greenish colored, planar-laminated calcareous mudstone at +135 m and +164 m above base of the formation.

The host rock is composed of quartz, illite, chlorite, calcite and dolomite. Pyrite crystals are common (Fig. 3.4).

3.4 Materials and methods

The collected samples were cut, powdered using a Siebtechnik disc mill, and then stored in 50 ml centrifuge tubes. The trace element analyses were carried out in the laboratories of the Saskatchewan Research Council, Saskatoon (SRC), using PerkinElmer Optima 4300DV or Optima 5300DV instruments. An aliquot of pulp was digested to dryness in a hot block digestion system using a mixture of ultra-pure concentrated acids HF, HNO₃, HClO₄. The residue was dissolved and made to volume using deionized water prior to analysis. Total digestion and analysis was performed on samples to determine the dilution required prior to ICP-MS analysis.

Samples for microprobe analyses were coated with carbon. A Jeol JXA-8600 superprobe was used to determine specific minerals within the organic matter and the matrix. Outcrop and scree slope specimens were analyzed.

3.5 Results

The organic patches as carbon films are found throughout the fossil bed range from 1 to 5 cm in diameter, the majority being between 1 and 2 cm across, and are circular in outline. The surface of most patches consists of a mass of dark-grey coloured carbon 'flakes' which are more apparent on slightly weathered surfaces because the host rock has taken on a greenish-brown hue. The patches have the shape of a disk 0.5 to 1 mm thick, representing a compressed agglomeration of flakes and

mud. The flakes are more or less uniform in size in each patch, but vary from patch to patch from about 1 to 5 mm in size and up to 0.5 mm thick (Fig. 3.2). There are also isolated flakes on many surfaces. Many of the patches have hyoliths and trilobites located on them. The associated fossils are preserved articulated and appear to be in feeding position.

The fossiliferous calcareous mudstones beds are enriched in silver, containing up to 0.43 ppm, which is about four times higher than the silver content in the underlying lime mudstone (0.08–0.14 ppm; Table 1). The overlying dolomitic siltstone is also enriched (0.47 ppm), compared to ‘average shale’ values (e.g., Wedepohl, 1971). Visible euhedral crystals of silver are present on the circular carbon patches (Fig. 3.2A, B; Fig. 3.3). They range in size from a few micrometers to about 300 µm in size and there is no pattern to their distribution. Samples both freshly excavated from the fossil beds and collected from the scree slope contain these silver crystals. Several specimens of hyoliths, bivalved arthropods, trilobites and macrophytic algae belonging to *Margaretia dorus* were also analysed, but none preserved any visible silver.

3.6 Discussion

Silver has not been reported from other BST deposits (e.g., Powell et al., 2003, 2006; McKirdy et al., 2011; Yang et al., 2012; Le Boudec et al., 2014). However, syngenetic or syngenetic association of silver with fossils and organic matter has been reported from the fossil record, albeit very rarely. Some late Permian fish up to about 10 cm in length are preserved in silver in the German Kupferschiefer of the Mansfeld area, northern Hessen (Deecke, 1923; Wanderer, 1932). In these, elemental

silver has replaced preferentially the soft tissues of the fish and replicates the scales and fins before substantial decay. By contrast, soft-bodied fossils in the Ravens Throat River Lagerstätte do not exhibit silver mineralization, and it is only present on the carbon films comprising the patches. The Kupferschiefer is considered to have been deposited under constant anoxic bottom waters, similar to the conditions reported from the Black Sea (Wedepohl, 1994; Paul, 2006), whereas trace element analysis indicates that the fossiliferous calcareous mudstone of the Ravens Throat River Lagerstätte was deposited under an oxic to occasionally dysoxic water column (Chapter 2). Although the general consensus is that anoxia, at least in the sediment, is a requirement for soft-tissue preservation (e.g., Allison, 1988; Sagemann et al., 1999; Babcock et al., 2001), heterotrophic bacterial activity leads to bottom-water anoxia if productivity is high enough or mixing is limited, but this does not stop decay because the reaction changes to a slower anaerobic one (Allison, 2001; Briggs, 2003).

3.6.1. Source of silver

A number of important ore deposits occur in the Mackenzie Mountains but only two silver-bearing deposits predate or are similar in age to the Rockslide Formation (Ootes et al., 2013). The Neoproterozoic (<780 Ma) Coates Lake Group, hosts Red-bed or Kupferschiefer-type copper deposits enriched in silver in the central Mackenzie Mountains. The Zn-Pb-Ag sedimentary exhalative deposits (SEDEX) of the Anvil District in the Selwyn Basin in the Yukon Territory to the west are considered to be Cambrian in age (Goodfellow, 2007). The silver content in these deposits ranges from 36 to 84 g/t. The Lower Devonian SEDEX deposits of

MacMillan Pass also contain significant amounts of silver, ranging from 38 to 80 g/t (Goodfellow, 2007).

The low amounts of copper in the Ravens Throat River Lagerstätte suggest that erosion of the Coates Lake Group was not the likely source for the silver. It is possible, then, that the silver came from conduits under the Selwyn Basin and carried by currents eastward into the embayment. Considering the long age span of these mineral deposits, there could have been considerable potential for silver to enter the marine environment via metalliferous fluids moving up along basement faults.

Like the Kicking Horse Rim and the Burgess Shale (Powell et al., 2006; Johnston et al., 2009a), the Ravens Throat River Lagerstätte is associated with a syndepositional fault, and it is possible that silver-bearing fluids were expelled there, even though the fault itself appears to have been inactive by the time of deposition of the fossil-bearing calcareous mudstone. However, the underlying beds are not enriched in silver and there is no evidence for metallogenesis along the fault. If the fault was indeed the source of silver-bearing fluids, there could have been an evolution in their chemistry, or that the flow was pulsed.

3.6.2. Organic accumulation of silver

Preservation of microorganisms is dependent on the degree of diagenetic alteration and thermal maturation, often causing the preserved fossils to look markedly different than their original form during life, and have different chemical signals (J. Li et al., 2013, 2014; Y.-L. Li et al., 2013). Experimental studies on bacteria have shown that calcified specimens have tendency to keep their overall morphology even if higher temperatures are applied, whereas non-calcified specimens

lose their original form and appear as unidentifiable organic residues (J. Li et al., 2014). Even so it is difficult to compare experimental results with natural occurring examples in the stratigraphic record, in part due to the extensive period of geological time and consequent diagenesis involved (e.g. Vandenbroucke and Largeau, 2007). Although lime mud made up a proportion of the sediment, the style preservation of organic matter in the Ravens Throat River Lagerstätte suggests that the microorganisms that gave rise to the patches and seams in the calcareous mudstone were not calcified before fossilization.

The role of microorganisms in the reduction and accumulation of noble metals has been documented and is thought to be of importance in the creation of some ore deposits (Lovley, 1993; Kashefi et al., 2001; Southam et al., 2009). Whereas most of these studies concentrated on gold, it has been observed that microbially mediated accumulation of silver can occur in a similar way (e.g., Lovley, 1993). The mechanisms behind this accumulation are not well understood, but it has been observed that bacterially mediated processes can precipitate silver and contribute to the overall enrichment (Zierenberg and Schiffman, 1990; Klaus-Joerger et al., 2001). Bacterial mediation involves metabolic processes in the form of enzymatically catalyzed reactions, whereas algae and fungi accumulate noble metals via passive biosorption (Reith et al., 2007).

3.6.3 Preservation of soft tissue

Microbial activity has long been linked with the preservation of soft tissue, in the decay process and creating anoxic conditions in the sediment (e.g., Allison, 1988; Allison and Briggs, 1991), and experimental studies have elucidated their

involvement (e.g., Sagemann et al., 1999). Microbial mats can create microenvironments that are anoxic, low in pH and high in sulfur (Sagemann et al., 1999; Zhu et al., 2005). Gabbott et al. (2008) found no evidence of microbial mats in the ‘phyllopod bed’ of the Burgess Shale, but due to the delicate nature of most benthic microbial biofilms they might have not been preserved and otherwise left no trace (e.g., Briggs, 2003). However, recent organic carbon and biomarker analyses on the lower Cambrian Emu Bay Lagerstätte has provided evidence for cyanobacterial microbial mats (Hall et al., 2011; McKirdy et al., 2011).

Biomarker analysis on samples from the Ravens Throat River Lagerstätte yielded no information because the rock has undergone too great a degree of thermal alteration. By contrast, C_{org} isotope signatures correspond to cyanobacterial signatures ($\sim -23.2\text{‰}$). Common organic seams visible in thin sections of the calcareous mudstone might represent fragments or ‘flakes’ of benthic microbial mats or accumulations of planktic cyanobacteria. They do not occur in the interbedded lime mudstone, either because of biodegradation and recycling back into the water column, or because they were not buried and sealed from complete decay.

Gaines et al. (2012) proposed that early calcium carbonate cementation acted as a seal that allowed preservation of soft tissues. Butterfield (2012) noted, however, that many layers preserving BST fossils are calcite-poor. Cyanobacteria and bacteria can be the trigger for calcite precipitation in shallow-marine microbial mats (e.g., Kremer et al., 2008; Dupraz et al., 2009), but there is no evidence for authigenic calcium carbonate precipitation in the laminae comprising the Ravens Throat River Lagerstätten. Bacteria aid precipitation in decaying carcasses in muddy sediment (Sagemann et al., 1999) but calcite enrichment around the fossils is also not observed. Sulfate reduction and changing alkalinity are involved in concretionary calcite

precipitation (e.g., Pratt, 2001; Raiswell and Fisher, 2004). Lime mudstone interbeds in the Ravens Throat River Lagerstätte have evidence for early cementation, but these are not associated with soft-bodied preservation.

3.6.4. Toxicity of silver

Silver itself is a relatively widespread noble metal in solution, compared to gold, and is known for its toxicity (e.g., Brooks and Watterson, 1992). The silver ion, together with mercury, are two of the most toxic heavy metals and are assigned to the highest class of toxicity, along with cadmium and chromium (e.g., Ratte, 1999). The level of toxicity of silver is related to silver species rather than concentrations, and the Ag^+ ion is the most toxic form and is released when silver nitrate dissolves. Tests on a range of marine invertebrates showed that juveniles are more sensitive to Ag^+ than adults of the same species. Depending on the species, amounts as low as $0.5 \mu\text{g/L}$ can influence the development of the animal (Ratte, 1999). In natural systems silver often binds with sulfur, which reduces its toxicity due to the lower solubility of silver sulfide (Levard et al., 2012). While silver has a tendency to colloidal binding in freshwater environments, the amount of colloidal binding is reduced with increasing salinity, and complex binding with chloride takes over, which keeps the silver-bearing molecule in solution (e.g., Förstner and Wittmann, 1981). These molecules can be transported via marine currents and deposited far away from source (Ratte, 1999).

Whereas silver is toxic to most organisms some species have high tolerances and can bioaccumulate it. In modern marine habitats, benthic macrophytic algae, such as *Fucus vesiculosus*, are known to bind dissolved silver and tolerate elevated silver, at least up to $0.25 \mu\text{g/L}$ in the environment (Langston and Burt, 1994; Fleeger et al.,

2003). Similarly some invertebrates, such as some species belonging to the brine shrimp *Artemia*, the bryozoan *Victorella*, gastropods such as *Littorina littorea*, and certain nereid polychaetes can bioaccumulate considerable amounts of heavy metals without symptoms of toxicity (Fisher, 1995; Ratte, 1999). Similarly it has been reported that some crustaceans, such as freshwater *Daphnia magna*, need a certain amount of silver in their diet to survive (Rangwala and Keating, 2008), and further studies on *D. magna* suggest that toxic levels of silver are reached at 0.001 mg/L of nano-sized (35 nm) silver and about 0.05 mg/L of micro-sized (0.6–1.6 μm) silver. This suggests that nano-sized silver particles are the more harmful form (Gaiser et al., 2011).

Kimmig and Pratt (2014) reported that the Ravens Throat River biota is specimen-rich, but species-poor in comparison to other BST deposits. Considering modern environments displaying similar specimen-to-species proportions are often related to inimical or high-stress settings, e.g., environments with increased toxicity, reduced oxygen or other pollutions; it might be that the elevated silver caused unfavorable environmental conditions, perhaps in addition to other environmental factors.

3.7 Conclusions

Burgess Shale-type fossilization has proven to be widespread in lower and middle Cambrian successions, but complete understanding of the fossilization pathway remains elusive. In the middle Cambrian Ravens Throat River Lagerstätte, carbonaceous patches and elemental silver, together with geochemical data, suggest that cyanobacterial microbial mats were common in this setting and may have played

a role in the conservation of the more robust soft tissues. The abundance of mineral deposits in this region of northwestern Canada suggest that the elevated silver concentrations were likely derived from localized sources due to silver-bearing fluids that may have leaked onto the seafloor via syndepositional faults. The anomalously high concentration of silver might also be part of the reason for the low diversity of the biota compared to other Burgess Shale-type communities, owing to the toxicity of this element to invertebrates.

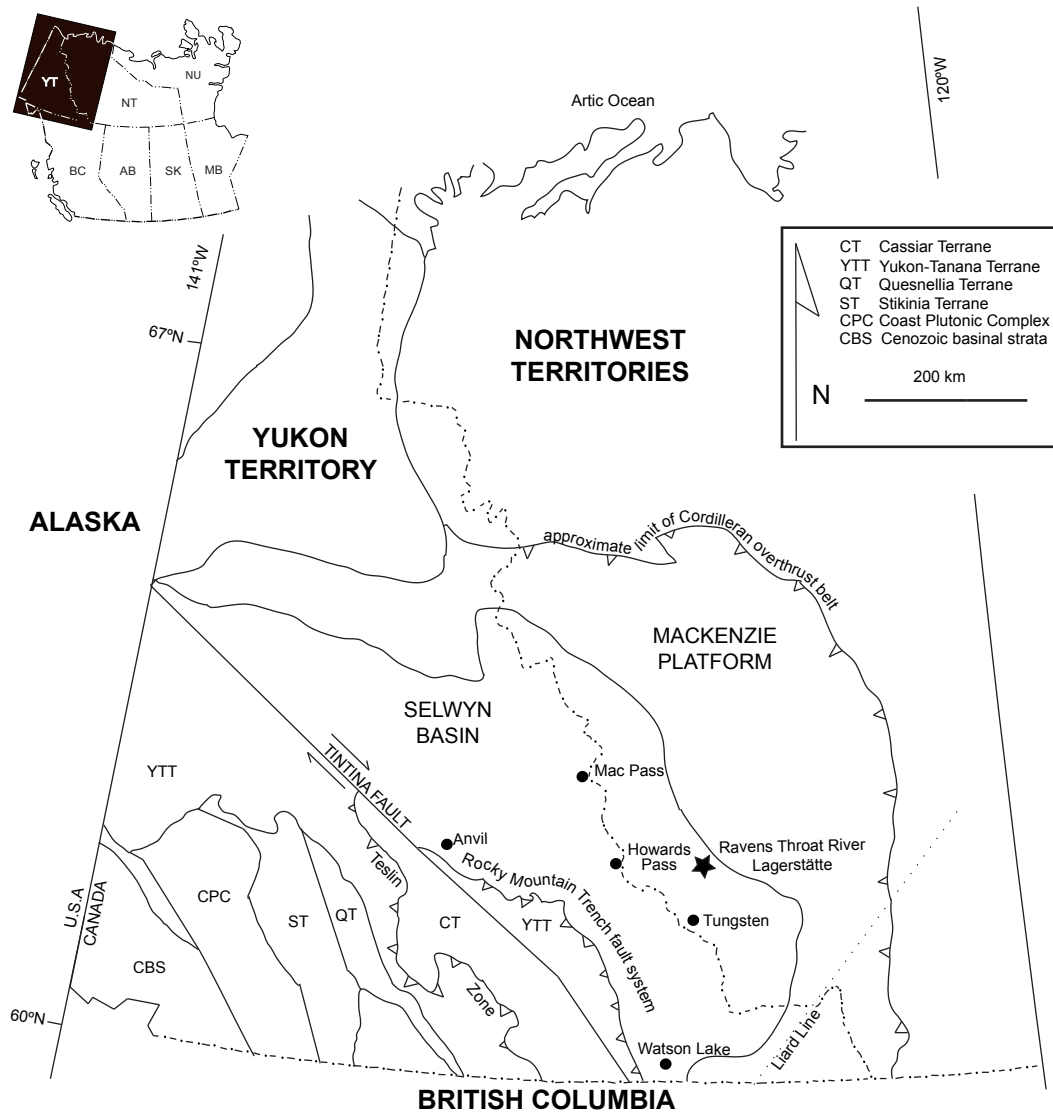


FIGURE 3.1—Map showing the main Ag deposits close to the Ravens Throat River Lagerstätte, as well as the main tectonic features.

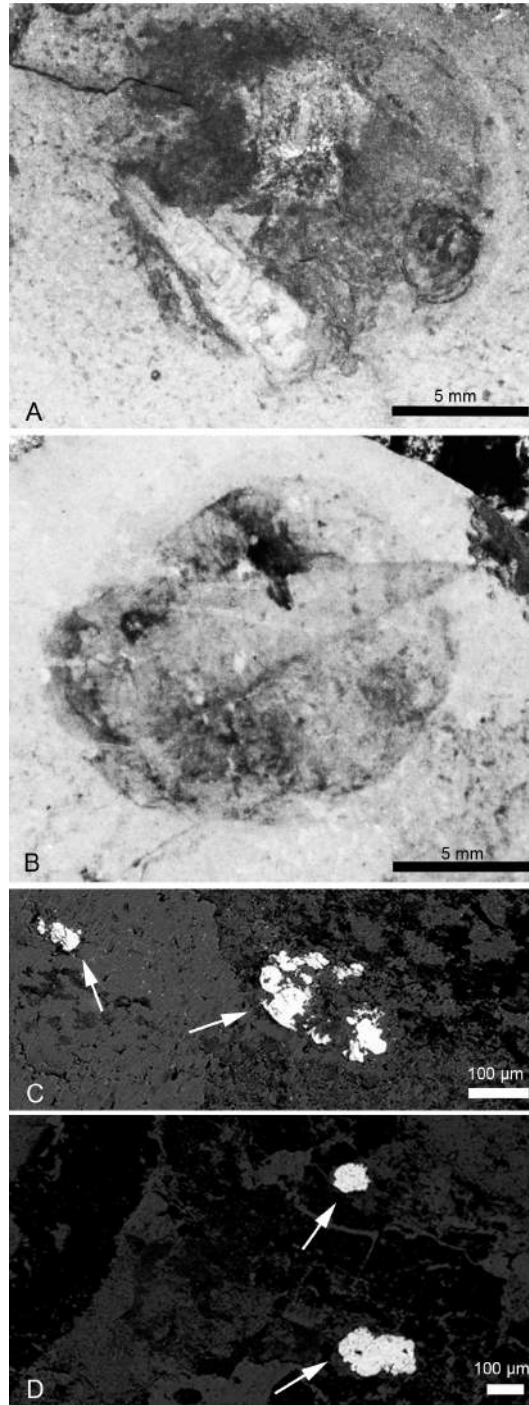


FIGURE 3.2— A) Photograph under reflected light of organic film hosting silver (TMP 2013.101.0084), taken under ethanol; B) Photograph under reflected light of organic film hosting silver (TMP 2013.101.0079), taken under ethanol; C) SEM photograph of the elemental silver in microbial mat, indicated by arrows (TMP 2013.101.0084); D) SEM photograph of the elemental silver in microbial mat, indicated by arrows (TMP 2013.101.0079).

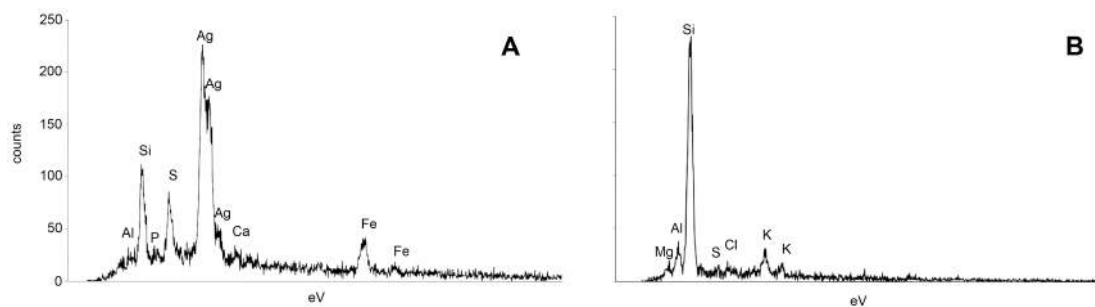


FIGURE 3.3—EDX spectra of A) Silver in the organic film (TMP 2013.101.0084); B) The surrounding matrix (TMP 2013.101.0084).

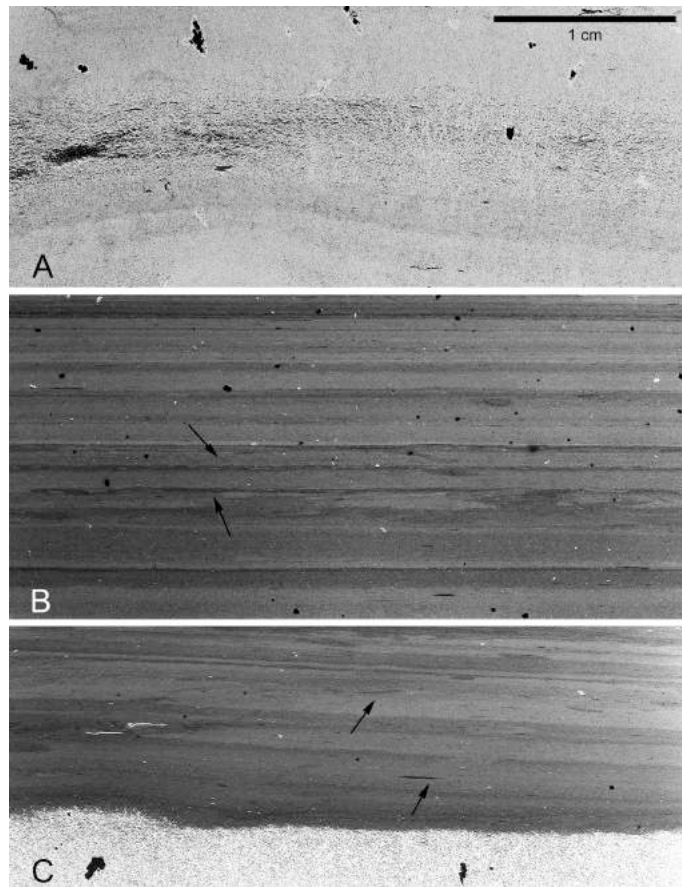


FIGURE 3.4—Thin sections of the Ravens Throat River Lagerstätte fossil bed. A) Lime mudstone facies without organic remains; B) Fine laminated layer with organic structures, likely representing microbial mats (indicated by arrows); C) Fine laminated layer with fossils and organic structures, likely representing microbial mats (indicated by microbial mats), overlying a coarser layer.

Unit	Height m	Sc ppm	V ppm	U ppm	Th ppm	Pb ppm	Mo ppm	Cu ppm	Co ppm	Ni ppm	Zn ppm	Cr ppm	Ag ppm
Black Shale	5	7.2	234	6.32	4.24	13	6.07	16.3	22	33.6	141	44	0.21
Lime mudstone	60	2.8	169	2.03	2.05	5.69	1.85	17.2	18.1	19.8	36	15	0.14
Debris Flow	79	5.2	67.2	2.44	4.3	11.6	2.16	10	34.8	18.5	70	27	0.22
Lime mudstone	133	4.2	36.9	2.14	1.64	5.39	0.88	14.4	68.4	19.8	19	11	0.08
Calcareous mudstone	134.35	14.1	141	4.34	12.1	3.74	1.08	4.5	17.2	26.9	61	81	0.43
Calcareous mudstone	134.42	11.5	123	3.46	10.3	3.01	0.42	15.2	37.8	35.2	89	73	0.39
Calcareous mudstone	134.51	11.2	121	2.89	9.58	2.32	0.71	5.9	50.9	30	78	71	0.37
Calcareous mudstone	134.63	13	128	3.46	10.8	2.5	0.47	12	33.7	29.5	74	77	0.39
Calcareous mudstone	134.79	12.2	122	3.5	10.7	2.36	0.52	11.5	46.1	23.1	68	77	0.42
Calcareous mudstone	135.14	12.8	123	3.03	10.3	1.85	0.22	21.3	82.7	25.4	61	81	0.41
Calcareous mudstone	135.76	12.1	119	2.89	10	1.93	0.63	6.6	34.4	25.5	73	73	0.24
Calcareous mudstone	136.06	7.9	69.2	2.75	5.74	2.69	0.74	50.1	76.4	53.2	64	48	0.42
Calcareous mudstone	136.21	11.4	121	3.19	11.4	2.25	0.71	4.3	29.6	21.6	60	75	0.41
Calcareous mudstone	136.76	10.3	106	2.73	9.8	2.41	0.58	5.2	111	23.3	61	74	0.37
Calcareous mudstone 2nd Calcareous mudstone	164	12.5	107	2.27	9.12	4.6	0.43	8.2	31.9	25.3	64	62	0.36
Dolomitic limestone	190	7.2	72.8	4.38	6.63	14.8	1.56	18.2	64.2	26.5	43	40	0.47

TABLE 3.1.—Trace element and organic carbon data of the BST unit of the Rockslide Formation at the Ravens Throat River outcrop.

SUMMARY

The Rockslide Formation is a deeper water succession of shales, mudstones, and limestones deposited on a seaward slope of a mixed siliciclastic–carbonate platform. At the herein described Ravens Throat River locality the Rockslide Formation sediments were deposited on a synsedimentary fault which cuts into sandstones of the Ediacaran Backbone Ranges Formation. The Rockslide Formation hosts two one-meter thick intervals of green-coloured, laminated calcareous mudstone that host Burgess Shale-type (BST) biota, unique in this formation.

These intervals, referred to as the Ravens Throat River Lagerstätte, yield important information on the diversity, preservation, and deposition environment of BST deposits. It represents a less well-studied type of BST deposits, as it preserves mainly robust parts of soft-bodied animals. Where soft-tissue is preserved, it shows signs of disintegration and scavenging. In this regard, the Ravens Throat River Lagerstätte does not rival the likes of the Burgess Shale or the Chengjiang and Emu Bay deposits for their preservation quality. Also, the diversity of the Ravens Throat River Lagerstätte is low, disregarding the trilobite fauna, as only nine species are identified. The shelly fauna yields hyoliths, agnostoids, trilobites, and rare languid brachiopods. In this respect, the overall diversity is similar to the other BST deposits of Laurentia, as it is arthropod dominated in terms of diversity. The main difference lies in the specimen diversity, where hyoliths and algae are far more prominent than any fossils belonging to the soft-bodied arthropods.

The green-coloured, laminated calcareous mudstone is similar to the host rocks reported from other BST deposits around the world. Trace element data indicates similarity to other BST deposits, in that the biota was deposited under oxic bottom waters, however, it may have had intermittent periods of dysoxic conditions. Oxic bottom waters are also supported by the presence of bioturbation, which is rarely seen in BST deposits and might be part of the reason why the fossils in the Ravens Throat River Lagerstätte are not pristine. Despite the presence of bioturbation, the burrowing by itself likely did not have a primary effect on Burgess Shale-type preservation. This data consequently indicates that the key to BST preservation relies on the nature of the host sediment. The specific mixture of lime mud, quartz silt and clay minerals—chlorite and illite—presented a unique medium that possibly slowed decay of the buried carcasses. In contrast to other BST deposits, early carbonate cementation is not

observed associated with the fossils and therefore cannot be invoked as a means to seal the sediment and prevent further decay.

One unique feature of the Ravens Throat River Lagerstätte is a high accumulation of silver in the fossiliferous calcareous mudstones. An even higher accumulation of silver is found in the organic circular films, possibly representing cyanobacterial microbial mats. The mat interpretation is also supported by organic carbon data that identified a clear cyanobacterial signature in the fossiliferous calcareous mudstones. The presence of microbial mats might explain the preservation of the more robust fossiliferous parts at this locality. The abundance of mineral deposits in this region suggest that the elevated silver concentrations were likely a local phenomenon due to silver-bearing fluids that may have infiltrated into the seafloor via syndepositional faults. The high concentration of silver might have created toxic levels for some animals and plants and thus be the reason for the low diversity of the biota compared to other Burgess Shale-type communities.

Overall the research on the Ravens Throat River Lagerstätte shows that even the less well-preserved BST deposits have great potential to help uncover the mysteries behind the mechanisms of extraordinary preservation. It also affirms that the propensity for Burgess Shale-type preservation was more widespread in Laurentia than previously understood.

LIST OF REFERENCES

- ABUSHIK, A. F. 1960. First discovery of leperditaceans from the Cambrian of the Siberian Platform. *Vestnik Leningradskogo Universitet, Seriya Geologii I Geografii*, 6:93–98. [In Russian]
- AITKEN, J. D., R. W. MACQUEEN, AND J. L. USHER. 1973. Reconnaissance studies of Proterozoic and Cambrian stratigraphy, lower Mackenzie River area (Operation Norman), District of Mackenzie. Geological Survey of Canada, Paper 73-9, 178 p.
- ALLISON, P. A. 1988. The role of anoxia in the decay and mineralization of proteinaceous macrofossils. *Paleobiology*, 14:139–154.
- ALLISON, P. A. AND D. E. G. BRIGGS. 1991. Taphonomy of nonmineralized tissues. *In*: Allison, P. A. and D. E. G. Briggs (eds.), p. 25–70. *Taphonomy: Releasing the data locked in the fossil record*. New York: Plenum, 560 p.
- ALLISON, P. A. AND C. E. BRETT. 1995. In situ benthos and paleo-oxygenation in the Middle Cambrian Burgess Shale, British Columbia, Canada. *Geology*, 23:1079–1082.
- BABCOCK, L. E. AND R. A. ROBISON. 1988. Taxonomy and paleobiology of some Middle Cambrian *Scenella* (Cnidaria) and hyolithids (Mollusca) from western North America. *The University of Kansas Paleontological Contributions*, 121, 22 p.
- BABCOCK, L. E. AND J. S. PEEL. 2007. Palaeobiology, taphonomy and stratigraphic significance of the trilobite *Buenellus* from the Sirius Passet Biota, Cambrian of North Greenland. *Memoirs of the Australasian Association of Palaeontologists*, 34:401–418.
- BABCOCK, L. E., W.-T. ZHANG AND S. A. LESLIE. 2001 The Chengjiang Biota: record of the Early Cambrian diversification of life and clues to exceptional preservation of fossils. *GSA Today*, 11:4–9.
- BILLINGS, E. 1861. On some new or little known species of Lower Silurian fossils from the Potsdam group (Primordial Zone), p. 942–960. *In* E. Hitchcock et al., *Report on the Geology of Vermont*, volume 2 (appendix). Claremont, New Hampshire.
- BRADY, A. L., G. DRUSCHEL, L. LEONI, D. S. S. LIM AND G. F. SLATER. 2013. Isotopic biosignatures in carbonate-rich, cyanobacteria-dominated microbial mats of the

- Cariboo Plateau, B.C. *Geobiology*, 11:437–456.
- BRETT, C.E., P. A. ALLISON, M. K. DESANTIS, W. D. LIDDELL, AND A. KRAMER. 2009. Sequence stratigraphy, cyclic facies, and lagerstätten in the Middle Cambrian Wheeler and Marjum Formations, Great Basin, Utah. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 277:9–33.
- BRIGGS, D. E. G. 1976. The Arthropod *Branchiocaris* n. gen., Middle Cambrian, Burgess Shale, British Columbia. Geological Survey of Canada, Bulletin 264, 29 p.
- BRIGGS, D. E. G. 1977. Bivalved arthropods from the Cambrian Burgess Shale of British Columbia: *Palaeontology*, 20:595–621.
- BRIGGS, D. E. G. 1978. The morphology, mode of life, and affinities of *Canadaspis perfecta* (Crustacea: Phyllocarida), Middle Cambrian, Burgess Shale, British Columbia. *Philosophical Transactions of the Royal Society of London, Series B*, 281:439–487.
- BRIGGS, D. E. G. 1992. Phylogenetic significance of the Burgess Shale crustacean *Canadaspis*. *Acta Zoologica*, 73:293–300.
- BRIGGS, D. E. G. 2003. The role of biofilms in the fossilization of non-biomineralized tissues. In: Krumbein, W.E., Paterson, D.M., Zavarzin, G.A. (Eds.). *Fossil and Recent Biofilms*, p. 281–290. *A Natural History of Life on Earth*. Springer Science+Business Media, Dordrecht.
- BRIGGS, D. E. G., D. H. ERWIN AND F. J. COLLIER. 1994. *The Fossils of the Burgess Shale*. Smithsonian Institution Press, Washington, D.C., 238 p.
- BRIGGS, D. E. G., B. S. LIEBERMAN, J. H. HENDRICKS, S. L. HALGEDAHL, AND R. D. JARRARD. 2008. Middle Cambrian Arthropods from Utah. *Journal of Paleontology*, 82:238–254.
- Brooks, R. R. and J. R. Watterson. 1992. The Noble Metal Biogeochemistry of Microorganisms. In: Brooks, R.R. (Ed.), *Noble Metals and Biological Systems*, p. 159–196. *Their Role in Medicine, Mineral Exploration, and the Environment*. CRC Press, Boca Raton, FL.
- BUATOIS, L. AND M. G. MÁNGANO. 2011. *Ichnology*. Organism-substrate interactions in space and time. Cambridge University Press, Cambridge, 358 p.
- BUTTERFIELD, N. J. 1990. Organic preservation of non-mineralizing organisms and the taphonomy of the Burgess Shale. *Paleobiology*, 16:272–286.
- BUTTERFIELD, N. J. 1994. Burgess Shale-type fossils from a Lower Cambrian

- shallow-shelf sequence in northwestern Canada. *Nature*, 369:477–479.
- BUTTERFIELD, N. J. 1995. Secular distribution of Burgess-Shale-type preservation. *Lethaia*, 28:1–13.
- BUTTERFIELD, N. J. 2012. Does cement-induced sulfate limitation account for Burgess Shale-type preservation? *Proceedings of the National Academy of Sciences of the United States of America*, 109:E1901.
- BUTTERFIELD, N. J. AND C. J. NICHOLAS. 1996. Burgess Shale-type preservation of both non-mineralizing and ‘shelly’ Cambrian organisms from the Mackenzie Mountains, northwestern Canada. *Journal of Paleontology*, 70:893–899.
- BUTTERFIELD, N. J., U. BALTHASAR, AND L. A. WILSON. 2007. Fossil diagenesis in the Burgess Shale. *Palaeontology*, 50:537–543.
- CALVERT, S. E. 1987. Oceanographic controls on the accumulation of organic matter in marine sediments. *In* Brooks, J. and A.J. Fleet (Eds): p. 137–151. *Marine Petroleum Source Rocks*. Geological Society of London Special Publication.
- CARON, J.-B. AND D. A. JACKSON. 2006. Taphonomy of the Greater Phyllopod Bed community, Burgess Shale. *Palaios*, 21:451–465.
- CARON, J.-B. AND D. A. JACKSON. 2008. Paleoecology of the Greater Phyllopod Bed community, Burgess Shale. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 258:222–256.
- CARON, J.-B., R. R. GAINES, C. ARIA, M. G. MÁNGANO, AND M. STRENG. 2014. A new phyllopod bed-like assemblage from the Burgess Shale of the Canadian Rockies. *Nature Communications*, 5:doi:10.1038/ncomms4210.
- CECILE, M. P. 1982. The lower Paleozoic Misty Creek embayment, Selwyn Basin, Yukon and Northwest Territories. *Geological Survey of Canada, Bulletin 335*, 78 p.
- CHEVIER, T. S. AND E. C. TURNER. 2013. Lithostratigraphy of deep-water Paleozoic strata in the central misty creek embayment, Mackenzie Mountains, Northwest Territories. *Geological Survey of Canada, Current Research 2013-2014*, 21 p.
- CHLUPÁČ, I. AND V. KORDULE. 2002. Arthropods of Burgess Shale type from the Middle Cambrian of Bohemia (Czech Republic). *Bulletin of the Czech Geological Survey* 77:167–182.
- COLLOM, C. J., P. A. JOHNSTON, AND W. G. POWELL. 2009. Reinterpretation of ‘Middle’ Cambrian stratigraphy of the rifted western Laurentian margin: Burgess Shale Formation and contiguous units (Sauk II Megasequence); Rocky

- Mountains, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology* 277:63–85.
- Cong, P., X. Ma, X. Hou, G. D. Edgecombe and N. J. Strausfeld. 2014. Brain structure resolves the segmental affinity of anomalocaridid appendages. *Nature*:doi:10.1038/nature13486.
- CONIGLIO, M. AND N. P. JAMES. 1990. Origin of fine-grained carbonate and siliciclastic sediments in an Early Palaeozoic slope sequence, Cow Head Group, western Newfoundland. *Sedimentology*, 37:215–230.
- CONWAY MORRIS, S. AND J.-B. CARON. 2014. A primitive fish from the Cambrian of North America. *Nature*:doi:10.1038/nature13414.
- CONWAY MORRIS, S. AND R. A. ROBISON. 1988. More soft-bodied animals and algae from the Middle Cambrian of Utah and British Columbia. *University of Kansas Paleontological Contributions*, 122, 48 p.
- CUVIER, G. 1797. *Tableau élémentaire de l’histoire naturelle des animaux*. Baudouin, Paris, 770 p.
- D’EICHWALD, E. 1840. Ueber das silurische Schichtensystem in Esthland. Aus dem ersten and zweiten Hefte der Zeithschrift für Natur und Heilkunde der medizinischen Akademi zu St. Petersburg, besonders abgedruckt, 210 p.
- DEECKE, W. 1923. *Die Fossilisation*. Gebrüder Borntraeger, Berlin, 216 p.
- DEMAISON, G. J. AND G. T. MOORE. 1980. Anoxic environments and oil source bed genesis. *Organic Geochemistry*, 2:9–31.
- DIXON, J. AND L.D. STASIUK. 1998. Stratigraphy and hydrocarbon potential of Cambrian strata, Northern Interior Plains, Northwest Territories. *Bulletin of Canadian Petroleum Geology*, 46:445–470.
- DOHRMANN, M., S. VARGAS, D. JANUSSEN, A. G. COLLINS AND G. WÖRHEIDE. 2013. Molecular paleobiology of early-branching animals: integrating DNA and fossils elucidates the evolutionary history of hexactinellid sponges. *Paleobiology*, 39:95–108.
- DUMÉRIL, A. M. C. 1806. *Zoologie analytique ou méthode naturelle de classification des animaux*. Allais, Paris, xxiv + 364 p.
- DUPRAZ, C., R. P. REID, O. BRAISSANT, A. W. DECHO, R. S. NORMAN AND P. T. VISSCHER. 2009. Processes of carbonate precipitation in modern microbial mats. *Earth-Science Reviews*, 96: 141–162.
- EDGECOMBE, G. D. AND D. A. LEGG. 2013. The arthropod fossil record, p. 393–415. *In*

- A. Minelli, G. Boxshall and G. Fusco (eds.), *Arthropod Biology and Evolution, Molecules, Development, Morphology*. Springer, Berlin.
- ENDO, R., AND C. E. RESSER. 1937. The Sinian and Cambrian formations and fossils of southern Manchoukuo. *Bulletin of the Manchurian Science Museum*, 1:1–406.
- ERWIN, D. H., AND J. W. VALENTINE. 2013. *The Cambrian Explosion: the construction of animal biodiversity*. Roberts & Company, Greenwood Village, Colorado, 406 p.
- FARRELL, Ú. C., D. E. G. BRIGGS, E. U. HAMMARLUND, E. A. SPERLING AND R. R. GAINES. 2013. Paleoredox and pyritization of soft-bodied fossils in the Ordovician Frankfort Shale of New York. *American Journal of Science*, 313:452–489.
- FLEEGER, J. W., K. R. CARMAN AND R. M. NISBET. 2003. Indirect effects of contaminants in aquatic ecosystems. *The Science of the Total Environment*, 317, 207–233.
- FRITZ, W. H. 1979. Cambrian stratigraphic section between South Nahanni and Broken Skull Rivers, southern Mackenzie Mountains. *Geological Survey of Canada, Paper 79-1B*:121–125.
- FRITZ, W. H., M. P. CECILE, B. S. NORFORD, D. MORROW, AND H. H. J. GELDSETZER. 1991. Cambrian to Middle Devonian assemblages. *In* H. Gabrielse and C. J. Yorath (eds.), *Geology of the Cordilleran Orogen in Canada*. Geological Survey of Canada, *Geology of Canada*, 4:151–218.
- FU, D., X. ZHANG, G. E. BUDD, W. LIU, AND X. PAN. 2013. Ontogeny and dimorphism of *Isoxyx auritus* (Arthropoda) from the Early Cambrian Chengjiang biota, South China. *Gondwana Research*, 25:975–982.
- GABBOTT, S. E., J. ZALASIEWICZ, AND D. COLLINS. 2008. Sedimentation of the Phyllopod Bed within the Cambrian Burgess Shale Formation of British Columbia. *Journal of the Geological Society, London*, 165:307–818.
- GABRIELSE, H., S. L. BLUSSON, AND J. A. RODDICK. 1973. *Geology of Flat River, Glacier Lake, and Wrigley Lake map-areas, District of Mackenzie and Yukon Territory*. Geological Survey of Canada, *Memoir 366*, 153 p.
- GAINES R. R. AND M. L. DROSER. 2010. The paleoredox setting of Burgess Shale-type deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 297:649–661.
- GAINES, R. R., M. J. KENNEDY AND M. L. DROSER. 2005. A new hypothesis for

- organic preservation of Burgess Shale taxa in the Middle Cambrian Wheeler Formation, House Range, Utah. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 220:193–205.
- GAINES, R. R., D. E. G. BRIGGS AND Y. ZHAO. 2008. Cambrian Burgess Shale-type deposits share a common mode of fossilization. *Geology*, 36:755–758.
- GAINES, R. R., J. A. MERING, Y. ZHAO AND J. PENG. 2011. Stratigraphic and microfacies analysis of the Kaili Formation, a candidate GSSP for the Cambrian Series 2–Series 3 boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 311:171–183.
- GAINES R. R., E. U. HAMMARLUND, X. HOU, C. QI, S. E. GABBOT, Y. ZHAO, J. PENG, AND D. E. CANFIELD. 2012a. Mechanism for Burgess Shale-type preservation. *Proceedings of the National Academy of Sciences, USA*, 109:5180–5184.
- GAINES, R. R., M. L. DROSER, P. J. ORR, D. GARSON, E. HAMMARLUND, C. QI AND D. E. CANFIELD. 2012B. Burgess shale-type biota's were not entirely burrowed away. *Geology*, 40:283–286.
- GARCÍA-BELLIDO, D. C., J. R. PATERSON, G. D. EDGEcombe, J. B. JAGO, J. G. GEHLING, AND M. S. Y. LEE. 2009. The bivalved arthropods *Isoxys* and *Tuzoia* with soft-part preservation from the Lower Cambrian Emu Bay Shale Lagerstätte (Kangaroo Island, Australia). *Palaeontology*, 52:1221–1241.
- GARSON, D. E., R. R. GAINES, M. L. DROSER, W. D. LIDDELL AND A. SAPPENFIELD. 2012. Dynamic palaeoredox and exceptional preservation in the Cambrian Spence Shale of Utah. *Lethaia*, 45:164–177.
- GLAESSNER, M. F. 1979. Lower Cambrian Crustacea and annelid worms from Kangaroo Island, South Australia. *Alcheringa*, 3:21–31.
- GOODFELLOW, W.D. 2007. Base metal metallogeny of the Selwyn Basin, Canada. *Mineral Deposits of Canada*. In: Goodfellow, W.D. (Ed.), *A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces and Exploration Methods*. Geological Association of Canada, Special Publication 5:553–579.
- GORDEY S. P. AND J. G. ANDERSON. 1993. Evolution of the northern Cordilleran miogeocline, Nahanni map area (105I), Yukon and Northwest Territories. Geological Survey Canada, Memoir 428, 214 p.
- GUO, Q.-J., H. STRAUSS, C.-Q. LIU, Y.-L. ZHAO, D.-H. PI, P.-Q. FU, L.-J. ZHU AND R.-D. YANG. 2005. Carbon and oxygen isotopic composition of Lower to Middle

- Cambrian sediments at Taijiang, Guizhou Province, China. *Geological Magazine*, 142:723–733.
- GUO, Q.-J., H. STRAUSS, Y. ZHAO, X. YANG, J. PENG, Y. YANG AND Y. DENG. 2014. Reconstructing marine redox conditions for the transition between Cambrian Series 2 and Cambrian Series 3, Kaili area, Yangtze Platform: Evidence from biogenic sulfur and degree of pyritization. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 398:144–153.
- HADLARI, T. W. J. DAVIS, K., DEWING, L. M. HEAMAN, Y. LEMIEUX, L. OOTES, B. R. PRATT AND L. J. PYLE. 2012. Two detrital zircon signatures for the Cambrian passive margin of northern Laurentia highlighted by new U–Pb results from northern Canada. *Geological Society of America Bulletin*:doi: 10.1130/B30530.1
- HAECKEL, G. 1866. *Generale Morphologie der Organismen*. Georg Reimer, Berlin, 462 p.
- HALL, P.A., D. M. MCKIRDY, G. P. HALVERSON, J. B. JAGO AND J. G. GEHLING. 2011. Biomarker and isotopic signatures of an early Cambrian Lagerstätte in the Stansbury Basin, South Australia. *Organic Geochemistry*, 42:1324–1330.
- HANDLE, K. C. AND W. G. POWELL. 2012. Morphologically simple enigmatic fossils from the Wheeler Formation: A comparison with definitive algal fossils. *Palaios*, 27:304–316.
- HARVEY, T. H. P., AND N. J. BUTTERFIELD. 2011. Great Canadian Lagerstätten 2. Macro- and microfossils of the Mount Cap Formation (Early and Middle Cambrian, Northwest Territories). *Geoscience Canada*, 38:165–173.
- HAYES, J.M., H. STRAUSS AND A. J. KAUFMAN. 1999. The abundance of ¹³C in marine organic matter and isotopic fractionation in the global biogeochemical cycle of carbon during the past 800 Ma. *Chemical Geology*, 161:103–125.
- HEGNA, T. A., D. A. LEGG, O. S. MØLLER, P. VAN ROY, AND R. LEROSEY-AUBRIL. 2013. The correct authorship of the taxon name ‘Arthropoda’. *Arthropod Systematics and Phylogeny*, 71:71–74.
- HERMANN, W., AND A.P. HILL. 2001. The origin of chlorite-tremolite-carbonate rocks associated with the Thalanga volcanic-hosted massive sulfide deposit, north Queensland, Australia. *Economic Geology*, 96:1149–1173.
- HINZ-SCHALLREUTER, I. 1993. Cambrian Ostracodes mainly from Baltoscandia and Morocco. *Archiv für Geschiebekunde*, 1:385–448.
- HOU, X. 1987. Early Cambrian large bivalved arthropods from Chengjiang, eastern

- Yunnan. *Acta Palaeontologica Sinica*, 26:286-298.
- HOU, X., AND J. BERGSTRÖM. 1991. The arthropods of the Lower Cambrian Chengjiang fauna, with relationships and evolutionary significance, p. 179–187. *In* Simonetta, A. M. and S. Conway Morris (eds.), *The Early Evolution of Metazoa and the Significance of Problematic Taxa*. Cambridge University Press, Cambridge.
- HOU, X., AND J. BERGSTRÖM. 1997. Arthropods of the Lower Cambrian Chengjiang fauna, southwest China. *Fossils and Strata*, 45, 116 p.
- HOU, X.-G., R. J. ALDRIDGE, J. BERGSTRÖM, DA. J. SIVETER, DE. J. SIVETER, AND X.-H. FENG. 2004. *The Cambrian fossils of Chengjiang, China. The Flowering of Early Animal Life*. Blackwell, Oxford, 233 p.
- HUO, S. C., D. SHU, AND Z. I. CUI. 1991 *Cambrian Bradoriida of China*. Geological Publishing House, Beijing, 249 p.
- IVANTSOV, A. YU. 1990. First finds of phyllocarids in the Lower Cambrian of Yakutia. *Paleontologicheskii Zhurnal*, 1990:130–132. [in Russian]
- JOHNSTON, K. J., P. A. JOHNSTON, AND W. G. POWELL. 2009a. A new, Middle Cambrian, Burgess Shale-type biota, *Bolaspidella* Zone, Chancellor Basin, southeastern British Columbia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 277:106–126.
- JOHNSTON, P. A., K. J. JOHNSTON, C. J. COLLOM, W. G. POWELL, AND R. J. POLLOCK. 2009b. Palaeontology and depositional environments of ancient brine seeps in the Middle Cambrian Burgess Shale at The Monarch, British Columbia, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 277:86–105.
- JONES, B. AND D. A. C. MANNING. 1994. Comparison of geochemical indices used for the interpretation of paleoredox conditions in ancient sediments. *Chemical Geology*, 111:111–119.
- KASHEFI, K., J. M. TOR, K. P. NEVIN AND D. R. LOVLEY. 2001. Reductive Precipitation of Gold by Dissimilatory Fe(III)-Reducing *Bacteria* and *Archea*. *Applied and Environmental Microbiology*, 67:3275–3279.
- KIMMIG, J. AND B. P. PRATT. IN PRESS. Soft-bodied biota from the middle Cambrian (Drumian) Rockslide Formation, Mackenzie Mountains, northwestern Canada. *Journal of Paleontology*.
- KIMURA, H. AND Y. WATANABE, Y. 2001. Ocean anoxia at the Precambrian–Cambrian boundary. *Geology*, 29:995–998.

- KING, W. 1846. Remarks on certain genera belonging to the class Palliobranchiata. *Annals and Magazine of Natural History*, 18:26–42.
- KOUCHINSKY, A., S. BENGSTON, B. RUNNEGAR, C. SKOVSTED, M. STEINER AND M. VENDRASCO. 2012. Chronology of early Cambrian biomineralization. *Geological Magazine*, 149:221–251.
- KREMER, B., J. KAZMIERCZAK AND L. J. STAL. 2008. Calcium carbonate precipitation in cyanobacterial mats from sandy tidal flats of the North Sea. *Geobiology*, 6:46–56.
- LANDING, E., G. GEYER, M. D. BRASIER AND S. A. BOWRING. 2013. Cambrian evolutionary radiation: context, correlation, and chronostratigraphy—overcoming deficiencies of the first appearance datum (FAD) concept. *Earth-Science Reviews*, 123:133–172.
- LE BOUDEC, A., J. INESON, M. ROSING, L. DØSSING, F. MARTINEAU, C. LÉCUYER, AND F. ALBARÈDE. 2014. Geochemistry of the Cambrian Sirius Passet Lagerstätte, northern Greenland. *Geochemistry, Geophysics, Geosystems*, 15:doi: 10.1002/2013GC005068.
- LEE, M. S. Y., J. SOUBRIER, AND G. D. EDGECOMBE. 2013. Rates of phenotypic and genomic evolution during the Cambrian Explosion. *Current Biology*, 23:1889–1895.
- LEGG, D. A., AND J. VANNIER. 2013. The affinities of the cosmopolitan arthropod *Isoxys* and its implications for the origin of arthropods. *Lethaia*, 46:540–550.
- LEGG, D. A., AND J.-B. CARON. 2014. New middle Cambrian bivalved arthropods from the Burgess Shale (British Columbia, Canada). *Palaeontology*:doi: 10.1111/pala.12081.
- LEGG, D. A., M. D. SUTTON, G. D. EDGECOMBE, AND J.-B. CARON. 2014. Cambrian bivalved arthropod reveals origin of arthropodization. *Proceedings of the Royal Society B*:doi:10.1098/rspb.2012.1958.
- LEGG, D. A., M. D. SUTTON, AND G. D. EDGECOMBE. 2013. Arthropod fossil data increase congruence of morphological and molecular phylogenies. *Nature Communications*, 4:doi: 10.1038/ncomms3485.
- LEVARD, C., E. M. HOTZE, G. V. LOWRY AND G. E. BROWN. 2012. Environmental Transformations of Silver Nanoparticles: Impact on Stability and Toxicity. *Environmental Science and Technology*, 46:6900–6914.

- LI, J., K. BENZERARA, S. BERNARD AND O. BEYSSAC. 2013. The link between biomineralization and fossilization of bacteria: Insights from field and experimental studies. *Chemical Geology*, 359:49–69.
- LI, J., S. BERNARD, K. BENZERARA, O. BEYSSAC, T. ALLARD, J. COSMIDIS AND J. MOUSSOU. 2014. Impact of biomineralization on the preservation of microorganisms during fossilization: An experimental perspective. *Earth and Planetary Science Letters*, 400:113–122.
- LI, Y.-L., K. O. KONHAUSER A. KAPPLER AND Z. L. HAO. 2013. Experimental low-grade alteration of biogenic magnetite indicates microbial involvement in generation of banded iron formations. *Earth and Planetary Science Letters*, 361:229–237.
- LIEBERMAN, B. S. 2003. A new soft-bodied fauna: The Pioche Formation of Nevada. *Journal of Paleontology*, 77:674–690.
- LINNAEUS, C. 1758. *Systema naturae per regna tria naturae: secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*. 10th edition. Holmiae, Laurentii Salvii, 823 p.
- LOVLEY, D.R. 1993. Dissimilatory metal reduction. *Annual Review in Microbiology*, 47:263–290.
- LUBESSEDER, S., J. REDFERN AND L. BOUTIB. 2009. Mixed siliciclastic-carbonate shelf sedimentation – Lower Devonian sequences of the SW Anti-Atlas, Morocco. *Sedimentary Geology*, 215:13–32.
- LUO, H. L., S. X. HU, L. Z. CHEN, S. S. ZHANG, AND Y. H. TAO. 1999. Early Cambrian Chengjiang Fauna from Kunming Region, China. Yunnan Science and Technology Press, Kunming, 129 p. [in Chinese with English summary]
- LUO, H. L., Z. JIANG, X. WU, X. SONG, AND O. LIU. 1982. The Sinian–Cambrian boundary in eastern Yunnan, China. People’s Publishing House of Yunnan, Kunming, 265 p.
- LUO, H. L., X. P. FU, S. H. HU, Y., LI, L. Z. CHEN, T. YOU, AND Q. LIU. 2006. New bivalved arthropods from the early Cambrian Guanshan fauna in the Kunming and Wuding area. *Acta Palaeontologica Sinica*, 45:460–472.

- LUO, H. L., LI, Y., HU, S. X., FU, X. P., HOU, S. G., LIU, X. R., CHEN, L. Z., LI, F. J., PANG, J. Y. AND Q. LIU. 2008. Early Cambrian Malong Fauna and Guanshan Fauna from Eastern Yunnan, China. Yunnan Science and Technology Press, Kunming, 122 p. [in Chinese with English summary]
- MACNAUGHTON, R. B., B. R. PRATT AND K. M. FALLAS. 2013. Observations on Cambrian stratigraphy in the eastern Mackenzie Mountains, Northwest Territories. Geological Survey of Canada Current Research, 2013-10:1–7.
- MALOOF, A. C., S. M. PORTER, J. L. MOORE, F. Ö. DUDÁS, S. A. BOWRING, S.A., HIGGINS, D. A. FIKE AND M. P. EDDY. 2010. The earliest Cambrian record of animals and ocean geochemical change. Geological Society of America Bulletin, 122:1731–1774.
- MÁNGANO, M. G. 2011. Trace-fossil assemblages in a Burgess Shale-type deposit from the Stephen Formation at Stanley Glacier, Canadian Rocky Mountains: Unraveling ecologic and evolutionary controls. Palaeontographica Canadiana, 31:89–118.
- MÁNGANO, M. G., R. G. BROMLEY, D. A. T. HARPER, A. T. NIELSEN, M. P. SMITH, AND J. VINTHER. 2012. Nonbiomineralized carapaces in Cambrian seafloor landscapes (Sirius Passet, Greenland): Opening a new window into early Phanerozoic benthic ecology. Geology, 40:519–522.
- MAREK, L. 1963. New knowledge on the morphology of *Hyolithes*. Sborník geologických věd, řada Paleontologie, 1:53–72.
- MATTHEW, G. F. 1899. Studies on Cambrian faunas, no. 3: Upper Cambrian fauna of Mt. Stephen, British Columbia. Transactions of the Royal Society of Canada, Series 2, 5:39–66.
- MCKIRDY, D.M., P. A. HALL, C. NEDIN, G. P. HALVERSON, B. H. MICHAELSEN, J. B. JAGO, J.G. GEHLING, AND R. J. F. JENKINS. 2011. Paleoredox status and thermal alteration of the lower Cambrian (Series 2) Emu Bay Shale Lagerstätte, South Australia. Australian Journal of Earth Sciences, 58:259–272.
- NICHOLSON, H. A. 1872. On the genera *Cornulites* and *Tentaculites* and on a new genus *Conchicolites*. American Journal of Science, 3:202–206.
- NOVOZHILOV, N. I. 1960. Rodklass Pseudocrustacea, p. 199. In Yu. A. Orlov (ed.), Osnovy Paleontologii, Arthropoda. Trilobitomorpha and Crustacea. Nedra, Moscow.
- OOTES, L., S. A. GLEESON, E. TURNER, K. RASMUSUN, S. GORDEY, H. FALCK, E.

- MARTEL AND K. PIERCE. 2013. Metallogenic Evolution of the Mackenzie and Eastern Selwyn Mountains of Canada's Northern Cordillera, Northwest Territories: A Compilation and Review. *Geoscience Canada*, 40:40–69.
- PAUL, J. 2006. Der Kupferschiefer: Lithologie, Stratigraphie, Fazies und Metallogenese eines Schwarzschiefers. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, 157:57–76.
- PEEL, J. S. AND J. R. INESON. 2011. The extent of the Sirius Passet Lagerstätte (early Cambrian) of North Greenland. *Bulletin of Geosciences*, 86:535–543.
- PIPER, D. J. W. 1972. Sediments of the Middle Cambrian Burgess Shale. *Lethaia*, 5:169–175.
- PIPER, D. Z. AND C. M. ISAACS. 1995. Minor elements in Quaternary sediment from the Sea of Japan: A record of surface-water productivity and intermediate-water redox conditions. *Geological Society of America Bulletin*, 107:54–67.
- POULSEN, C. 1927. The Cambrian, Ozarkian and Canadian faunas of northwest Greenland. *Meddelelser om Grønland*, 70:233–343, pls. 14–21.
- POWELL, W. G. 2003. Greenschist-facies metamorphism of the Burgess Shale and its implications for models of fossil formation and preservation. *Canadian Journal of Earth Sciences*, 40:13–25.
- POWELL, W. G. 2009. Comparison of geochemical and distinctive mineralogical features associated with the Kinzers and Burgess Shale formations and their associated units. *Palaeoclimatology, Palaeoecology, Palaeogeography*, 277:127–140.
- POWELL, W. G., P. A. JOHNSTON AND C. J. COLLOM. 2003. Geochemical evidence for oxygenated bottom waters during deposition of fossiliferous strata of the Burgess Shale Formation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 201:249–268.
- POWELL, W.G., P. A. JOHNSTON, C. J. COLLOM AND K. J. JOHNSTON. 2006. Middle Cambrian Brine Seeps on the Kicking Horse Rim and Their Relationship to Talc and Magnesite Mineralization and Associated Dolomitization, British Columbia, Canada. *Economic Geology*, 101:431–451.
- PRATT, B. R. 1989. Deep-water *Girvanella-Epiphyton* reef on a mid-Cambrian continental slope, Rockslide Formation, Mackenzie Mountains, Northwest Territories. *In* H. H. J. Geldsetzer, N. P. James and G. E. Tebbutt (eds.). *Reefs, Canada and Adjacent Areas*. Canadian Society of Petroleum Geologists,

- Memoir 13, p. 161–164.
- PRATT, B. R. 1992. Trilobites of the Marjuman and Steptoean Stages (Upper Cambrian), Rabbitkettle Formation, Southern Mackenzie Mountains, Northwest Canada. *Palaeontographica Canadiana*, 9, 179 p.
- PYLE, L.J., T. L. ALLEN, T. A. FRASER, L. P. GAL, T. HADLARI, A. L. JONES, Y. LEMIEUX AND W. G. ZANTVOORT. 2007. Field-based stratigraphic studies in the Peel Plateau, Peel Plain, and adjacent areas, Northwest Territories and Yukon. *Geological Survey of Canada Current Research*, 2007-A7:1–11.
- RAISWELL R. AND Q. J. FISHER. 2004. Rates of carbonate cementation associated with sulphate reduction in DSDP/ODP sediments: Implications for the formation of concretions. *Chemical Geology*, 211:71–85.
- RANDELL, R. D., B. S. LIEBERMAN, S. T. HASIOTIS, AND M. C. POPE. 2005. New chancelloriids from the early Cambrian Sekwi Formation with a comment on chancelloriid affinities. *Journal of Paleontology* 79:1002–1011.
- RATTE, H. T. 1999. Bioaccumulation and toxicity of silver compounds: a review. *Environmental Toxicology and Chemistry*, 18:89–108.
- RAYMOND, P. E. 1935. *Leancoilia* and other Mid-Cambrian Arthropoda. *Bulletin of the Museum of Comparative Zoology, Harvard University*, 76:205–230.
- REES, M. N. 1986. A fault-controlled trough through a carbonate platform: Middle Cambrian House Range embayment. *Geological Society of America Bulletin*, 97:1054–1069.
- REITH, F., M. F. LENGKE, D. FALCONER, D. CRAW AND G. SOUTHAM. 2007. The geomicrobiology of gold. *International Society for Microbial Ecology Journal*, 1:567–584.
- RESSER, C. E. 1929. New Lower and Middle Cambrian Crustacea. *Proceedings of the U.S. National Museum*, 76:1–18.
- RESSER, C. E. 1937. Third contribution to nomenclature of Cambrian trilobites. *Smithsonian Miscellaneous Collections*, 95(22), 29 p.
- RESSER, C. E., AND B. F. HOWELL. 1938. Lower Cambrian *Olenellus* Zone of the Appalachians. *Geological Society of America Bulletin*, 49:195-248.
- REICHENBACH, H. G. L., 1834. *Johann Christoph Mössler's Handbuch der Gewächskunde*, 3rd Edn., Vol. 3, Phanerogamia. J. F. Hammerich, Altona, 768 p.

- RICHTER, R., AND E. RICHTER. 1927. Eine Crustacee (*Isoxys carbonelli* n. sp.) in den Archaeocyathus-Bildungen der Sierra Morena und ihre Stratigraphische Beurteilung. *Senckenbergiana*, 9:188–195.
- RIMMER, S.M. 2004. Geochemical paleoredox indicators in Devonian–Mississippian black shales, Central Appalachian Basin (USA). *Chemical Geology*, 206:373–391.
- ROBISON, R. A. 1991. Middle Cambrian biotic diversity: examples from four Utah lagerstätten, p. 77–98. *In* A. Simonetta and S. Conway Morris (eds.), *The Early Evolution of Metazoa and the Significance of Problematic Taxa*. Cambridge University Press, Cambridge.
- ROBISON, R. A., AND L. E. BABCOCK. 2011. Systematics, paleobiology, and taphonomy of some exceptionally preserved trilobites from Cambrian Lagerstätten of Utah. *Paleontological Contributions* 5, 47 p.
- ROBISON, R. A., AND B. C. RICHARDS. 1981. Larger bivalve arthropods from the Middle Cambrian of Utah. *The University of Kansas Paleontological Contributions* 106, 28 p.
- SAGEMANN, J., S. J. BALE, D. E. G. BRIGGS AND R. J. PARKES, R.J. 1999. Controls on the formation of authigenic minerals in association with decaying organic matter: An experimental approach. *Geochimica et Cosmochimica Acta*, 63:1083–1095.
- SAWLOWICZ, Z. 1993. Organic Matter and its Significance for the Genesis of the Copper-Bearing Shales (Kupferschiefer) from the Fore-Sudetic Monocline (Poland). *In*: Parnell, J., Kuch, H., Landais, P. (Eds.). *Bitumens in Ore Deposits*, p. 431–446. Springer, Berlin. Special Publication No. 9 of the Society of Geology Applied to Mineral Deposits.
- SELDEN, P. A., AND J. R. NUDDS. 2012. *Evolution of fossil ecosystems*. Mason Publishing Ltd, 288 p.
- SEILACHER, A., W.-E. REIF, AND F. WESTPHAL. 1985. Sedimentological, ecological and temporal patterns of fossil Lagerstätten. *Philosophical Transactions of the Royal Society of London, Series B* 311:5–23.
- SIEBOLD, C. T. VON. 1848. *Lehrbuch der vergleichenden Anatomie der Wirbellosen Thiere. Erster Theil*, p. 1–679. *In* C. T. von Siebold and H. Stannius (eds.): *Lehrbuch der vergleichenden Anatomie*. Veit und Comp, Berlin.
- SIMONETTA, A. M., AND L. DELLE CAVE. 1975. The Cambrian non-trilobite arthropods

- from the Burgess Shale of British Columbia. A study of their comparative morphology, taxonomy and evolutionary significance. *Palaeontographica Italiana*, 69 (n. ser. 39):1–37.
- SIEVETER, D. J. AND M. WILLIAMS. 1997. Cambrian bradoriid and phosphatocopid arthropods of North America. *Special Papers in Palaeontology*, 57, 69 p.
- SMITH, D. 2007. Sequence Stratigraphy of the Middle Cambrian Marjum Formation: Response of Sedimentary Facies and Biota to Sea-level Fluctuations [Master's Thesis]. Utah State University, Utah, 184 p.
- SOUTHAM, G., M. F. LENGKE, L. FAIRBROTHER AND F. REITH. 2009. The Biogeochemistry of Gold. *Elements*, 5:303–307.
- STEIN, M. 2010. A new arthropod from the early Cambrian of North Greenland, with a “great-appendage”-like antennula. *Zoological Journal of the Linnean Society*, 158:477–500.
- STOW, D. A. V., J.-C. FAUGÈRES, J. A. HOWE, C. J. PUDSEY AND A. R. VIANA. 2002. Bottom currents, contourites and deep-sea sediment drifts: current state-of-the-art. *In* Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugères, J.-C., Viana, A.R. (Eds): *Deep-water Contourite Systems; Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics*, 7–20. Geological Society, London, *Memoirs*, 22.
- SYSSOIEV [Sysoev, V.A.], 1958. Superorder Hyolithoidea. *In* Yu. A. Orlov, N. P. Luppov, and V. V. Drushchits (eds.), *Osnovy Paleontologii. Molluski–golovonogie 2*, p. 184–190. Akademia Nauk SSSR, Moscow. [in Russian]
- THÉEL, H. 1906. Northern Arctic Invertebrates in the Collection of the Swedish State Museum. II. Priapulids, Echiurids etc. *Kungliga Svenska Vetenskapsakademiens Handlingar*, 40, 28 p.
- TRIBOVILLARD, N., T. J. ALGEO, T. LYONS AND A. RIBOULLEAU. 2006. Trace metals as paleoredox and paleoproductivity proxies: An update. *Chemical Geology*, 232:12–32.
- TUREKIAN, K. K. AND K. H. WEDEPOHL. 1961. Distribution of the elements in some major units of the earth's crust. *Geological Society of America Bulletin*, 72:175–192.
- VANDENBROUCKE, M. AND C. LARGEAU. 2007. Kerogen origin, evolution and

- structure. *Organic Geochemistry*, 38:719–833.
- VANNIER, J. AND J. Y. CHEN. 2000. The Early Cambrian colonization of pelagic niches exemplified by *Isoxys* (Arthropoda). *Lethaia*, 33:295–311.
- VANNIER, J., CARON, J.-B., YUAN, J.-L., BRIGGS, D. G., COLLINS, D., ZHAO, Y.-L. AND M.-Y. ZHU. 2007. *Tuzoia*: Morphology and lifestyle of a large bivalved arthropod of the Cambrian seas, *Journal of Paleontology*, 81:445–471.
- WAGGONER, B. AND J. W. HAGADORN. 2004. An unmineralized alga from the Lower Cambrian of California, USA. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, 231:67–83.
- WALCOTT, C. D. 1890. The fauna of the Lower Cambrian or *Olenellus* Zone. *Reports of the U.S. Geological Survey*, 10:509–763.
- WALCOTT, C. D. 1912. Cambrian geology and paleontology II; Middle Cambrian Branchiopoda, Malacostraca, Trilobita, and Merostomata: *Smithsonian Miscellaneous Collections*, 57:145–228.
- WALCOTT, C. D. 1924. Cambrian and Ozarkian Brachiopoda. *Cambrian Geology and Paleontology IV. Smithsonian Miscellaneous Collections* 67:477–554.
- WALCOTT, C. D. 1931. Addenda to descriptions of Burgess Shale fossils. *Smithsonian Miscellaneous Collections*, 85:1–46.
- WANDERER, K. 1932. Ein “Silberfisch” aus dem Mansfelder Kupferschiefer. *Sitzungsberichte und Abhandlungen der Naturwissenschaftlichen Gesellschaft ISIS in Dresden*, 1931:168–170.
- WANG, Y., D. HUANG, AND B. S. LIEBERMAN. 2010. New *Isoxys* (Arthropoda) from the Cambrian Mantou Formation, Shandong Province. *Acta Palaeontologica Sinica*, 40:398–406.
- WARMING, E., 1884. *Haandbog i den systematiske Botanik* (2nd Edn.). P. G. Philipsens, Copenhagen, 434 p.
- WEBSTER, M., R. R. GAINES AND N. C. HUGHES. 2008. Microstratigraphy, trilobite biostratigraphy, and depositional environment of the “Lower Cambrian” Ruin Wash Lagerstätte, Pioche Formation, Nevada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 264:100–122.
- WEDEPOHL, K. H. 1971. Environmental influences on the chemical composition of shales and clays. *In* Ahrens, L.H., Press, F., Runcorn, S.K., Urey, H.C. (Eds): p. 307–331. *Physics and Chemistry of the Earth*, vol. 8. Pergamon, Oxford.

- WEDEPOHL, K.H. 1994. Composition and origin of the Kupferschiefer bed. *Geological Quarterly*, 38:623–638.
- WHITTINGTON, H. B. 1985. *The Burgess Shale*. Yale University Press, New Haven, 151 p.
- WILLIAMS, M., DA. J. SIVETER, AND J.S. PEEL. 1996. *Isoxys* (Arthropoda) from the Early Cambrian Sirius Passet Lagerstätte, North Greenland. *Journal of Paleontology*, 70:947–954.
- WILSON, L. A. AND N. J. BUTTERFIELD. 2014. Sediment effects on the preservation of Burgess Shale-type compression fossils. *Palaios*, 29:145–154.
- YUAN, J.-L., AND Y.-L. ZHAO. 1999. *Tuzoia* (bivalved arthropods) from the Lower-Middle Cambrian Kaili Formation of Taijiang, Guizhou. *Palaeontologica Sinica*, 38, supplement:88–93.
- YUAN, J.-L., J. PENG AND Y.-L. ZHAO. 2011. New bivalve arthropods from the mid-Cambrian Kaili Biota of southeastern Guizhou, southwest China. *Acta Geologica Sinica*, 85:801–840.
- ZHANG, X., J. BERGSTRÖM, R. G. BROMLEY AND X. HOU. 2007. Diminutive trace fossils in the Chengjiang Lagerstätte. *Terra Nova*, 19:407–412.
- ZHAO, Y., M. ZHU, L. E. BABCOCK, J. YUAN, R. L. PARSLEY, J. PENG, X. YANG, AND Y. WANG. 2005. Kaili Biota: A taphonomic window on diversification of metazoans from the basal Middle Cambrian: Guizhou, China. *Acta Geologica Sinica*, 79:751–765.
- ZHAO Y. 2011. *The Kaili Biota: Marine Organisms from 508 million years ago*. Guizhou Science and Technology Press, Guiyang, 251 p.
- ZHU, M., L. E. BABCOCK AND M. STEINER. 2005. Fossilization modes in the Chengjiang Lagerstätte (Cambrian of China): testing the roles of organic preservation and diagenetic alteration in exceptional preservation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 220:31–46.

APPENDIX A

ABSTRACT PALAEOLOGICAL ASSOCIATION ANNUAL MEETING 2012

The Burgess Shale's little brother: A new Lagerstätte from the Middle Cambrian of the Mackenzie Mountains, Northwest Territories, Canada

JULIEN KIMMIG AND BRIAN R. PRATT

Burgess Shale-type Lagerstätten are known from the Cambrian and Ordovician of most continents, and these snapshots of benthic marine communities are critical for the understanding of the early evolution and diversity of life. Here we present a new Lagerstätte in the Rockslide Formation of northwestern Canada. It is of similar middle Cambrian age as the Burgess Shale itself, but is non-metamorphosed. Fossils include hyolithids, agnostoid and ptychoparioid trilobites, Isoxys and one or two other arthropod taxa, priapulids, sponges, lingulid brachiopods, Margaretia, and circular organic blobs that represent either microbial mats, coprolites or regurgitites. The fossils occur in unit of greenish siliciclastic mudstone, ~1 m thick, that is part of a deeper water succession of shales and lime mudstones that onlaps a fault scarp cutting lower Cambrian sandstone. The host beds consist of illite, quartz, clinochlore (Mg-rich chlorite) , and dolomite. Trace element analysis shows an oxygenated water column but with some fluctuations, and there is also variation in the total organic carbon content of the fossil-bearing beds.

APPENDIX B

ABSTRACT GEOLOGICAL ASSOCIATION OF CANADA – MINERALOGICAL ASSOCIATION OF CANADA ANNUAL MEETING 2013

A new middle Cambrian Burgess Shale-type Lagerstätte from the Middle Cambrian
of the Mackenzie Mountains, Northwest Territories, Canada

JULIEN KIMMIG AND BRIAN R. PRATT

Burgess Shale-type Lagerstätten are known from the Cambrian and Ordovician of most continents, and these snapshots of benthic marine communities are critical for the understanding of the early evolution and diversity of life. Here we present an overview of a new Lagerstätte from the Mackenzie Mountains of northwestern Canada. The fossils occur in a unit of greenish mudstone, ~1 m thick, that is part of a deeper water succession of shales and lime mudstones that onlaps a fault block of Lower Cambrian sandstone. The host bed consists of illite, quartz, clinochlore and dolomite. Trace element analysis shows an oxygenated water column but with some fluctuations. The fossiliferous mudstone is of similar age as the Burgess Shale itself (*Elrathina* Zone), and has a similar fossil community as the 'Thin Stephen' Formation in British Columbia. The biota includes sponges, the crustaceans *Isoxys* and *Perspicularis*, the priapulid *Ottoia*, and the macroalga *Margaritia*, along with hyolithids, agnostoid and ptychoparioid trilobites, and round organic blobs that represent either microbial mats, coprolites, regurgitites or maybe anomalocarid parts. While a couple of the fossils represent new species, most are known from the early to middle Cambrian Lagerstätten in western Canada and the United States. Arthropods dominate this new assemblage with respect to diversity, whereas hyolithids are the most abundant macrofossil.

APPENDIX C

ABSTRACT GEOLOGICAL SOCIETY OF AMERICA ANNUAL MEETING 2013

Taphonomy of a new middle Cambrian (Series 3) fossil Lagerstätte from the Mackenzie Mountains, northwestern Canada

JULIEN KIMMIG AND BRIAN R. PRATT

A new Lagerstätte in the Rockslide Formation, Mackenzie Mountains of northwestern Canada, is a Burgess Shale-type (BST) deposit of Drumian age (*Bolaspidella* Biozone). A 1 m thick mudstone (composed of illite, quartz, clinochlore and dolomite) contains a low-diversity biota similar to that of the Wheeler and Marjum formations of Utah, and to some extent the Burgess Shale itself. The lithologically heterogeneous composition of the formation (shale, dolomite, lime mudstone, sandstone, mudstone) and absence of metamorphism offer an opportunity to analyze the depositional environment and taphonomy of this deeper water unit via organic/inorganic geochemistry (trace element, $\delta^{13}\text{C}_{\text{org}}$, biomarker, XRD and synchrotron XRF). Similar to other BST Lagerstätten, the environment could not have been deposited under stable anoxic conditions, as the amount of organic matter is too low (TOC= 0.10–0.32%). Trace element ratios, especially V/Sc, indicate low oxygenation of the bottom waters during the deposition of the fossil-bearing interval but a higher oxygen content thereafter. The results differ from most other BST deposits, which suggest oxygenated bottom waters were maintained throughout sedimentation. In addition, organic matter in the sediments and $\delta^{13}\text{C}_{\text{org}}$ values (-22.3–26.9) suggest the presence of benthic microbial mats. Heavy elements are concentrated mostly in nm- μm -sized particles, but some can reach up to 50 μm in size. These are most likely due to bioaccumulation by microbes as they only occur in circular organic residues several centimeters in diameter and there is no indication of hydrothermal activity. These organic residues and the evidence for hyoliths feeding on them suggest an in situ preservation of the biota, perhaps from sudden and short anoxic events and quick burial under either microbial mats and the muddy sediment. This is also supported by the presence of only very rare trace fossils.

APPENDIX D

ABSTRACT GEOLOGICAL SOCIETY OF AMERICA ANNUAL MEETING 2014

Silver in microbial mats of the middle Cambrian Ravens Throat River deposit: an environmental and preservation factor?

JULIEN KIMMIG AND BRIAN R. PRATT

Burgess Shale-type (BST) Lagerstätten are early Paleozoic deposits with extraordinary preservation. While the fossils are well known and extensively studied, the mode of preservation of these fossils is still controversial. The Ravens Throat River Lagerstätte, in the Drumian of the Mackenzie Mountains, is a prime subject for an investigation of the ecological factors that contributed to the exceptional preservation, as it has a low metamorphic degree. The deposit is specimen rich, but species poor and likely represents a high stress environment fauna. In contrast to the well-known BST deposits, this Lagerstätte conserves mainly robust parts, even so it was deposited under an oxic to disoxic water column similar to the Burgess Shale or the Emu Bay deposits. The sediments though conserve large amounts of organics, likely representing microbial mats. On the bedding plain the microbial remains are circular and up to 5 cm in diameter. They occur throughout the main fossil bed of the deposit, and are found in association with trilobites and hyoliths. In many cases the associated fossils are completely preserved and appear to be in feeding position. One unique feature of the Ravens Throat River Lagerstätte is the high concentration of Ag in the fossil bed (up to 0.45 ppm), and an even higher concentration in the microbial remains. The Ag particles in the microbial remains range in size from a few μm up to several 100 μm and microprobe studies indicate it is elemental Ag. The underlying lime mudstones only contain a fraction of the Ag amount (0.07), and preserve only a few trilobite fossils. The role of microorganisms in the reduction and accumulation of noble metals has been well documented and is thought to be of great importance in the creation of mineral deposits. Both algae and bacteria have the potential to leach nanoparticles out of the water column. Considering the extensive accumulation of Ag in microbial mats in the Ravens Throat River Formation, there is some indication that similar processes might have caused the Ag accumulation in this deposit. The

Mackenzie Mountains contain several important ore deposits, but only the Anvil District (Yukon Territory) of the Selwyn Basin and the Proterozoic (<780 Ma) Coates Lake Group predate the Rockslide Formation and can be considered as source for the Ag.