This is to certify that the
thesis entitled

SEDIMENTARY DYNAMICS AND STRATINOMY OF A
MIDDLE CAMBRIAN ICHNOFOSSIL LAGERSTÄTTE, GROS
VENTRE FORMATION, WYOMING, USA

presented by

JAYME DAY CSONKA

has been accepted towards fulfillment
of the requirements for the

M.S degree in Geological Sciences

Danita Brandt
Major Professor's Signature

May 15, 2009
Date

SEDIMENTARY DYNAMICS AND STRATINOMY OF A MIDDLE CAMBRIAN ICHNOFOSSIL LAGERSTÄTTE, GROS VENTRE FORMATION, WYOMING, USA

By

Jayme Day Csonka

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Geological Sciences

2009

ABSTRACT

SEDIMENTARY DYNAMICS AND STRATINOMY OF A MIDDLE CAMBRIAN ICHNOFOSSIL LAGERSTÄTTE, GROS VENTRE FORMATION, WYOMING, USA

By

Jayme Day Csonka

The ichnofossil *Rusophycus* is the product of a typical behavior of trilobites, but is only preserved under unique conditions. A unique confluence of conditions existed in the Middle Cambrian Gros Ventre environment and resulted in the preservation of a *Rusophycus* lagerstätte. These conditions include the background deposition of firm, cohesive muds possibly bound by bacterial mats. The muds had a firmness that allowed the burrows to maintain their shape until they were filled in and cast during the next phase of sand deposition, likely from a storm. The deposition of sands following episodic high energy events provided an ideal casting medium for *Rusophycus* . The absence of spreite and presence of individual storm events in sectioned *Rusophycus* support this conclusion. These results contradict previous assertions that the *Rusophycus* ichnofossil was excavated by trilobites burrowing through sand to a muddy interface. The Gros Ventre Formation falls in the middle of the Cambrian Substrate Revolution. Bacterial mats were present before, during, and after the deposition of the Gros Ventre Formation. Bioturbation indices for the Gros Ventre Formation are comparable to those documented for the Cambrian by other workers and support the idea of a gradual increase of bioturbation intensity during the Middle Cambrian.

This project is dedicated in its entirety to the memory of Myles Alexander Redder (1984-2008), whose advice, support, and physical labor were sorely missed for the duration of this project.

ACKNOWLEDGMENTS

My utmost gratitude is given to my advisor, Dr. Danita Brandt (Michigan State University), and additional committee members, Dr. Robert Anstey and Dr. Brian Hampton (Michigan State University). Additional thanks particularly to Dr. Carlton Brett (University of Cincinnati) for numerous useful discussions. Thanks to Aric Velbel for help conducting fieldwork. Thanks to my network of friends and family for their advice and support. This project could not have been completed with the donation of funds from the Aureal Cross Fund for Fieldwork in Paleontology and the Pringle-Drake Fellowship. Thanks to Dan Scaife, Will Young, and Cheri Jones of the Big Horn National Forest Service for allowing fieldwork to be conducted on National Forest land. Thanks to Dr. Warren Wood (Michigan State University) for the loan of equipment used in the field. Thanks to the users of Lansing Michigan Freecycle and Mid-Michigan ReUseIt Networks for the donations of many useful supplies used in this project.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

This project describes animal-sediment relationships, biostratinomy, and sedimentary dynamics in the Middle Cambrian Gros Ventre Formation of north-central Wyoming. The Middle Cambrian is an interval of interest because it spans the transition from Late Neoproterozoic matground substrates to Late Cambrian mudground substrates in what has been called the Cambrian Substrate Revolution (Bottjer, et al., 2000) and Agronomic Revolution (Seilacher & Pfluger, 1994), events that may be partially documented in exposed sections of the Gros Ventre Formation in the Big Horn Mountains of Wyoming.

The Gros Ventre Formation is also interesting because it contains an unusual abundance of the trilobite trace fossil, *Rusophycus*. This abundance of trace fossils from the Gros Ventre Formation offers an exceptional window into early Paleozoic sedimentary dynamics and ecological change following the Cambrian Explosion (Runnegar, 1982) and subsequent Agronomic Revolution (Seilacher and Pfluger, 1994) (Figure 1). Substantial work has been done on the association of ichnotaxa and substrates of the Proterozoic/Paleozoic boundary (Bottjer, et al., 2000) and the Cambrian/Ordovician boundary (Droser and Bottjer, 1989). Less work has been done on the significance of Middle Cambrian ichnotaxa and the substrate relationships of their trace-makers.

In this project the Gros Ventre Formation was examined at three scales, which include from smallest to largest: (1) description of the dynamics of *Rusophycus* excavation and preservation, (2) description and interpretation of the sedimentary conditions that resulted in the exceptional preservation of the ichnofossils, and (3) evaluation of how these ichnofossils contribute to our understanding of the transition of marine substrates from undisturbed bacterial matgrounds at the Proterozoic/Paleozoic boundary to completely bioturbated mudgrounds at the base of the Ordovician System.

Three hypotheses, one corresponding to each scale of investigation, were tested: (1) *Rusophycus* formation is the result of active backfilling by trilobite trace-makers (Seilacher, 2007); (2) ichnofossil preservation in the Gros Ventre is the result of episodic storm deposits and tidal deposition; (3) at the transition from Late Neoproterozoic matgrounds to Late Cambrian mudground, Middle Cambrian strata will show a mix of bacterial matgrounds and bioturbation, and that depth and intensity of bioturbation will be greater in the Middle Cambrian than described for the Proterozoic/Paleozoic transition, but less than that of the Cambrian/Ordovician transition.

The Cambrian Substrate Revolution/Agronomic Revolution

Marine substrates of the Late Neoproterozoic are typically characterized by abundant bacterial mats (Bottjer, et al., 2000). These bacterial matgrounds formed a sharp sediment-water interface and thrived in the absence of vertical bioturbation. The Cambrian Explosion, of the early Cambrian (Series Two, Stage Three—informally called the Atdabanian) (International Commission on Stratigraphy, 2008), in which there was a presumptively rapid diversification of phyla (Runnegar, 1982), resulted in fundamental change in the trophic structure of seafloor faunal communities. Bacterial mats were an abundant, but diminishing biotope that also hosted predators, which could feed on the organisms that fed on the bacterial mats. By the end of the Cambrian, an increase in predation and relocation of microbes from bacterial mats to the coatings of clastic grains due to vertical bioturbation led to a decline in abundance of bacterial matgrounds, and a subsequent increase in water content within the substrate, causing a less distinct sediment-water interface and less cohesive, muddier substrates (Droser et al, 1999; Bottjer, et al., 2000, Seilacher, 2007). By the earliest Ordovician, the majority of bacterial matgrounds had been converted to mudgrounds (Droser and Bottjer, 1989). This change in substrates is referred to as the Cambrian Substrate Revolution (Bottjer, et al, 2000)(Figure 1), which can be considered a sedimentary effect of the Agronomic Revolution (Figure 1), the process by which the substrate-linked feeding patterns of organisms were permanently altered due to changes in substrate consistency, location of food sources, and safety from predation (Seilacher, 2007).

Agronomic Revolution

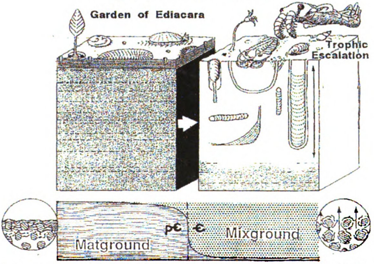


Figure 1. Agronomic Revolution. Image source: Seilacher, 2007. This figure also documents the transition of matgrounds to mudgrounds (mixgrounds) during the Cambrian Substrate Revolution. Note transition from surface to vertical burrowing.

Ichnofossils (e.g., tracks, trails, or burrows) are a key tool for understanding the Cambrian Substrate Revolution. They provide evidence for the behavior of organisms, and are extremely valuable for studying deposits void of body fossils, but rich in ichnofossils, a typical paradoxical characteristic of many ichnofossil deposits in the sedimentary record. This study examines a critical window of the Middle Cambrian, which is less well-documented than the earliest stages of the Cambrian and Ordovician Periods. The sediment-animal dynamics of the Middle Cambrian is of particular importance for understanding the chronological development of the Cambrian Substrate Revolution. The results of this study will help paleontologists and stratigraphers understand whether the transformation from Proterozoic sedimentary fabric to Ordovician fabric was transitional or whether the middle Cambrian may have marked an abrupt "tipping point" (*sensu* Gladwell, 2002) in the evolution of the sedimentary fabric of the marine seafloor.

Geologic Setting

The seven localities studied in the area around Burgess Junction in the Big Horn Mountains of Wyoming (U.S.A) were all Cambrian exposures (Figures 2, 3, 4, and 5). The primary stratigraphic interval of interest was the Middle Cambrian Gros Ventre Formation, but the underlying Flathead (sandstone) and overlying Gallatin (limestone) Formations were also examined in the area near Burgess Junction for contextual data.

The Gros Ventre Formation was first formally described by Blackwelder (1918) as having:

> Greenish and gray calcareous shales, with gray, striped conglomeratic and oolitic limestones, separating overlying Gallatin Limestone from underlying Flathead quartzite. Contains Middle Cambrian fossils.

The type section of the Gros Ventre is exposed on the western slope of Doubletop Peak in the Gros Ventre Range of western Wyoming (Blackwelder, 1918). The Gros Ventre of the Big Horn Mountains is primarily composed of mudstones, silts, and sands that were deposited during the Sauk Sea transgression.

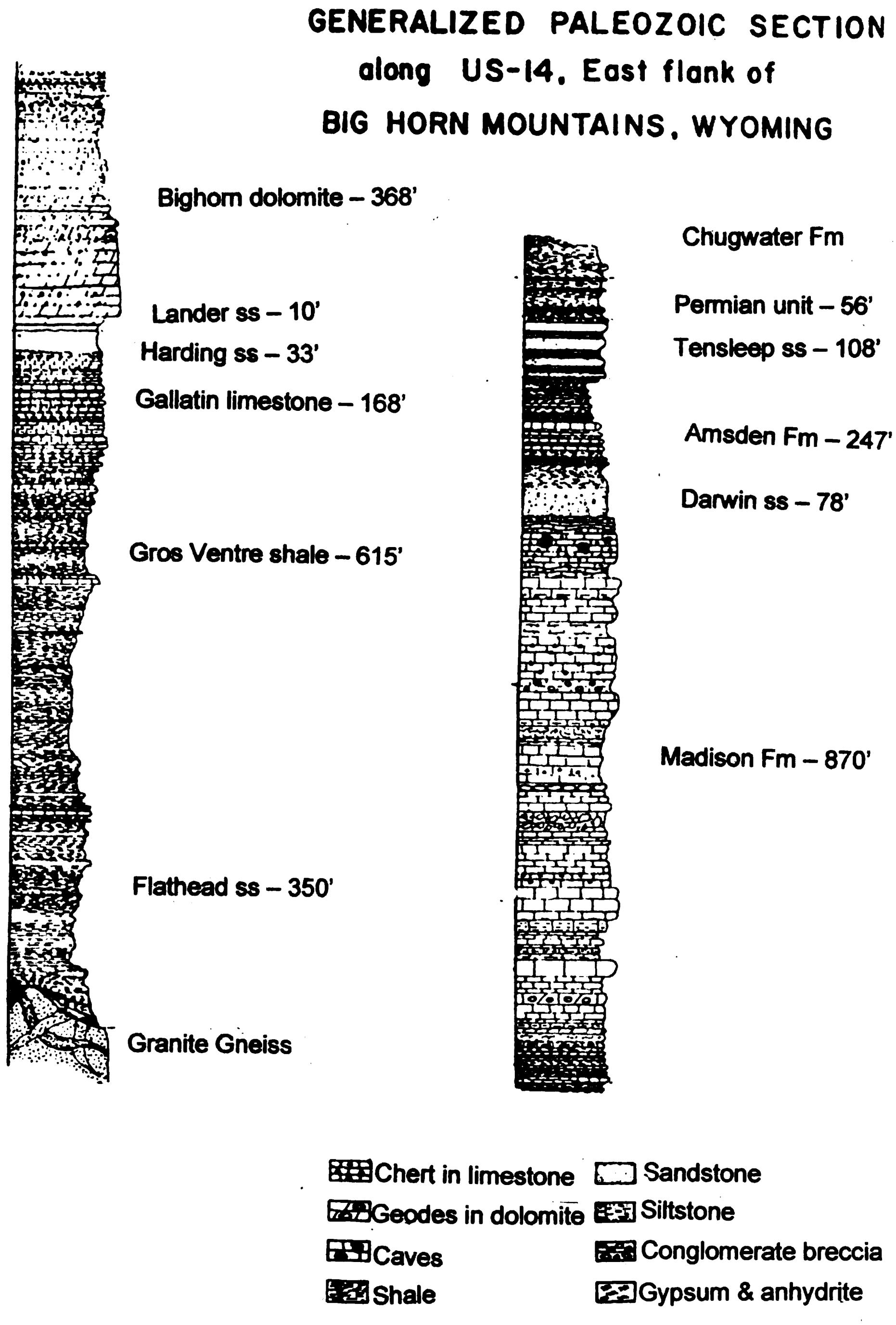


Figure 2. Generalized stratigraphic column summarizing the Paleozoic stratigraphy of the Big Horn Mountains. From Koucky and Cygan (1963).

Figure 3. Map of Wyoming highlighting Burgess Junction. Arrow Points to Burgess Junction. Image source: Google Earth

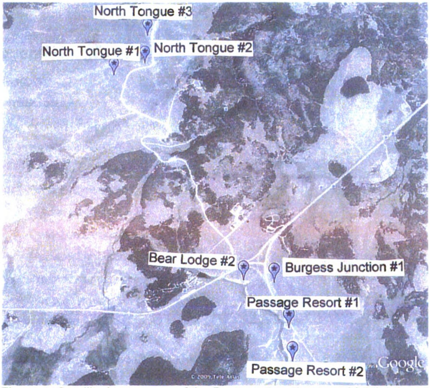


Figure 4. Satellite image map of the Burgess Junction area highlighting studied exposures. Field of view is approximately 1 mile. Image source: Google Earth

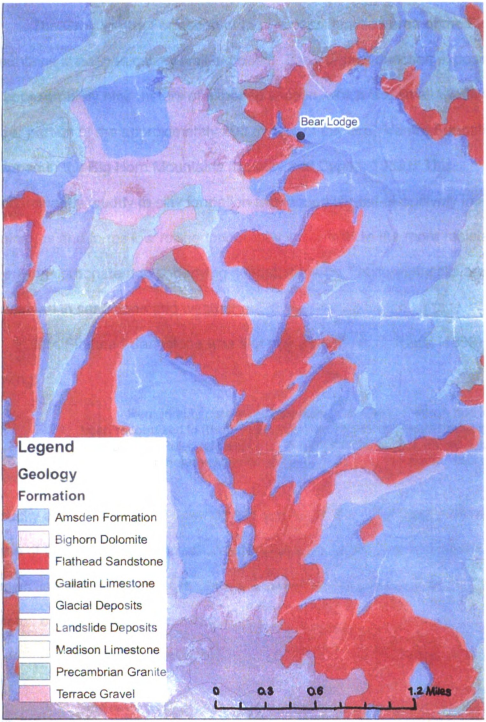


Figure 5. Geologic Map of the Burgess Junction area. Note, Gros Ventre Formation is grouped with the Flathead Sandstone on this map. Image source: Big Horn National Forest Service.

The Gros Ventre Formation of the Burgess Junction area of the Big Horn Mountains is not particularly well-exposed. The Burgess Junction exposures are of approximately nine meters of exposed section, which is a small window of the lower portion of the approximately 200 meters of the Gros Ventre Formation mapped in the Big Horn Mountains (Koucky and Cygan, 1963). The predominantly muddy to silty formation is exposed almost exclusively in drainages and forms low rolling topography in contrast to the more resistant overlying carbonate and underlying sandstone units. The ichnofossils are preserved in sandstone and weather out in abundance on the surface.

The Flathead Sandstone was first described by A.C. Peale (1893) as having:

> Remarkably persistent quartzite or sandstone, which has long been recognized in [the] Rocky Mountain region as lying in most cases at [the] base of Paleozoic section…In places rests on Belt series and in places on Archean schists or gneisses.

Koucky and Cygan (1963) describe the contact at the top of the Flathead with the base of the Gros Ventre formation in the Big Horn Mountains as a series of brown limestone trilobite hash beds (Figure 6a and 6b). See Appendix 2 for field photos of the Flathead Sandstone.

The Gallatin Limestone was first described by A.C. Peale (1893) as

> mainly calcite…[and] conformably overlain by Jefferson Limestone and rests on Flathead Shales…Named for typical occurrence in Gallatin Range (the southern extension of which is in [the] Northwest corner of Yellowstone Park…It is essentially a series of limestones, more massively bedded than those of underlying Flathead Formation, and forms first prominent limestone bluff that rises above the Archean areas.

Koucky and Cygan (1963) described the contact at the top of the Gros Ventre Formation with the base of the Gallatin Limestone as the first prominent limestone ledge creating a break in the slope. The Gallatin is described having more massive limestone beds and fewer mudstone beds, in contrast to the muddy underlying Gros Ventre Formation. See Appendix 2 for field photos of the Gallatin Limestone.

Figure 6a. Trilobite hash from top of Flathead Sandstone at NT1. Scale bar is 2 cm.

Figure 6b. Trilobite hash from top of Flathead Sandstone. Scale bar is 1cm

The Flathead, Gros Ventre, and Gallatin Formations are all part of a facies transition from a sandy shoreface during the time of Flathead deposition to an open marine carbonate shelf during the deposition of the Gallatin Formation. Morgan (1998) described the Flathead Formation and Wolsey Formation (a lateral equivalent of the Gros Ventre Formation in the nearby Clarks Fork region of Wyoming), as a classic transgressive succession for the Middle Cambrian, which occurred from west to east with a shoreline trending North-South. The thickness of the Flathead Formation is variable depending on the underlying topography created by the 2.7 Ga Precambrian granite complex (Middleton, 1980; Sepkoski, 1982). Morgan (1998) described the Wolsey as a transition from predominant deposition of sands to predominant offshore muds at fair-weather wave base with sand layers incorporated into the Wolsey during periods of storm activity causing increased wave energy.

Sepkoski (1982) wrote about the Sauk Sea transgression, focusing on the flat-pebble conglomerates present in the Gallatin Formation, but described an overall depositional system for the Cambrian in this region as a storm dominated shallow-water depositional environment and described the paleoenvironment of the Gros Ventre Formation as a subtidal lagoon (Figure 7).

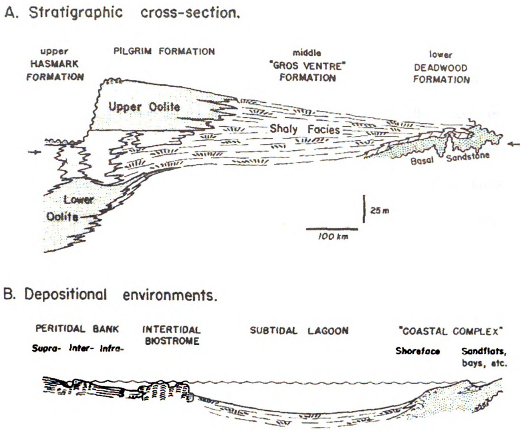


Figure 7. Sepkoski's (1982) paleoenvironmental interpretation. Note, the Pilgrim is a lateral equivalent to the Flathead Sandstone and the Deadwood Formation is a lateral equivalent to the Gallatin Limestone.

MATERIALS AND METHODS

Seven exposures (Figure 4, Appendix 2) were studied in the area around Burgess Junction, Wyoming. Four of these exposures were of the Gros Ventre Formation (Burgess Junction 1, Bear Lodge 2, Passage Resort 1 and Passage Resort 2). All of the Gros Ventre exposures were measured. Three sections were sampled at a 5-10 cm interval: Burgess Junction 1, Passage Resort 1, and Passage Resort 2. Ichnofossils found *in situ* were also collected and recorded in the stratigraphic chart (see Appendix 1 and Figures 20a and 20b). An abundance of ichnofossils found in float were collected, though a substantial number were left at the exposure because of the overwhelming number of ichnofossils in float.

The samples were unpacked and stored in the Paleontology Laboratory at Michigan State University's Department of Geological Sciences. Twenty specimens of *Rusophycus* and ten specimens of *Teichichnus* ichnofossils were cut in cross section in multiple orientations with a diamond-blade rock saw and then polished to examine internal structure. Twenty-two samples were prepared and shipped to Vancouver GeoTech Labs to be prepared as thin sections. A thin section sample was selected for each of the major sedimentary packages and marker beds represented in the exposed sections. The majority of the thin section samples were selected from beds that could have a thin section made of both the bedding and an *in situ* ichnofossil (the use of *in situ* implies that the sample was collected and documented while measuring the exposed section). Bioturbation intensity was determined using the index of Droser and Bottjer

(1986) for within-bed bioturbation and that of Miller and Smail (1997) for bioturbation on bedding surfaces. Images in this thesis are presented in color.

DESCRIPTION OF ICHNOFOSSILS PRESENT

Rusophycus

The ichnofossil *Rusophycus* (Figures 8a-h) is a bilobed, hypichnial ichnofossil found as casts on the sole surface of sedimentary beds, and was originally described in 1852 by James Hall as being a "fucoid" with a presumed algal origin (Hall, 1852) followed by a later interpretation as an ichnofossil produced by an arthropod trace-maker (Dawson, 1864; Nathorst, 1883, 1886). Subsequent ethological interpretations of *Rusophycus* as an arthropod ichnofossil include its possible origin as a nesting structure (Fenton and Fenton, 1937), a burrow for hiding from predators or hunting for prey (Seilacher, 1953, 1955, 1959; Osgood, 1970; Bergström, 1973; Osgood and Drennan, 1975; Brandt, et al., 1995) or a structure excavated for feeding (Glaessner, 1957; Whittington, 1980; Seilacher, 1985). For a more detailed description of *Rusophycus* ethology, see Brandt's (2008) description of multiple *Rusophycus* assemblages. It is not the purpose of this thesis to review the taxonomy of *Rusophycus* (e.g., placement of *Rusophycus* in synonomy with *Cruziana* or the number of ichnospecies present). For more detail on *Rusophycus* taxonomy, see Osgood (1970), Birkenmajer and Bruton (1971), Crimes (1975), Bergström (1976), Bromley and Asgaard (1979), Pollard (1985), Buatois and Mángano (1993), Keighley and Pickerill (1996), Bromley (1996), and Seilacher (2007). The definition of *Rusophycus* used in this thesis follows that described by Hänzschel (1975) as short, bilobate traces, with or without transverse striae or wrinkles. The probable *Rusophycus*-makers in the Gros Ventre Formation were *Elvinia, Irvingella, Parabolinoides, Ehmania, Arapahoia, Cedaria,* and *Tricrepicephalus.*

Figure 8a. *Rusophycus* from Passage Resort 2 (Gros Ventre Formation). Scale bar is 2 cm.

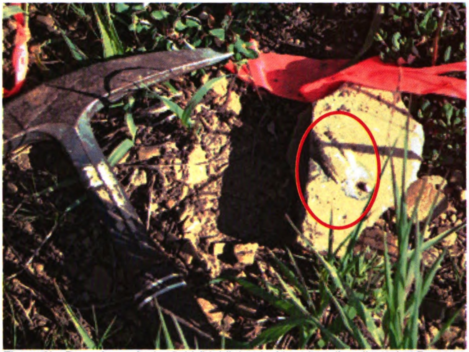


Figure 8b. *Rusophycus* in the field (highlighted with red oval), collected at Burgess Junction 1 (Gros Ventre Formation). Hammer (12 inches exposed) for scale.

Figure 8c. Slab with multiple *Rusophycus* and other traces. Scale is 2 cm

Figure 8d. *Rusophycus* with pebble of potassium feldspar, highlighted with red oval. Collected at Bear Lodge 2 (Gros Ventre Formation). Scale bar is 2cm.

Figure 8e. *Rusophycus* with large pebble (3 cm) cross-cutting specimen. Pebble is absent, but mold of it remains. Scale bar is 2 cm

Figure 8f. Smallest size *Rusophycus* collected in Burgess Junction. Scale bar is 1 cm

Figure 8g. Small sized Rusophycus collected in Burgess Junction. Scale bar is 1 cm

Figure 8h. Medium sized *Rusophycus* collected at Burgess Junction. Scale bar is 1cm.

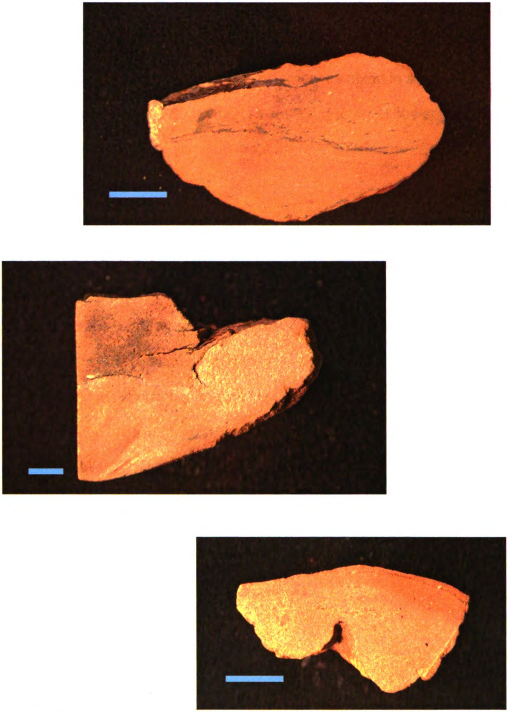


Figure 9. Cross-sectioned specimens of *Rusophycus*. Scale bars are all 2 cm.

In the Gros Ventre Formation at Burgess Junction, the *Rusophycus* occur as isolated sand lenses in muds, or on the sole surfaces of sandstone beds. The *Rusophycus* tend to be more concentrated in horizons that are stratigraphically above sandstone beds (see ichnofossil occurrences noted in stratigraphic columns, Figures 20a and 20b). In cross-section (Figure 9), the specimens show fine sandy to silty laminae with mud drapes; some specimens yield cross-bedding.

Teichichnus

The ichnofossil *Teichichnus* (Figures 10a and 10b) is also found in abundance at the Burgess Junction Gros Ventre exposures. *Teichichnus* is commonly attributed to the work of worms, but sometimes interpreted as the work of arthropods simply because of the breadth of the structure, which has been considered too wide for the body of an annelid or any other worm-like organisms (Seilacher, 2007).

Teichichnus bears a morphologic similarity to the ichnofossil *Diplocraterion* with its serial repetition of spreiten, but the tubes of the *Teichichnus* ichnofossil have a J-shape, rather than the U-shape seen in *Diplocraterion.* Seilacher (2007) described *Teichichnus* as:

> characterized by transversal backfill structures that are not evenly draped between the two shafts of a U-tube. Rather, they were generated by J-tubes, very shallow U-tubes, or only in a limited stretch of an undefined tunnel system. Most of them have a retrusive backfill system.

Teichichnus is one of the most abundant ichnofossils found at the Burgess Junction exposures. They tend to occur in the thinner sandy lenses in the silty to muddy beds (see ichnofossil occurrences noted in stratigraphic columns in Figures 20a and 20b). *Teichichnus* is usually not found in conjunction with *Rusophycus* at the studied exposures. In cross-section (Figures 11a and 11b), the specimens show concave up spreiten.

Figure 10a. *Teichichnus* from PR2 (Gros Ventre Formation), scale bar is 2cm.

Figure 10b. *Teichichnus* from PR2 (Gros Ventre Formation), scale bar is 2cm.

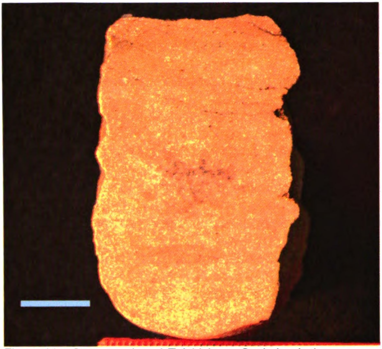


Figure 11a. Cross-sectioned *Teichichnus.* Scale bar is 1 cm.

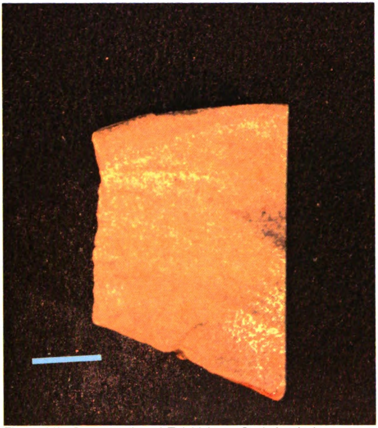


Figure 11b. Cross-sectioned *Teichichnus.* Scale bar is 1 cm.

Chondrites

Seilacher (2007) described *Chondrites* (Figure 12) with a stratigraphic range of Ordovician to Paleogene in shelf facies, and in Recent deep sea muds, with newer discoveries of *Chondrites* in modern deep sea muds. Häntzschel (1975) listed a lower Cambrian occurrence of *Chondrites*. These simple, branching burrows are often considered an indicator of low-oxygen conditions and typically occur along bedding planes in turbidite series, shallow marine shales, and storm sands (Seilacher, 2007). A *Chondrites*-bearing bed is a distinct stratigraphic unit within the Gros Ventre Formation at the Burgess Junction localities that serves as a marker bed for correlation between exposures with its green siltstones, mudstones, and abundant *Chondrites* ichnofossils (Figures 20a and 20b).

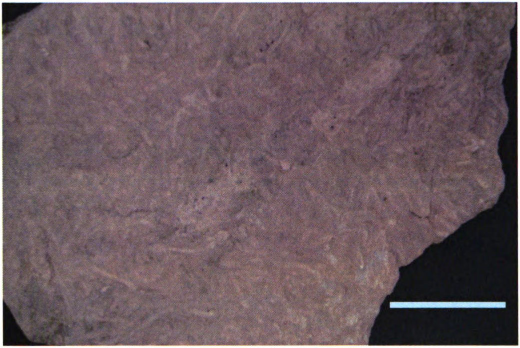


Figure 12 *Chondrites* from PR2 (Gros Ventre Formation). Scale bar is 5cm.

Skolithos

Simple cylindrical, vertical burrows found extending to both the top and sole surfaces of sandstone beds in the Flathead Sandstone (Figure 13). These types of burrows are typical of the *Skolithos* ichnofacies (figure 24), which characterizes the Flathead sandstones as originating from a sublittoral, high energy, sandy environment. *Skolithos* burrows are also present in the Gros Ventre, but are not as abundant.

Figure 13. *Skolithos* Burrows from NT1 (Flathead Sandstone). Scale bar is 2 cm.

PSEUDOICHNOFOSSILS PRESENT

This section is designated for sedimentary structures associated with bacterial mats.

Kinneyia

The wrinkle structure, Kinneyia (Figures 14a and 14b), is not an ichnofossil, but rather a sedimentary structure often interpreted as a pseudofossil and formerly treated as problematica (Häntzchel, 1975). Kinneyia is presumed to form in the earlier stages of bacterial mat development, and not formed by sediment loading or burial processes on the bacterial mat, but rather, by oscillations of water flowing beneath a partially liquefied area at the interface between the bacterial mat and the underlying sediment (Porada, et al, 2008).

Figure 14a. *Kinneyia* preserved in sandstone from NT1 (Flathead Sandstone). Scale bar is 10cm.

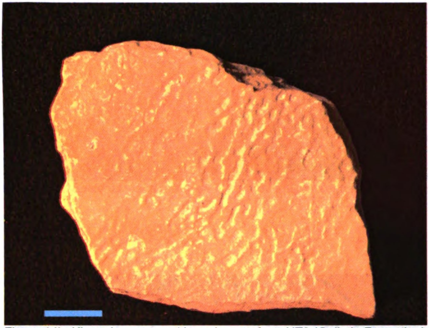


Figure 14b. Kinneyia preserved in carbonate from NT3 (Gallatin Formation). Scale bar is 2 cm.

Bacterial Mat Structures

A number of specimens were collected that were interpreted by this author as bacterial mat structures (Figures 15a and 15b), but are different from Kinneyia, as these structures are likely either fossilized bacterial mats or casts of bacterial mats. They differ from Kinneyia because they are not interpreted as the results of fluid dynamics (Porada, et al,. 2008).

Figure 15a. Bacterial mat structures (?) from BJ1 (Gros Ventre Formation), scale bar is 2cm

Figure 15b. Probable bacterial mat structure from Gallatin Limestone. Scale is 2 cm.

RESULTS

Rusophycus Biostratinomy

Rusophycus occur as discrete sand lenses within beds of micaceous silty mudstone (shale classifications are based upon the descriptions of Potter, Maynard, and Pryor, 1980), as well as casts on the sole of sandstone beds. Preservation of the *Rusophycus* ichnofossils ranges from indistinct bilobed structures to specimens showing impressions of the ventral anatomy, outline of the cephalon, and detailed scratch marks. Several *Rusophycus* have large angular rocks fragments of arkosic (primarily potassium feldspar and quartz) incorporated into the trace (Figures 8D and 8E). The sectioned and polished specimens (Figure 9) show an internal structure of fine laminae of sand and silt with mud drapes.

Sedimentary Dynamics in the Gros Ventre

The base of the exposed sections of Gros Ventre have well-sorted sandstones that grade into green silty mudstones with abundant *Chondrites.* The *Chondrites* beds served as a stratigraphic marker for correlating the four exposures of Gros Ventre studied in the Burgess Junction area. Some very poorly preserved *Rusophycus* were found in these lower intervals, though they become abundant and better preserved in the upper portions of the stratigraphic sections. The beds have an overall fining upwards trend (Figures 20a and 20b) with more abundant silt beds draped in mud with regularly spaced sandy lenses towards the top of the exposed sections. The thicker sand beds have graded bedding with sole marks (Figure 16a) and mud lenses and rip-up clasts (Figure 17) within the bedding as well as mud drapes around the beds. Additionally, the thicker sand beds are almost always topped with a densely bioturbated layer (Figures 18a and 18b) of silt draped in mud. This very rhythmic pattern of sandy, silty, and muddy layers (Figure 19) repeats itself all the way to the top of the section.

Figure 16a. Scour marks on sole of bed from BJ1. Scale bar is 5 cm

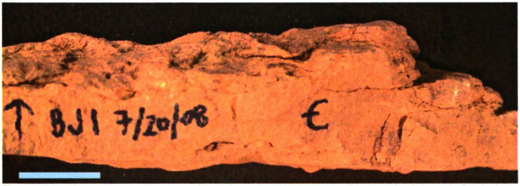


Figure 16b. Cross-sectional view of bed from BJ1 featured in Figure 16a (above). Scale bar is 5 cm

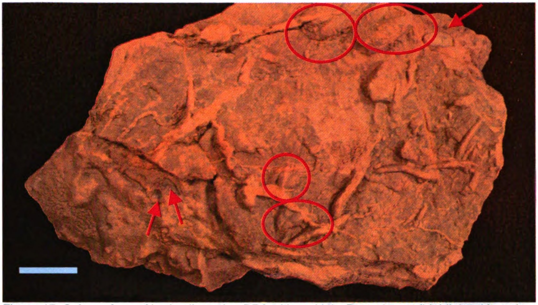


Figure 17. Sole surface of bed collected at PR2 with multiple *Rusophycus* (highlighted in red ovals) and rip-up clasts (shown with red arrows). Scale bar is 5 cm.

Figure 18a. Bed PR2+810 in the field. Notebook (12 cm wide) for scale. This bed is contains heavily bioturbated muds with a bioturbation index of 4.

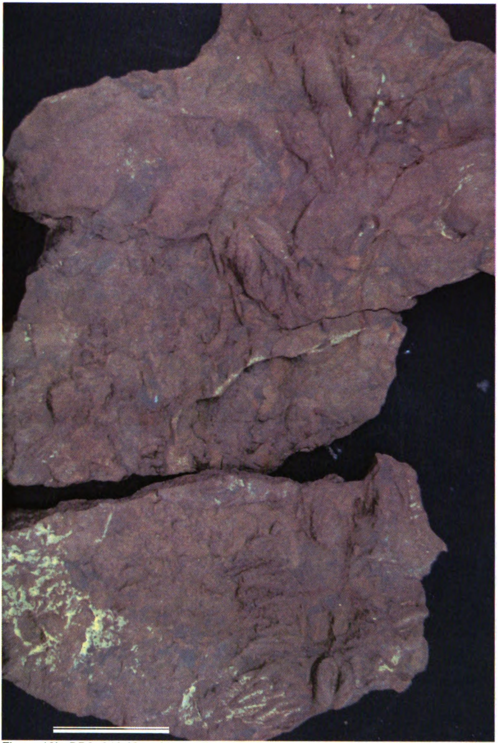


Figure 18b. PR2+810 (Gros Ventre Formation), densely bioturbated layer with multiple *Rusophycus*. Index of Bioturbation for this bed is 4. Scale Bar is 5cm.

Figure 19. Mud/silt/sand beds topped with rippled sandstone at PR2 (Gros Ventre Formation). Hammer (22 inches) for scale.

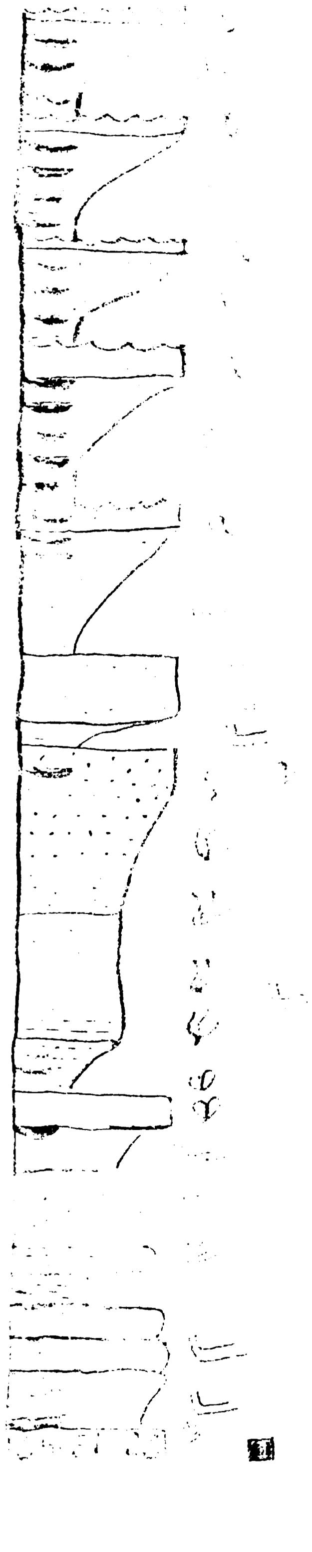


Figure 20. Composite stratigraphic column (hand drawn) of the Burgess Junction area.

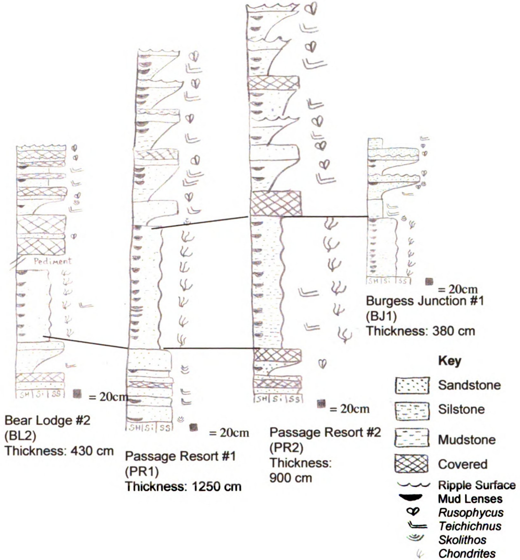


Figure 20b. Correlated stratigraphic section (hand drawn) of exposures in the Burgess Junction area. Lines are drawn correlating the *Chondrites* marker beds.

No body fossils were found in the measured sections of the Gros Ventre Formation, though fragments of trilobites were collected from the Flathead Sandstone, and body fossils are present in the overlying Gallatin Limestone. The lowermost exposed portions of the section contained well-sorted sandstones that grade into muddier green shale/silt with abundant *Chondrites* (Figure 20a and 20b).

Ichnofabric of the Middle Cambrian Gros Ventre Formation

121 samples of beds from the Gros Ventre Formation were collected from the Burgess Junction area. Each sample was described in detail for composition, grain size, sorting, rounding of grains, and bioturbation index of both the bedding plane and cross-section of the sample (detailed descriptions given in Appendix 1). The average bioturbation index for the bedding planes is 2.332 (on a scale of 0 through 5), using the Miller and Smail (1998) index of bioturbation. The average bioturbation index for the cross section of samples is 2.105 (on a scale of 0 through 5), using the index of bioturbation developed by Droser and Bottjer (1986). Bioturbation was most well-developed in the beds with abundant *Chondrites* (Figure 20a and 20b), which have an average cross-sectional and bedding plane index of 3.5. These results are shown in the histograms below.

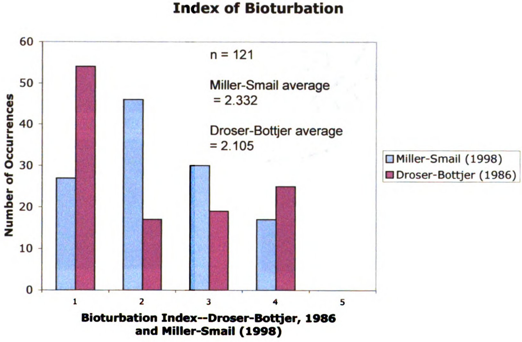


Figure 21. Histogram combining both the Droser-Bottjer (1986) and Miller-Smail (1998) bioturbation indices.`

Petrographic Data

The ichnofossil and associated bedding thin sections were composed of sandstones that were dominantly monocrystalline quartz and potassium feldspar with some polycrystalline quartz and zircon in a matrix of fine-grained pyrite and clay present as black stringers and as brown coatings around the quartz and feldspar grains. Comparisons were made between ichnofossils samples and associated bedding from the same horizon, specifically focusing on *Rusophycus* and *Teichichnus.*(Figure 22). The *Rusophycus* thin sections show a similar grain size as well as a comparable amount of brown coating on the clastic grains than the associated bedding from the same horizon. The *Teichichnus* thin sections have a smaller grain size and less of the brown coating on the clastic grains than the associated bedding from the same horizon.

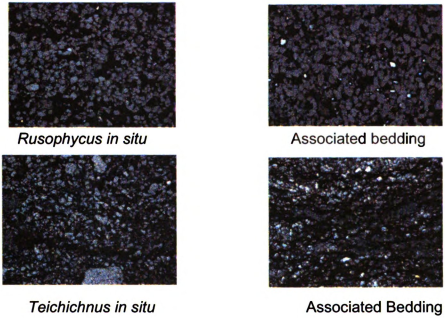


Figure 22. Thin section photomicrographs at 10x power.

DISCUSSION

Rusophycus Biostratinomy

The method of excavation by the *Rusophycus* trace-maker has been a subject of debate in the ichnofossil community. Some ichnologists have inferred that *Rusophycus* was excavated on the surface of muddy substrates and subsequently infilled by sedimentation (Osgood, 1970; Crimes, 1975; Baldwin, 1977). Other ichnologists have proposed an intrastratal origin for *Rusophycus*, claiming that the organism burrowed in sand to a muddy interface and actively backfilled the trace as it was being excavated (Seilacher, 1955, 1970, 1983, 1985; Birkenmajer and Bruton, 1971).

The abundance of *Rusophycus* in the Gros Ventre Formation made it possible to section and polish 20 specimens (Figure 9*)* and test the interstratal hypothesis by looking for the spreiten (internal structures) predicted by Seilacher's scenario.

The sectioned and polished specimens showed fining upward laminae of sand and silt with mud drapes, indicative of episodic deposition and sedimentary processes. Spreiten would look like concentric U-shaped laminae created by the trilobite trace-maker. The *Rusophycus* appear to be filled by multiple sedimentary events (three or more pulses of sedimentation) following the excavation of a burrow in exposed muds.

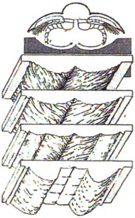


Figure 23a.Seilacher's (2007) diagram of *Rusophycus* burrowing techniques. Note, no cross-sectional detail given.

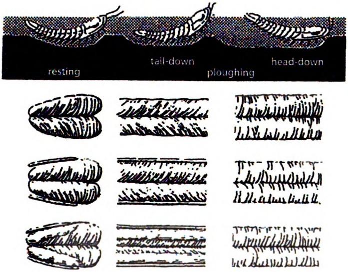


Figure 23b. *Rusophycus* excavation techniques proposed by Seilacher (2007). Note, excavation is inferred to be done subsurface at a sand-mud interface.

Additional support for the scenario that the *Rusophycus* were passively filled comes from the grain size of some of the sand beds in which the *Rusophycus* are preserved (Figures 8d and 8e). These *Rusophycus* have large angular grains cross-cutting the specimen and were clearly deposited after the trace was excavated.

Evaluation of the photomicrographs (Figure 22) taken from thin sections of ichnofossils and their associated bedding from the same horizon show sandstones with clastic grains of quartz and potassium feldspar, matching the composition to the underlying and nonconforming Precambrian granites. The brown coatings on the grains are organic matter derived from the abundant bacterial mats present in the Sauk Sea. The brown coatings were evaluated by comparison to photomicrographs of similar sandstone facies (Scholle, 1979) and photomicrographs of Kinneyia (Porada, et al., 2008). Other supporting evidence for the presence of organic matter (bacterial mat-derived) coating the clastic grains include the presence of bacterial mat structures in the Gros Ventre Formation and overlying units and the abundance of *Rusophycus* ichnofossil, which suggests an abundant food source (bacterial mats) in the Sauk Sea.

In thin section, the *Rusophycus* ichnofossils show a similar grain size to associated bedding of the same horizon. This observation suggests that the *Rusophycus* contain a casting medium that is the result of sedimentary deposition, rather than biologic reworking of the sediment by the *Rusophycus* trilobite trace-maker. In contrast, *Teichichnus* ichnofossils in thin-section show less organic material and smaller grains than the associated bedding of the same horizon. The *Teichichnus* ichnofossils show substantially less organic matter in the matrix or on the coatings of clastic grains. This suggests that the *Teichichnus* ichnofossil is the product of active work of the *Teichichnus* trace-maker burrowing down through the sediment, producing spreite and ingesting organic matter (Figure 22).

These results are congruent with other results from this project derived from evaluation of hand samples, cross-sectioned hand samples, and the sedimentary dynamics of the Sauk Sea transgression. The *Rusophycus* ichnofossils were excavated in open muds and subsequently filled by sedimentation.

Sedimentary dynamics in the Gros Ventre Formation

The fining upward rhythmic pattern of the sandy, silty, and muddy Gros Ventre Formation is consistent with previous descriptions (Sepkoski ,1982; Morgan, 1998; Middleton, 1980) of this sequence as a fining upward transgressive system. The underlying Flathead Formation is primarily characterized by shoreface sands and ichnofossils typical of the *Skolithos* ichnofacies (Figure 24). The depositional environment transitions to a sublittoral zone during the deposition of the Gros Ventre Formation. The Gros Ventre is characterized by mud-drapes and flaser-bedded sands, silts, and muds and contains ichnofossils typical of the *Cruziana* ichnofacies (Figure 24) with particularly abundant and excellently preserved *Rusophycus*, *Teichichnus, Skolithos*, and *Chondrites* ichnofossils. During the deposition of the stratigraphically overlying Gallatin Formation, the transition to an open marine carbonate zone is completed. There is an overall transition from near shore sands of the Flathead Sandstone grading to sublittoral lagoonal muds, silts, and sands of the Gros Ventre deposition, and ultimately to open marine carbonates during the deposition of the Gallatin Limestone at the end of the Middle Cambrian.

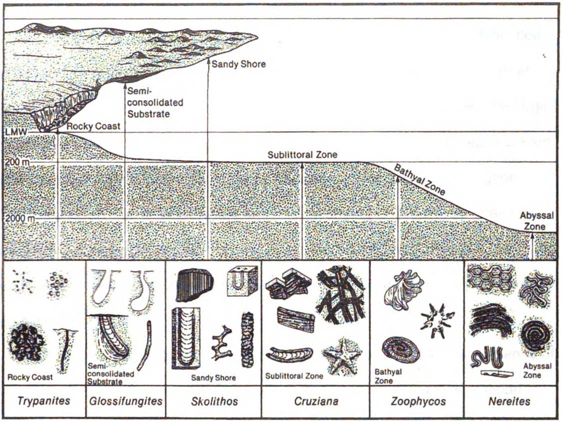


Figure 24. Ichnofacies. The Flathead Sandstone comprises the sandy shoreface *Skolithos* ichnofacies. The Gros Ventre Formation comprises the sublittoral zone *Cruziana* ichnofacies, which includes the *Rusophycus* ichnofossil.

Gros Ventre desposition compares closely to the model proposed for the coeval Wolsey Formation (Middleton, 1980; Morgan, 1998). The Wolsey comprises predominantly fine-grained muds and silts interspersed with coarse-grained arkosic sands, which are interpreted as derived from the nearby granitic shorelines. The large, subangular grains seen in many of the sandstone beds of the Gros Ventre Formation suggest derivation from a nearby sediment source. Geologic maps (Figure 5) show the Flathead Sandstone and Gros Ventre

Formation in contact with Precambrian granites, implicating the granites as the shorelines in the Sauk Sea. Middleton (1980) described the Precambrian granites as "crystalline highs [that] were islands in an epeiric sea."

Sepkoski's (1982) description of the Gros Ventre Formation as deposited in a lagoonal setting fits well with the observations made of the Gros Ventre at Burgess Junction. The predominant rock type is mudstone to siltstone. The large, subangular to subrounded arkosic sand grains found in the sandstones and even in the *Rusophycus* ichnofossils imply a nearby sediment source. The lagoon within the Sauk Sea would have allow for sequestering of the coarser-grained sediments during episodic storms in what is otherwise a lower energy environment in which muds and silts were deposited during periods of relative quiescence.

The isolated *Rusophycus* in mudstone beds provide additional evidence of episodic storms that swept arkosic sands from nearby exposed Precambrian granitic shorelines into this shallow littoral environment, possibly being transported in tidal channels as a storm surge ebb deposit. The fine detail in many of the *Rusophycus* implies a cohesive substrate and suggests the presence of bacterial mats in the Wyoming Sauk Sea during the Cambrian, which is supported by the presence of Kinneyia and bacterial mat structures in stratigraphically adjacent strata. The bacterial mats likely contributed to firm, cohesive muds, which allowed excavated structures (e.g. *Rusophycus*) to survive long enough to be filled and cast by sands sweeping in during episodic storm deposition. The bacterial mats may have also been the source of food mined by the trace-makers.

It is unlikely that trilobites would excavate burrows in such coarse material. One specimen (Figure 8e) has an impression from a pebble (3 cm) in the middle of one of the *Rusophycus* lobes, cross-cutting the *Rusophycus* scratch marks.

The resolution of time between the sedimentary events that filled and cast the *Rusophycus* was probably narrow. Episodic storms initially deposited sand, silts and muds were deposited as energy waned. Deposition of the mud resulted in (1) better preservation of the ichnofossils and (2) opportunistic exploitation of the substrate by trilobites and other mud-dwelling/feeding organisms (e.g. the *Teichichnus* trace-maker). Brett and Seilacher (1991) described lagerstätten developing as a result of event sedimentation. The exposures at Burgess Junction have numerous event deposits that preserve an anomalously large number of ichnofossils, thus warranting the description of the Burgess Junction Gros Ventre Formation as an ichnofossil lagerstätte.

The presence of a meters-thick *Chondrites* unit provides evidence of the oxygenation conditions during Gros Ventre deposition. Seilacher (2007) interpreted *Chondrites* as indicative of low levels of oxygenation. The transition from beds with abundant *Chondrites* to beds with abundant *Rusophycus* may therefore indicate an increase in oxygen levels.

The return of burrowing trilobites above the *Chondrites* beds likely reflect this increase in oxygenation. No trilobite body fossils were found in the exposures of the Gros Ventre Formation, suggestion that trilobites either (1) escaped the environment after excavating the *Rusophycus* burrows, but before storms swept through and cast their burrows with sands and lags of silt and mud, or (2) were killed during the storms that deposited the *Rusophycus*-casting sandstones, but did not fossilize because of taphonomic biases due to the poor chance of preservation in sandstones. By the time of Gallatin deposition, lithologies were carbonate-dominated, indicating less siliciclastic input and a more open marine environment.

Ichnofabric of the Middle Cambrian Gros Ventre and its place in the Cambrian Substrate Revolution

The average bioturbation index for the bedding planes in the Gros Ventre Formation is 2.332, (on a 0-5 scale) using the Miller and Smail (1998) index of bioturbation. The average bioturbation index for the cross section of beds is 2.105 (on a 0 through 5 scale), using the index of bioturbation developed by Droser and Bottjer (1986). Bioturbation was most abundant in the *Chondrites* beds (Fig 20. Composite strat column), which have an average cross-sectional and bedding plane index of 3.5 (on a 0 through 5 scale).

Droser, et al., (1988) recorded an average ichnofabric index of 1.02 in the Early Cambrian, and increase to 3.1 in later Early Cambrian strata and a maximum of approximately 3.5 in Late Cambrian strata of the inner and middle shelf carbonate facies of the Great Basin of California, Nevada, and Utah. The average index of 2.11 observed in the Gros Ventre Formation of Burgess Junction falls between the Early Cambrian and Late Cambrian ichnofabric values of Droser and Bottjer (1988) and support the idea that the Cambrian Substrate Revolution was a gradual transition, rather than an abrupt "tipping point" (*sensu* Gladwell, 2002).

The slightly higher average index of 2.33 derived using the Miller and Smail (1998) index for bedding planes is consistent with the hypothesis that during this interval, most biotic activity took place at or near the substrate, and therefore is found on bedding planes, and not within the bedding.

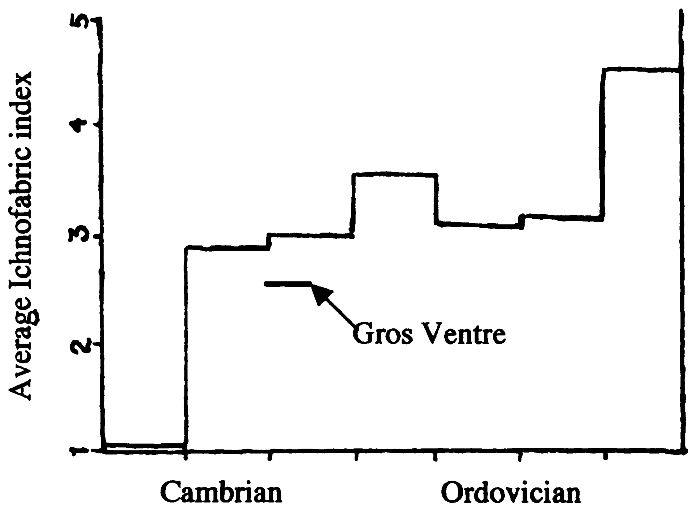


Figure 25a. Bioturbation figure modified from Droser et al., (1988) noting average ichnofabric index for Cambrian and Ordovician and the interval in which the Gros Ventre of Burgess Junction is positioned.

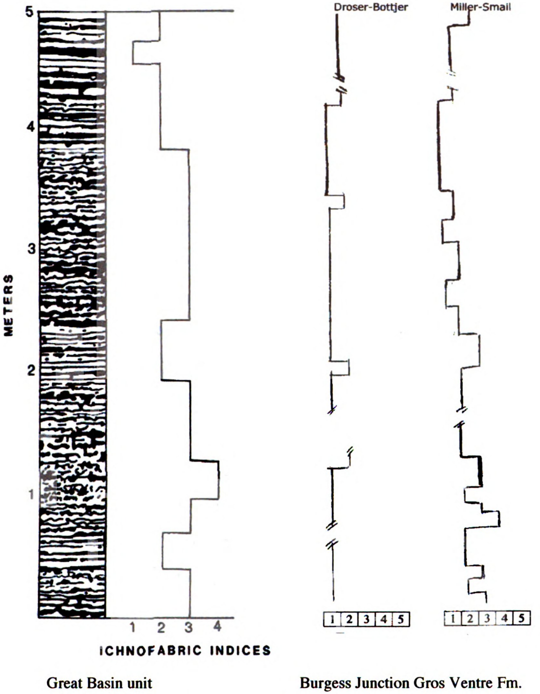


Figure 25B. Comparison of 5 meters of measured Gros Ventre Formation (a predominantly siliciclastic unit) with 5 meters of an approximately coeval carbonate-dominated section published in Droser, et al., (1988).

CONCLUSIONS

The ichnofossil *Rusophycus* is the product of a typical behavior of trilobites, but is only preserved under unique conditions. A unique confluence of conditions existed in the Middle Cambrian Gros Ventre environment and resulted in the preservation of a *Rusophycus* lagerstätte. These conditions include the background deposition of firm, cohesive muds possibly bound by bacterial mats. The muds had a firmness that allowed the burrows to maintain their shape until they were filled in and cast during the next phase of sand deposition. The medium-to-coarse-grained arkosic sand that cast the *Rusophycus* was probably derived from the nearby granitic shoreline during tidal channel ebb flow following storms. The absence of spreiten and presence of individual depositional events in sectioned *Rusophycus* support this conclusion. These results are in contrast to previous assertions that the *Rusophycus* ichnofossil was excavated by trilobites burrowing through sand to a muddy interface.

The presence of *Chondrites* in Middle Cambrian strata of the Big Horn Mountains is in contrast to the narrower stratigraphic range advocated by other workers (e.g., Seilacher, 2007), but congruent with earlier reports (Häntzchel, 1975).

The Gros Ventre Formation falls in the middle of the Cambrian Substrate Revolution. Bacterial mats were present before, during, and after the deposition of the Gros Ventre Formation. Bioturbation indices for the Gros Ventre Formation are comparable to those documented for the Middle Cambrian by other workers (e.g., Droser, et al., 1988) and support the idea of a gradual increase of bioturbation intensity during the Middle Cambrian.

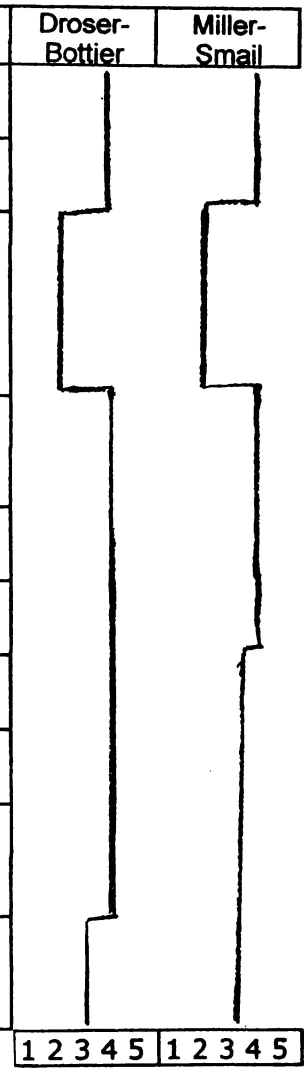
There is still an abundance of work that can be done with this project. Some future directions for work include correlation of sections elsewhere of the same age (Middle Cambrian) and similar facies to more widely document the Cambrian Substrate Revolution. Additionally, there is the prospect for analyses using quantitative methods and chemostratigraphy. The use of quantitative analyses could help better ascertain the number of ichnospecies present in addition to modeling diversity and faunal distributions in the Middle Cambrian.

Appendix 1, Bed-by-Bed Descriptions of Measured Localities

All measurements are given from the lowest exposed portion of the section (0cm) to the top of the exposed section. The measurements from the sampled exposures were recorded with the abbreviated outcrop name (e.g., BJ1, PR2) followed by a number that corresponds to the number of centimeters above the base (0cm) where the sample was collected. An asterisk (*) next to the sample number indicates an *in situ* ichnofossil sample was collected. Lithologic samples were collected at every recorded

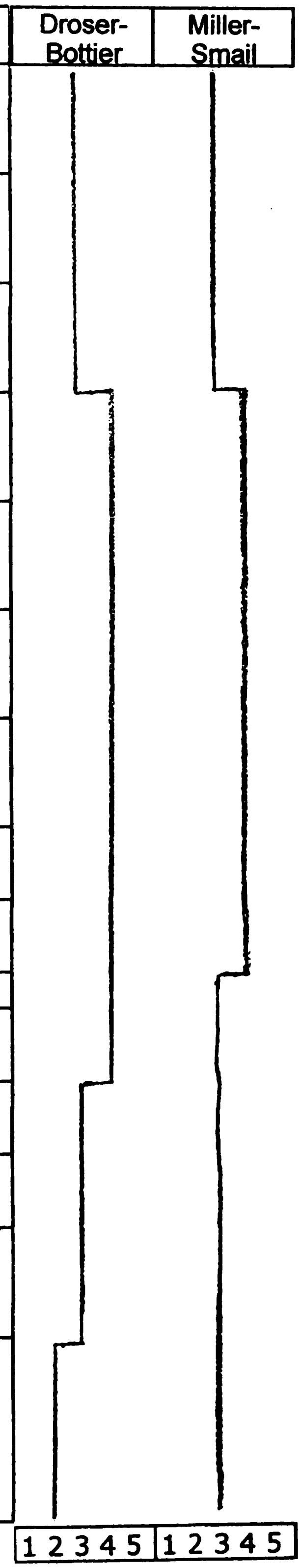
Burgess Junction 1 (BJ1)

Sample	Description	Φ	Droser-Bottier	Miller-Smail
BJ1 0	green mudstone with *Chondrites*	2	4	4
BJ1+10*	green mudstone with *Chondrites*	2	4	4
BJ1+20	silty, tan to green muddy sandstone with *Teichichnus* on sole, medium sorting, Subangular grains	1	2	2
BJ1+35*	green mudstone with *Chondrites* and Teichichnus at base	2	4	4
BJ1+45	green to tan mudstone with *Chondrites*	2	4	4
BJ1+55	green to tan mudstone with *Chondrites*	2	4	4
BJ1+65	green to tan mudstone with *Chondrites*	2	4	3
BJ1+75	green to tan mudstone with *Chondrites*	2	4	3
BJ1+85	green to tan silty mudstone with *Chondrites*	1.5	4	3
BJ1+95	green to tan silty mudstone with *Chondrites*	1.5	3	3



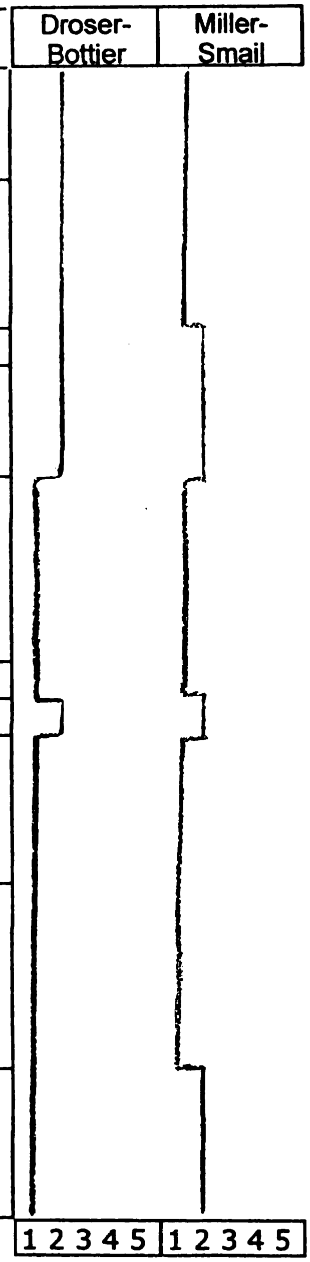
BJ1, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
BJ1+105	green to tan silty mudstone with *Chondrites*	1.5	3	3
BJ1+115	green to tan silty mudstone with *Chondrites*	1.5	3	3
BJ1+125*	tan to green silty mudstone with *Chondrites*	1.5	3	3
BJ1+135*	tan to green silty mudstone with abundant *Chondrites*	1.5	4	4
BJ1+145	tan to green silty mudstone with abundant *Chondrites*	1.5	4	4
BJ1+155	tan to green silty mudstone with abundant *Chondrites*	1.5	4	4
BJ1+165	tan to green silty mudstone with abundant *Chondrites*	1.5	4	4
BJ1+175	tan to green mudstone, less silt	1.5	4	4
BJ1+185	tan to green mudstone, less silt	2	4	4
BJ1+195	tan mudstone	2	4	3
BJ1+205*	tan mudstone with sand-filled *Teichichnus*	2	4	3
BJ1+215*	tan mudstone with sand-filled Teichichnus	2.5	3	3
BJ1+225*	tan mudstone with sand-filled *Teichichnus*	2.5	3	3
BJ1+230*	tan sandy mudstone with sand-filled *Teichichnus*	2.5	3	3
BJ1+235*	tan sandy mudstone with type burrows and scour marks on sole; graded bedding with subrounded grains	1.5-1	2	3



BJ1, continued

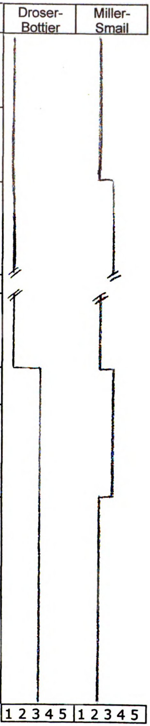
Sample	Description	Φ	Droser-Bottier	Miller-Smail
BJ1+245	tan sandy siltstone; medium-well sorted with subrounded grains	1.5	2	1
BJ1+255	tan sandstone, fine to medium grained; medium-well sorted with subrounded grains	1	2	1
BJ1+305	tan mudstone	2.5	2	2
BJ1+315*	tan mudstone with sand-filled *Rusophycus* burrow	2.5	2	2
BJ1+340	tan sandstone with rippled top surface, fine to medium grained; graded bedding with subrounded grains	3.5	0	0
BJ1+325	brown mudstone	1	1	1
BJ1+350	tan mudstone	2.5	2	2
BJ1+360	tan sandstone, fine to medium grained; medium-well sorted with subrounded grains	1	1	1
BJ1+370	tan sandstone with rippled top surface, fine to medium grained; graded bedding with subrounded grains	1	1	1
BJ1+380	tan sandstone, fine to medium grained; medium-well sorted with subrounded grains	1	1	2



*Weathered mudstone above, forming top of hill on which outcrop is exposed, which grades into a meadow where numerous *Rusophycus* were collected in float.

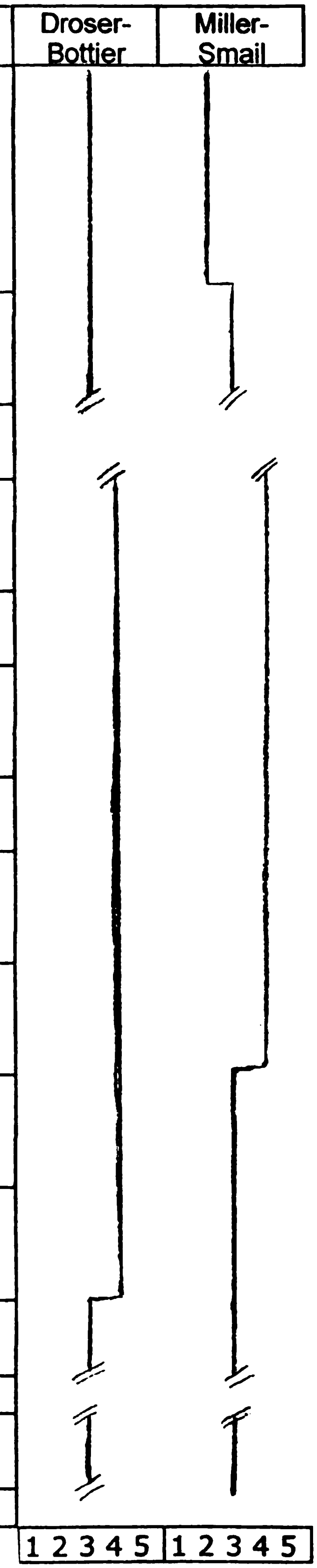
Passage Resort 2 (PR2)

Sample	Description	Φ	Droser-Bottjer	Miller-Smail
PR2 0	tan sandstone, fine to medium grained, medium sorting with subrounded grains	1	1	1.5
PR2+10	tan sandstone, fine to medium grained, medium sorting with subangular grains	1	1	1.5
PR2+20	tan sandstone, more massive, medium grained, medium sorting with subangular grains	1.5	1	3
25cm	covered (shaley)	-	-	-
PR2+45	tan sandstone, fine to medium grained, medium-well sorted with subangular grains	2	1	2
PR2+55*	tan mudstone with sandfilled *Rusophycus*	2	3	3
PR2+65	tan sandstone, fine to medium grained with mud/clay lenses, medium sorting with subrounded grains	1.5	3	3
PR2+70	tan sandstone, fine to medium grained with mud/clay lenses, medium sorting with subrounded grains	1.5	3	2
PR2+80	more massive tan sandstone, fine to medium grained with mud/clay lenses medium sorting with subangular grains	1	3	2



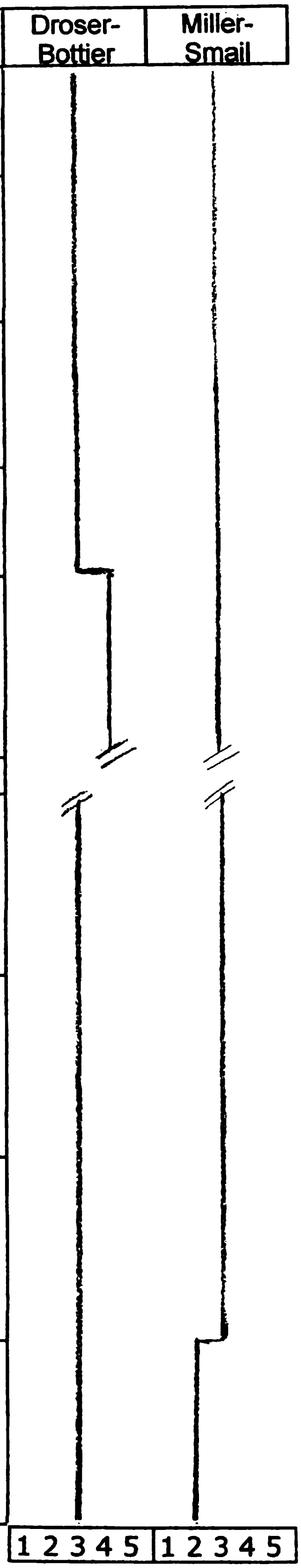
PR2, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR2+90	more massive tan sandstone, fine to medium grained with mud/clay lenses, medium sorting with subangular grains	1	3	2
PR2+100*	green silty mudstone with *Chondrites* (basal *Chondrites* bed)	1.5	3	3
30cm	covered (shaley with *Chondrites*)	-	-	-
PR2+130*	green silty mudstone, approximately 10cm thick with *Chondrites*	2	4	4
PR2+140*	green silty mudstone, thinner with *Chondrites*	2	4	4
PR2+150*	green silty mudstone, approximately 10cm thick with *Chondrites*	2	4	4
PR2+160*	green silty mudstone, thinner with *Chondrites*	2	4	4
PR2+170*	green silty mudstone, approximately 10cm thick with *Chondrites*	2	4	4
PR2+175*	green silty mudstone, approximately 5cm thick with *Chondrites*	2	4	4
PR2+185*	green silty mudstone, approximately 10cm thick with *Chondrites*	2	4	3
PR2+195*	green silty mudstone, thinner with *Chondrites* and *Teichichnus*	2.5	4	3
PR2+205*	green silty mudstone, thin with *Chondrites*	2	3	2.5
40cm	covered	-	-	-
PR2+245*	green silty mudstone, thin with *Chondrites*	2.5	3	2.5
30cm	covered	-	-	-



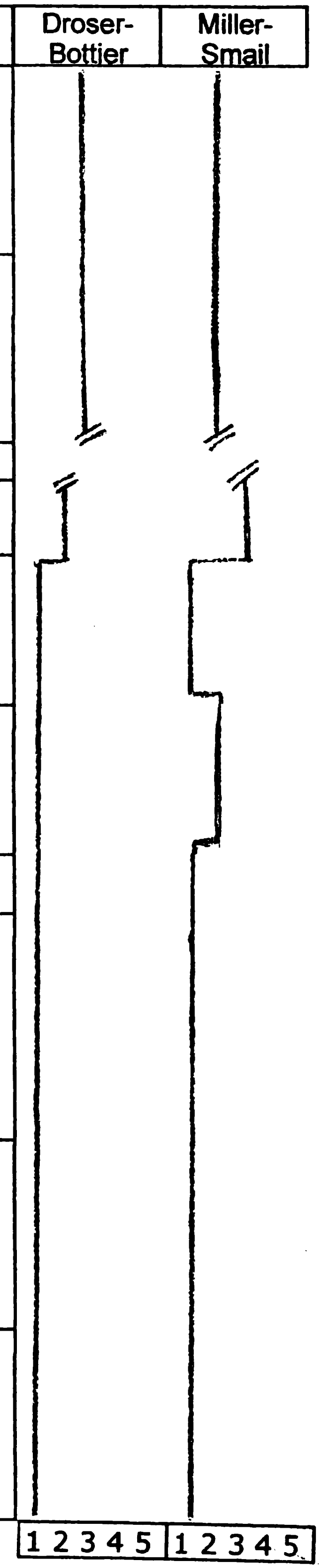
PR2, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR2+275*	green silty mudstone, medium thickness (less than 10cm)	2.5	3	2.5
PR2+285*	green silty mudstone, thin with black stain between beds and *Teichichnus*	2.5	3	2.5
PR2+295*	green silty mudstone, medium thickness (less than 10cm) with *Chondrites*	2.5	3	2.5
PR2+310*	green silty mudstone, medium thickness with *Chondrites*	2	3	2.5
PR2+320*	green silty mudstone with interbedded silt laminae, medium thickness with *Chondrites*	2	4	2.5
60cm	covered	-	-	-
PR2+380*	green siltstone, coarser grained than underlying beds, thicker bedding (approximately 20cm) with *Chondrites*	2	2.5	3
PR2+400*	green siltstone, coarser grained than underlying bedding, approximately 20cm thick with *Chondrites*	1.5	2.5	3
PR2+420*	green siltstone, coarser grained than underlying beds, approximately 20cm thick with *Chondrites*	2	2.5	2.5
PR2+440*	green siltstone, coarser grained than underlying beds, approximately 20cm thick with *Chondrites*	1.5	2.5	2



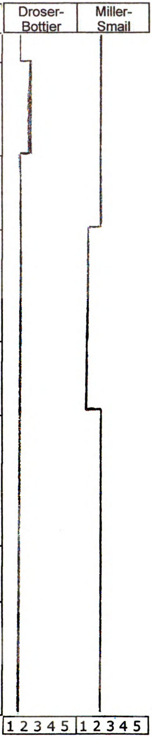
PR2, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR2+445*	green siltstone, coarser grained than underlying beds, approximately 15cm thick with *Chondrites*	1.5	2.5	2
PR2+455*	green siltstone, coarser grained than underlying beds, approximately 10cm thick with *Chondrites*	2	2.5	2
60cm	covered	-	-	-
PR2+515*	fissile mudstone with scratch marks	1	2	2.5
PR2+520	medium grained sandstone, medium sorting with subrounded grains	1	1	1
PR2+535	medium grained sandstone, medium sorting with subrounded grains	1.5	0	1.5
PR2+545	fissile mudstone	4	0	1
PR2+555*	medium grained sandstone with green clay rip-up clasts and large *Rusophycus*, medium sorting with subangular grains	0.5	0	1
	*This interval begins very abundant *Rusophycus* , which are present in the sandier lenses.	1.5	1	1
PR2+565*	medium grained sandstone with *Rusophycus*, medium sorting with subrounded grains	4	0	1



PR2, continued

Sample	Description	Φ	Droser-Bottjer	Miller-Smail
PR2+570	tan siltstone	1.5	1	1.5
PR2+575*	medium grained tan sandstone with *Rusophycus*, medium sorting with subrounded grains	2	2	2
PR2+580*	thinly bedded tan siltstone with scratch marks, medium-well sorted	1	1	2
PR2+590*	medium grained sandstone with type burrows on sole surface, medium sorting with subangular grains	1	0	1
PR2+595	medium grained sandstone, medium sorting with subangular grains	0.5	0	0
PR2+600	medium grained sandstone, thicker than beds below with interspersed laminated mud drapes, medium sorting with subangular grains	2	1	2
PR2+610	muddy siltstone, thin bedding with mud draped surface	1.5	0	2
PR2+620	medium grained sandstone with interspersed laminated mud drapes, medium sorting with subrounded grains	1.5	0	2

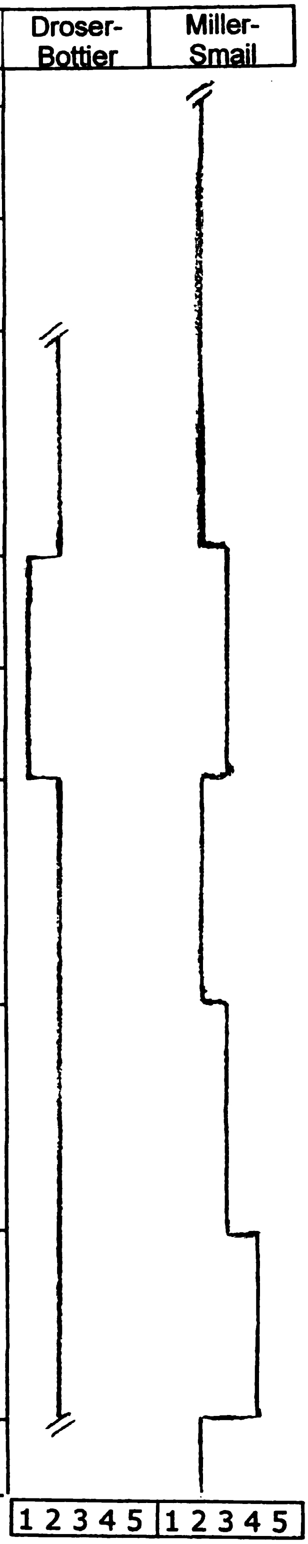


PR2, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR2+630*	thinner, mud-draped silty sandstone with *Teichichnus,* medium sorting with subrounded grains	1.5	0	1.5
PR2+640*	thicker, medium grained sandstone with rippled top surface, scratch marks, and tiny serially repeated *Rusophycus,* with graded bedding and subrounded grains	1.5	1.5	1.5
PR2+650	thinner, silty sandstone with mud lenses, medium sorting with subrounded grains	1	1.5	2
PR2+660	thinner, silty sandstone with mud lenses, medium sorting with subrounded grains	1	1.5	2
PR2+670*	tan muddy siltstone with very abundant burrows	1.5	1.5	3
PR2+680	tan muddy siltstone	1.5	1.5	3
PR2+690*	thicker, medium grained sandstone with interspersed mud drapes and tiny serially repeated *Rusophycus,* medium sorting with subrounded grains	1.5	2	3
PR2+700	green silty sandstone with rippled top surface, graded bedding with subangular grains	1	1	2
PR2+710	green muddy siltstone with muscovite flakes	1.5	1.5	2
PR2+720*	green muddy siltstone with muscovite flakes and *Teichichnus*	2.5	1.5	2

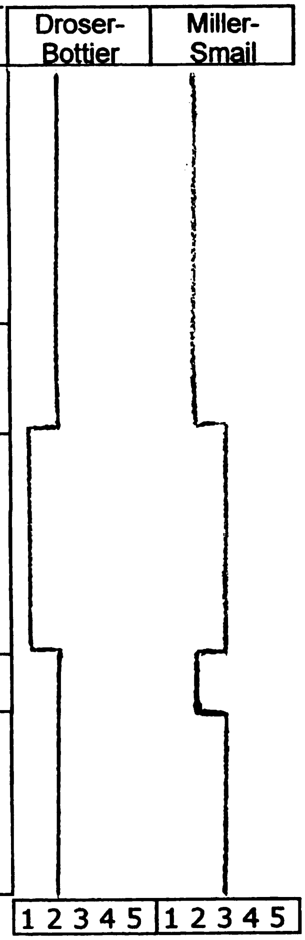
PR2, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
30cm	covered	-	-	-
PR2+750*	green to brown mudstone with sand filled *Rusophycus*	3.5	?	2
PR2+760	green to brown mudstone with sand lenses	3.5	?	2
PR2+770*	medium grained sandstone with interspersed mud drapes and traces, medium well sorted with subrounded grains	1.5	2	2
PR2+780*	thin muddy siltstone with poorly preserved traces	2.5	1	3
PR2+790*	thin muddy siltstone with poorly preserved traces	3	1	3
PR2+800*	thinly bedded medium grained sandstone with multiple tiny *Rusophycus,* medium-well sorted with subrounded grains	2	1.5	2
PR2+805	thinly bedded medium grained sandstone with interspersed mud drapes, medim-well sorted with subrounded grains	2	1.5	3
PR2+810	grey to brown siltstone with mud drapes very productive—numerous *Rusophycus* , scratch marks, and burrows	2	1.5	4
PR2+820	grey to brown silty mudstone	3	?	2



PR2, continued

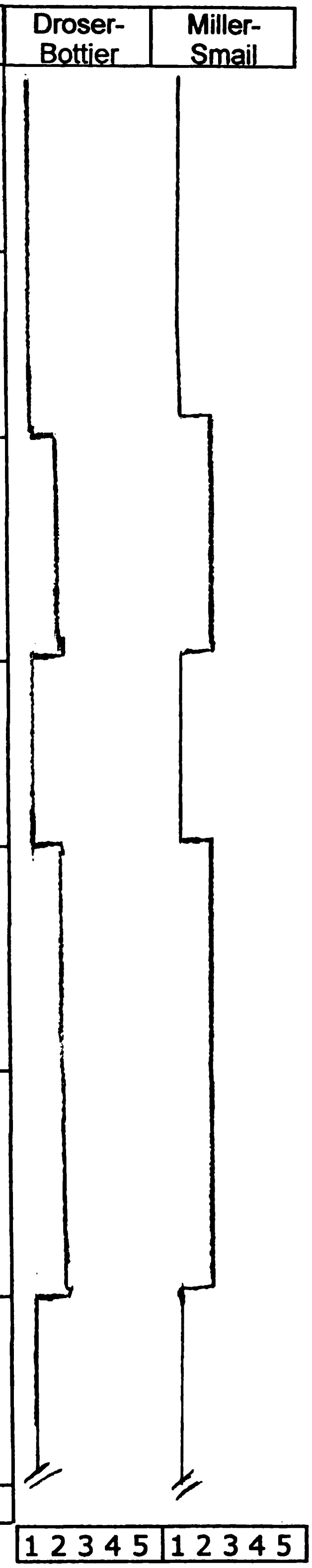
Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR2+830*	thinly bedded medium grained sandstone with interspersed mud drapes and *Rusophycus,* medium-well sorted with subrounded grains	2	1.5	2
PR2+840*	silty mudstone with pooly preserved burrows	1.5	1.5	2
PR2+880*	medium grained sandstone with rippled top and burrows on the sole surface, graded bedding with subrounded grains	2	1	3
PR2+890	coarser silty mudstone	2.5	1.5	2
PR2+900	medium grained rippled sandstone approximately 5cm thick, graded bedding with subrounded grains	2	1.5	3



TOP OF SECTION

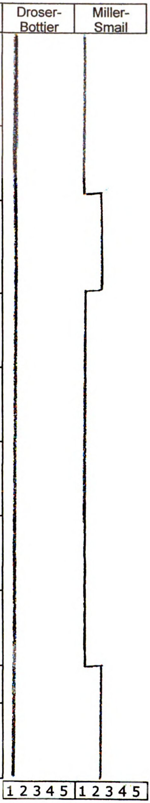
Passage Resort #1
(PR1)

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR1 0	pink to green medium grained consolidated sandstone, medium sorting, subangular grains	1	1	1
PR1+15	pink to green medium grained consolidated sandstone, medium sorting, subangular grains	1	1	1
PR1+25	pink to green medium grained consolidated sandstone with visible surface burrows, medium sorting with subangular grains	1	1.5	2
PR1+35	pink to green medium grained consolidated sandstone, more arkosic (potassium feldspar)	1	1	1
PR1+45*	buff sandstone, more nodular with interspersed muds and *Teichichnus*, medium sorting with subangular grains	1	1.5	2
PR1+55*	pink to green medium grained consolidated sandstone with surface burrows, medium sorting with aubangular grains	1	1.5	2
PR1+80	massive (25cm thick) pink to green sandstone, medium sorting with subrounded grains	1	1	1
20cm	covered	-	-	-



PR1, continued

Sample	Description	Φ	Droser-Bottier	Miller-Smail
PR1+100	pink to green medium grained sandstone with mud drapes, medium-well sorted with subrounded grains	1	1	1
PR1+115*	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	1	1	1
PR1+130	tan medium grained crumbly sandstone with *Teichichnus,* medium-well sorted with subrounded grains	1	1	2
PR1+140	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	1	1	1
PR1+150	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	1	1	1
PR1+160	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	1	1	1
PR1+170	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	1	1	1
PR1+185	tan medium grained crumbly sandstone, medium-well sorted with subrounded grains	2	1	1
PR1+195*	basal *Chondrites* bed, green muddy siltstone	1	1	2
PR1+415	Massive (50 cm) tan sandstone, burrows on sole, well sorted with subrounded grains	1	1	2



PR1, continued

Begin unsampled measurements

Base

40cm	green muddy siltstone with *Chondrites*
40cm	pink to green medium grained sandstone
40cm	fissile green silty mudstone, coarsening upwards
100cm	green muddy siltstone with *Chondrites*
110cm	fissile green muddy siltstone with *Chondrites*
25cm	green medium grained consolidated sandstone with *Chondrites*
20cm	fissile mudstone
40cm	massive medium grained arkosic sandstone with burrows on sole surface
100cm	fissile mudstone with sandy lenses and abundant traces, coarsening upwards
20cm	massive medium grained arkosic sandstone with numerous mud lenses
20cm	cover (suspect productive layer over sandstone bed)
80cm	silty mudstone coarsening upwards with sand lenses

PR1, continued
unsampled
measurements

25cm	massive medium grained sandstone with rippled top surface, rip-up clasts, and mud drapes
10cm	covered
60cm	fissile silty mudstones with abundant ichnofossils, coarsening upwards
10cm	medium grained sandstone with rippled top surface and ichnofossils on sole surface
5cm	productive layer—silty mudstone with abundant ichnofossils
75cm	fissile silty mudstones with abundant ichnofossils, coarsening upwards
10cm	medium grained sandstone with rippled top surface
5cm	productive layer—silty mudstone with abundant ichnofossils

TOP OF SECTION

Bear Lodge 2 (BL2)

Base of Section

0cm	nodular sandstone, well-sorted, medium grained, highly "pocked" top and bottom surfaces
20cm	covered
10cm	platy sandstone with mud drapes
20cm	massive nodular sandstone
5cm	covered
60cm	begin *Chondrites* green silty mudstones, coarsen upwards to muddy siltstones
60cm	green muddy siltstones with abundant *Chondrites* , more consolidated
35cm	thinner green muddy siltstones with fewer *Chondrites*
30cm	thinner green muddy silstones with fewer *Chondrites*
	At this point, there is a 20 meter long pediment in the outcrop. This seems to mark the end of the *Chondrites* beds and where the sand/silt/mud oscillations begin. No *Rusophycus* were collected in the bottom part of the outcrop, but are weathered out in abundance in the top section (described below)
40cm	covered

Bear Lodge 2 (BL2), continued

unsampled measurements

10cm	medium grained sandstone with muddy rip-up clasts
50cm	covered
10cm	medium grained sandstone with muddy rip-up clasts (sample collected)
20cm	covered
20cm	productive silty mudstones
10cm	covered
10cm	medium grained sandstone with rippled top surface
20cm	covered
10cm	medium grained sandstone with rippled top surface

Top of Section

APPENDIX 2

DESCRIPTIONS OF LOCALITIES STUDIED

Burgess Junction 1 (BJ1)

This locality is an exposure of the Gros Ventre Formation on US Highway 14 at its intersection with U.S. Highway 14-Alternate Route (Figure 4). Approximately four meters of section are exposed with predominant lithologies of shale, silt, and sandstone (Figures 20a and 20b), which coarsen upwards with sandstones becoming more arkosic towards the top of the section. Ichnofossils collected at this locality include *Chondrites* (found in the *Chondrites* marker bed at the base of the section), *Teichichnus*, *Rusophycus*, and *Skolithos.* No body fossils were found at this locality.

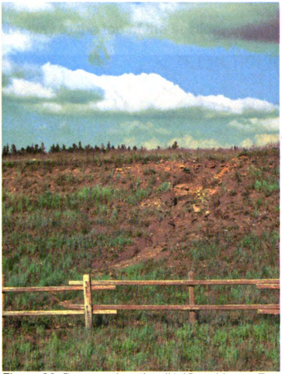


Figure 26. Burgess Junction #1 (Gros Ventre Formation).

Passage Resort 1 (PR1)

Located in a drainage gully near park access road number 155 (Figure 4), the base of the section has well-sorted sandstones that grade into muddier green shale with abundant chondrites—very few *Rusophycus* are found and they are poorly preserved (Figures 20a and 20b). In the third meter of the section, the *Rusophycus* become very abundant, as more sand and silt beds enter the section. Further upsection, the mudstones become more silty which seem to be silt beds draped in mud with a few sandy lenses. The thicker sand beds have graded bedding with mud lenses and muddy rip-up clasts within the bedding as well as mud drapes around the beds. The thick sand beds are almost always topped with a densely bioturbated silty layer grading into silty mudstones and topped by succeeding sand, silt, and mudstone beds repeating themselves all the way to the top of the section.

Figure 27. Massive Sandstone Bed at PR1

Figure 28. Passage Resort #1 (Gros Ventre Formation)

Figure 29. PR1, (Gros Ventre Formation) pink to green sandstones at base of section. Hammer (22 inches) for scale.

Passage Resort 2 (PR2)

Located at the intersection of US Highway 14 with park access road number 155 (Figure 4), this section is nearly identical to the exposure of Passage Resort 1, as the two localities are within close proximity to each other. The exposure at the Passage Resort 2 locality has the lowest exposed portion of the stratigraphic column, approximately 1.5 meters below the base of Passage Resort 2 (Figures 20a and 20b). Also present at this locality is a massive bed of sandstone (approximately 55 cm) that is not present at any of the other localities. This bed, however, has simply been interpreted by this author as an infilled channel. The exposure was sampled at a 5-10 centimeter interval.

This outcrop is an exposure in a gully in an alpine meadow. The meadow is steeply sloped with a stream running through it, cutting into weak shaley beds. The exposure is highly weathered in some spots, causing lots of cover in the exposure. In some places, you can walk a meter or more laterally across the more resistant sandstone beds. The highly weathered slopes around the exposure are littered with *Rusophycus, Teichichnus*, and other ichnofossils. Almost every single piece of float has something of interest.

Figure 30. Passage Resort #2 (PR2)

Figure 31. PR2 (Gros Ventre Formation), Rippled Sandstone Bed. Hammer (22 inches) for scale.

Bear Lodge 2 (BL2)

This exposure of the middle Cambrian Gros Ventre Formation is located in a meadow across US Alternate Route 14 from the Bear Lodge in Burgess Junction (Figure 4) in a drainage gully leading to the same stream exposed at the base of the Passage Resort localities. This exposure is nearly identical to the Passage Resort exposures, but is much more weathered and has a shelf in the middle of the exposure, creating a sizable ledge in the middle of the exposure . The Bear Lodge 1 exposure is more weathered than the Passage Resort Exposures, so it was not sampled, only measured (Figures 20a and 20b), described, photographed, and surface collected for ichnofossils.

Figure 32. Bear Lodge #2 (Gros Ventre Formation).

North Tongue 1 (NT1)

This exposure of the upper Flathead Formation is located approximately one half mile north of the intersection with US Alternative Route 14 along National Forest Road #15 (Figure 4) on a switchback portion of the road that leads to the turnoff for the Twin Buttes, an exposure of the Ordovician Big Horn Formation, which is in clear view from the North Tongue exposures. The three North Tongue sections are all part of the same exposure, but have been separated due to location within the stratigraphic column or position within the switchback on the road. The Flathead is exposed in a ravine at the base of the switchback and contains thin to medium-thickness sandstone and mudstone beds. There is a minimal amount of bioturbation present on the sole and top surfaces of the sandstone beds. The majority of the traces were *Skolithos* burrows, but some *Chondrites* were also found. A series of trilobite hash beds were found, and help confirm the stratigraphic positioning with the upper Flathead, as they are a considered a key marker bed (Koucky and Cygan, 1963). Numerous fragments of the sedimentary structure *Kinneyia* collected in float, interpreted as the product of bacterial mats.


Figure 33. North Tongue #1 (Flathead Formation).

Figure 34. North Tongue #1 (Flathead Formation).

North Tongue 2

This exposure of the Upper Cambrian Gallatin Formation is located next to North Tongue 1 (Figure 4) along the middle and upper section of the switchback. Stratigraphically, it is positioned anomalously on the upper Flathead Formation. There is a fault present in the exposure, which pinches out all the shaley Gros Ventre Formation (Figure 5). Present at this locality were flat pebble conglomerates. Flat pebble conglomerates have been interpreted as evidence of the presence of bacterial mats in the Upper Cambrian (Sepkoski, 1982).

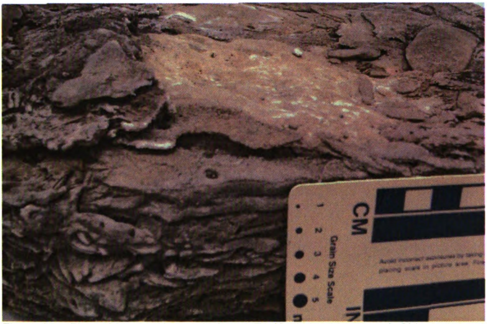


Figure 35a. Flat pebble conglomerate from NT2 (Gallatine Limestone). Side and top view. Top of scale bar is 4 cm.

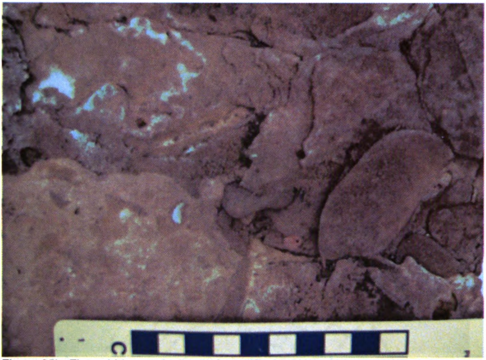


Figure 35b. Flat pebble conglomerate from NT2 (Gallatine Limestone). Top view.
Scale bar is 10cm.


Figure 36. Slab of flat pebble conglomerate collected in float at NT2.
Hammer (22 inches) for scale.


Figure 37. Arrow pointing to exposure at North Tongue #2 Locality (NT2).
Gravel road to right of arrow for scale.

North Tongue 3

This exposure of the Upper Cambrian Gallatin Formation is adjacent to North Tongue 2 on the opposite side of the switchback in the upslope direction (Figure 1, locality map). Samples of carbonate *Kinneyia* and stromatolite-like structures were collected in float from this highly weathered locality, providing further evidence, which is interpreted as having been produced by bacterial mats.

Figure 38. Flat pebble conglomerate from NT3 (Gallatin Formation). Scale bar is 2 cm.

Steamboat Point

This is the only locality studied outside of Burgess Junction. It located east of Burgess Junction along US Highway 14 (Figure 4). There is a trailhead and parking lot at the base of the exposure for the Steamboat Point trail. This large section exposes the Middle Cambrian Flathead Sandstone through the Ordovician Big Horn Dolomite, which is exposed at the top of the exposure and bears a similarity to the hull of a steamboat.

At the base of the trail leading to the Steamboat Point ledges, which are massive beds of Bighorn Dolomite, the Flathead Sandstone is exposed. In the Flathead, there are two prominent ledges of cross-bedded sandstone approximately seven meters apart. The top ledge could possibly be the Flathead/Gros Ventre contact, abovewhich the slope drastically lessens. The exposure of the Gros Ventre Shale is extremely weathered, covered with vegetation, and not well exposed. Pine trees seem to prefer growing in the sandstone and carbonate beds, but not in the silty/muddy Gros Ventre Formation. This area is grassed over, but no trees are growing. The Gallatin Limestone crops out above the weathered Gros Ventre with the massive Ordovician Bighorn Dolomite exposed above the Gallatin Limestone. The Gallatin Limestone is a fine-grained limestone with four distinct flat pebble conglomerate beds (each bed is approximately 40 cm thick). Carbonate *Kinneyia* slabs were found in float near the basal portion of the section. *Kinneyia* was also found in float from the Flathead Formation, though preserved in sandstone. Unfortunately, neither occurrence could be documented *in situ*.

Figure 39. Steamboat Point (Middle Cambrian Flathead Formation through Ordovician Bighorn Formation).

APPENDIX 3

Global Positioning System (GPS) Coordinates for Studied Exposures

Burgess Junction #1 (BJ1)

N 44° 46' 10.6"
W 107° 31' 3.5"
Elevation 2445 meters

North Tongue #1 (NT1)

N 44° 47' 24.3"
W 107° 32' 28.1"
Elevation 2444 meters

North Tongue #2 (NT2)

N 44° 47' 33.3"
W 107° 32' 15.2"
Elevation 2455 meters

Passage Resort #1 (PR1)

N 44° 45' 34.5"
W 107° 30' 51.4"
Elevation 2479 meters

Passage Resort #2 (PR2)

N 44° 45' 48.1"
W 107° 30' 51.2"
Elevation 2505 meters

Steamboat Point

N 44° 48' 28.07"
W 107° 21' 35.76"
Elevation 2246 meters

REFERENCES

Baldwin, C.T.,1977. Internal structures of trilobite trace fossils indicative of an open surface furrow origin. *Paleogeography, Paleoclimatology, Paleoecology*, vol. 21, pp. 273-84.

Bergström, J.,1973. Organization, life and sytematics of trilobites. *Fossils and Strata*, 2:69p.

Birkenmajer, K. and Bruton, D.L., 1971. Some trilobite resting and crawling traces. *Lethaia*, 4:303-319.

Blackwelder, E., 1918, Washington Academy of Sciences Journal, vol. 8, p 417

Bottjer, David J., Droser, Mary L., and Jablonski, David, 1988. Paleoenvironmental trends in the history of trace fossils. *Nature*, vol. 333, pp. 252-255, May 1988

Bottjer, David J; Hagadorn, James W; Dornbos, Stephen Q, 2000. The Cambrian substrate revolution. *GSA Today*, vol.10, no.9, pp.1-7,

Brandt, D.S., Meyer, D.L., and Lask, P.B., 1995. *Isotelus* (Trilobita) "hunting burrow" from the Upper Cincinnatian Strata, Ohio. *Journal of Paleontology*, 69:1079-1083

Brandt, D.S., 2008. Multiple-*Rusophycus* (Arthropod Ichnofossil) Assemblages and Their Significance, *Ichnos*, 15:28-43

Brett, C.E., and Seilacher, A., 1991. Fossil Lagerstätten: a Taphonomic Consequence of Event Sedimentation. *In* Einsele, et al. (eds.), *Cycles and Events in Stratigraphy.* Springer-Verlag, Berlin.

Bromley, R. and Asgaard, U.,1979; Triassic freshwater ichnocoenoses from Carlsberg Fjord, East Greenland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 28:39-80.

Bromley, R.G.,1996. *Trace Fossils, Biology, Taphonomy, and Applications.* Chapman and Hall, London: 361p.

Buatois, L.A. and Mángano, M.G.,1993. Trace fossils from a Carboniferous turbiditic lake: Implications for the recognition of additional nonmarine ichnofacies. *Ichnos,* 2:237-258.

Crimes, T.P., 1975. The production and preservation of trilobite resting and furrowing traces. *Lethaia*, vol. 8, pp. 35-48.

Dawson, J.W., 1864. On the fossils of the genus *Rusophycus. Canadian Naturalist and Geologist,* 1:363-367.

Droser, Mary L; Bottjer, David J, 1986. A semiquantitative field classification of ichnofabric. *Journal of Sedimentary Petrology*, vol.56, no.4, pp.558-559.

Droser & Bottjer, 1989.Ordovician increase in extent and depth of bioturbation: Implications for understanding early Paleozoic ecospace utilization. *Geology* (Boulder), vol.17, no.9, pp.850-852.

Fenton, C.L. and Fenton, M.A., 1937. Trilobites nests and feeding burrows. *American Midland Naturalist,* 18:446-451

Glaessner, M.F., 1957. Paleozoic arthropod trails from Australia. *Paläontologische Zeitschrit,* 31:103-109

Gladwell, Malcolm, 2002. *The Tipping Point: How Little Things Can Make a Big Difference*. Back Bay Books, New York.

HALL, J.,1852. *Natural History of New York, Palaeontology,* vol. 2, Albany, NY: 362p.

Hänzschel, W., 1975. Trace Fossils and Problematica. *In* Teichert, C. (ed.), Treatise on Invertebrate Paleontology Part W, Miscellanea, Supplement 1. The Geological Society of America and the University of Kansas, Boulder, CO, and Lawrence, KS: 269p.

International Commission on Stratigraphy, 2008.

Keighley, D.G. and Pickerill, R.K., 1996. Small *Cruziana*, *Rusophycus*, and related ichnotaxa from eastern Canada: The nomenclatural debate and systematic ichnology. *Ichnos,* 4:261-285.

Koucky, Frank L and Cygan, Norbert E, 1963. Paleozoic Rocks Exposed Along U.S. Highway 14 on the East Flank of the Big Horn Mountains, Wyoming. Field guide printed by Wyoming Geological Association, Wyoming.

Middleton, L.T., 1980, Sedimentology of the Middle Cambrian Flathead Sandstone, Wyoming: Laramie, University of Wyoming, Ph.D. dissertation, 164 p.

Miller, M.F., and Smail, S.E., 1997. A semiquantitative field method for evaluating bioturbation on bedding planes, *Palaios*; August 1997; v. 12; no. 4; p. 391-396.

Morgan, D., 1998. Paleoenvironmental interpretation of the Middle Cambrian Flathead Sandstone and Wolsey Shale, Clarks Fork region, Wyoming, Keck Research Symposium in Geology, vol. 11, pp.275-278.

Nathorst, A.G., 1883. Quelques remarques concernant les algues fossils. *Société gèoligique de France, Bulletin, Series 3*, 11:452-455.

Nathorst, A.G., 1886. Nouvelles observations sur les traces d'Animaux et autres phenomenes d'origine purement mècanique dècrits commes "Algues fossiles." *Kongliga svenska Veternkaps-Akademiens Handlingar,* 21 (14):58.

Osgood, R.G., Jr. 1970. Trace fossils of the Cincinnati area. *Palaeontolographica Americana,* 41:281-444

Osgood, R.G. and III., Drennan, W.T., 1975. Trilobites trace fossils from the Clinton Group (Silurian) of east-central New York State. *Bulletins of American Paleontology,* 67:299-349.

Peale, A.C., 1893. United State Geological Service Bulletin 110.

Pollard, J.E., 1985. *Isopodichnus*, related arthropod trace fossils and notostracans from Triassic fluvial sediments. *Transactions of the Royal Society of Edinburgh Earth Science,* 76:272-285.

Porada, et al. 2008. Kinneyia-Type Wrinkle Structures—Critical Review And Model Of Formation, *Palaios*; February 2008; v. 23; no. 2; p. 65-77

Potter, P.L., et al., 2005. *Mud and Mudstones,* Springer-Verlag, New York.

Potter, P.L., et al., 1980. *Sedimentology of Shale*, Springer-Verlag, New York.

Runnegar, B., 1982. The Cambrian explosion: animals or fossils? *Journal of the Geological Society of Australia*, vol.29, no.4, pp.395-411.

Scholle, P.A., 1979. *A Color Illustrated Guide to Constituents, Textures, Cements, and Porosities of Sandstones and Associated Rocks*, The American Association of Petroleum Geologists Press, Tulsa, OK.

Seilacher, A., 1955. Spuren und Leben weise der Trilobiten. *IN* Schindewolf, O.H. and Seilacer, A (eds) Beiträge zur Kenntnis des Kambriums in der Salt range (Pakistan). *Abhanlungen der mathematischnaturiwissenschaftlichen Klasse, Akademie der Wissenshaften und der literature inMainz,* vol. 10.:373-399

Seilacher, A., 1959. Vom Leben der Trilobiten. *Naturwissenschaften*, 16:389-393.

Seilacher, A., 1985. Trilobite paleoecology and substrate relationships. *Transactions of the Royal Society of Edinburgh, Earth Sciences,* 76: 231-237.

Seilacher, 1970. Cruziana stratigraphy of non-fossiliferous Paleozoic sandstones. In Crimes and Harper, eds., *Trace Fossils I*: Liverpool, England, Seel House Press, pp. 447-476.

Seilacher, 1985. Trilobite paleobiology and substrate relationships. Transactions of the Royal Society of Edinburgh, v.76, pp. 231-237

Seilacher, A., & Pfluger, F., 1994, From biomats to benthic agriculture: A biohistoric revolution, in Krumbein, W.E., et al., eds., Biostabilization of sediments: Oldenburg, Germany, Bibliotheks und Informations-system der Carl von Ossietzky Universitat Oldenburg (BIS), p. 97-105.

Seilacher, A., 2007. *Trace Fossil Analysis*, Springer-Verlag, Berlin.

Sepkoski, J.J., 1982. Flat-Pebble Conglomerates, Storm Deposits, and the Cambrian Bottom Fauna, *in* Einsele and Seilacher, (eds.), *Cyclic and Event Stratification*, editors. Springer-Verlag Publishers, Berlin.

Whittington, H.B., 1980. Exoskeleton, moult stage, appendage morphology, and habits of the Middle Cambrian trilobite *Olenoides serratus. Palaeontology,* 23:171-204.

OTHER RESOURCES

Bergström, J., 1976. Lower Palaeozoic trace fossils from eastern Newfoundland. *Canadian Journal of Earth Sciences, 13:1613-1633.*

Boggs, Jr., S., 2001. *Principles of Sedimentology and Stratigraphy*, Third Edition. Prentice Hall, NJ.
Brett, Carlton E; Baird, Gordon C, 1986. Comparative taphonomy; a key to paleoenvironmental interpretation based on fossil preservation. *Palaios*, vol.1, no.3, pp.207-227.

Crimes, T.P. and Harper, J.C., 1970. *Trace Fossils*, editors. Seel House Press, Liverpool, England.

Crimes, T.P., 1970. Trilobite tracks and other trace fossils from Upper Cambrian of North Wales. *Geology Journal* vol. 7, p. 4768.

Curran, H.A., 1985. *Biogenic Structures: Their Use in Interpreting Depositional Environments,* editor. Society of Economic Paleontologists and Mineralogists, Special Publication No. 35, Tulsa, OK.

Darton, N.H., 1906, Geology of the Big Horn Mountains. Government Printing Office, Washington, D.C.

Degenstein, Joel, 1978. *Geology of the Flathead Formation (middle Cambrian) on the Perimeter of the Bighorn Basin, Beartooth Mountains, and Little Belt Mountains in Wyoming and Montana.* Masters Thesis, University of North Dakota

Frey, R.W., 1975. *The Study of Trace Fossils: A Synthesis of Principles, Problems, and Procedures in Ichnology,* editor. Springer-Verlag Publishers, New York.

Glass, Gary B., and Blackstone, D.L., 1988. Geology of Wyoming. The Geological Survey of Wyoming, Laramie, Wyoming

Goldring, R., 1985. The formation of the trace fossil *Cruziana*. *Geology Magazine*, vol. 122 (1), pp. 65-72.

Hallam, A., 1977. *Patterns of Evolution: As Illustrated by the Fossil Record*, editor. Elsevier Scientific Publishing Company, Amsterdam.

Hughes, Richard V., 1933, The Geology of the Beartooth Mountain Front in Park County, Wyoming. In *Proceedings of the National Academy of Sciences of the United States of America*, vol. 19, no. 2 (February 15, 1933), pp. 239-253

Kepley, G., 1994, United States Forest Service Records Paleontology, Big Horn National Forest, Sheridan, Wyoming.

Kreisa, R.D., 1981. Storm Generated Sedimentary Structures. *Journal of Sedimentary Petrology*, vol. 51, No. 3, pp. 823-848.

Maples, C.G., and West, R.R., 1992. *Fifteenth Annual Short Course of the Paleontological Society*, editors. Paleontological Society Press, Knoxville, TN.
Prothero, D.R. and Schwab, F., 1996. *Sedimentary Geology: An Introduction to Rocks and Stratigraphy*. W.H. Freeman and Company, NY.

Savrda, Charles E., 1995. Ichnologic Applications in Paleoceanographic, Paleoclimatic, and Sea-Level Studies. *Palaios,* vol. 10, no. 6, Tenth Anniversary Theme Issue (December 1995), pp. 565-577

Samuelson, Alan C, 1974. Introduction to the Geology of the Big Horn Basin and Adjacent Areas, Wyoming and Montana in *Rock Mechanics: The American Northwest*, Barry Voight, editor. Experiment State, College of Earth and Mineral Sciences, The Pennsylvania State University, University Park, PA

Weedon, G.P., 1991. The Spectral Analysis of Stratigraphic Time Series, in *Cycles and Events in Stratigraphy,* Einsele, Ricker, and Seilacher, editors. Springer-Verlag Publishers, Berlin.