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Amy Elizabeth Singer

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Benthic Invertebrate Paleontology of the late Mississippian (Serpukhovian) Bear Gulch Limestone, Central Montana

Amy Elizabeth Singer

MSc, Earth and Environmental Sciences, University of Illinois at Chicago, IL, 2009
BSc, Geology, University of Montana, Missoula, MT, 2002
BA, Fine Art, University of Montana, Missoula, MT, 2002

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Approved by:

Scott Whittenburg,
Graduate School Dean

Nancy W. Hinman, Chair
Geosciences Department

Megan Dethier
Department of Biology, Friday Harbor Labs, University of Washington

Roy Plotnick
Department of Earth and Environmental Sciences, University of Illinois at Chicago

Robert Riding
Department of Earth and Planetary Sciences, University of Tennessee Knoxville

J. B. Alexander Ross
Department of Chemistry and Biochemistry

Singer, Amy E., Ph.D., Spring 2021 *Geosciences*

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Chairperson: Nancy W. Hinman

The Bear Gulch Limestone of the late Mississippian central Montana is a significant Konservat Lagerstätte known and a part of one of the most complete mid-Carboniferous stratigraphic sections in the world. Despite containing a well-described fish fauna, the most diverse and abundant Carboniferous fish fauna known, nothing was known of the invertebrate assemblages, and many aspects of the geology remained enigmatic. With few rocks of this age available for study worldwide, the Bear Gulch Limestone contains an important record of life and Earth history near the Pennsylvanian boundary, a time of climatic change.

Using new outcrop data combined with subsurface information a multidisciplinary integrative study was necessary to gain a fuller understanding of the Bear Gulch. In this study, the first of its kind undertaken in the Bear Gulch, I combined sedimentology, limited preliminary geochemistry, and invertebrate paleontology to understand the physiochemical parameters that led to the formation of the flinz and fäule laminasets and the important record of life they contain. The flinz and fäule are, broadly, the only two facies to have been recognized in the Bear Gulch Limestone. Detailed microfacies analysis, presented here, has identified 5 facies that elucidate the development of the basin. This higher resolution insight reveals that the BGL shallowed through time—the fully marine giving way to the increasingly estuarine conditions of the upper Tyler formation and glacial Pennsylvanian.

Furthermore, I confirmed the stratigraphic position of the Bear Gulch Limestone within the late Mississippian portion of the Tyler Formation. The Bear Gulch Limestone is a marine limestone tongue that transitions to the increasingly fluvial upper Tyler Formation within the Big Snowy Trough of central Montana.

Finally, this work represents the first comprehensive collection and taxonomic analysis that included all fossils found; vertebrate, invertebrate, botanical, and trace. New fossil collections with modern collecting techniques that include detailed locality and stratigraphic information allow testing of various hypotheses related to the fauna of the flinz and fäule. Invertebrate diversity and abundance, previously underestimated from historic collections, have been reported here for the first time.

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PREFACE

This dissertation is based upon doctoral research conducted at the Geosciences Department of the University of Montana between 2009 and 2021. The goals of this dissertation were to generate an accurate picture of the invertebrates of the Bear Gulch Limestone and to elucidate the processes that led to the formation of the flinz and fäule laminasets. This work was undertaken through an interdisciplinary approach of invertebrate paleontology, sedimentology, and limited preliminary geochemistry, based upon new excavations of the Bear Gulch Limestone over three field seasons on the Cox Family Ranch at Rose Canyon near Becket, MT during the summers of 2011–2013. This dissertation contains five chapters, of which Chapters 2–4 have either been published or are being prepared for publication in different journals, requiring different formatting.

Chapter one is a general introduction, providing background on the topics covered in this dissertation, including a brief history of the controversies and challenges that have limited research in the Bear Gulch Limestone, a review of paleontological exploration over the past 50+ years, and some background on the topics covered in the remaining chapters.

Chapter two confirms the stratigraphic position of the Bear Gulch Limestone within the Tyler Formation with an age of latest Mississippian (Serpukhovian) and was published in *FACIES* (Singer et al., 2019). This important work puts to rest years of speculation by reporting the upper contact with the Tyler as a fluvial conglomerate with Bear Gulch clasts.

Chapter three reports for the first time the invertebrates of the Bear Gulch Limestone as they occur in the outcrop, regardless of condition. New excavations for invertebrate fossils were undertaken to gather a true census of the fossils because museum collections of the Bear Gulch Limestone are focused on the vertebrate fauna and much information about the invertebrate fauna lacking. It was unknown if the reduced abundance and diversity of BGL invertebrate fauna was a true reflection of the life assemblage, lost taphonomically, or a sampling oversight as much of the existing research was focused on the fish fauna. The invertebrate fossils from this research were used to further explore the flinz and fäule laminasets, the two primary facies of the Bear Gulch Limestone and potential causes for their variation.

Chapter four defines the microfacies of the Bear Gulch Limestone beyond simply the distinction of the flinz and fäule laminasets. This study focused on the sedimentary processes and some of the geochemical conditions that led to the formation of the flinz and fäule laminasets and explored subtle changes that indicate freshwater influence, shallow burial diagenesis, and physiochemical differences between the microfacies.

Chapter five summarizes the research presented in this dissertation. It reviews all of the data collected, draws conclusions about the environmental influences on the formation of the flinz and fäule laminasets, the invertebrate fossil assemblages and how they vary, and presents a model for the deposition of the Bear Gulch Limestone from its early, fully marine conditions, to the close with the sequence boundary of the Tyler, as indicated by the conglomerate.

CHAPTER 1 –

Introduction

1.1 Overview.—The well known, yet understudied late Mississippian (Serpukhovian) Bear Gulch Limestone (BGL) in central Montana is an outstanding marine Konservat Lagerstätte. The biota were only partially known, as researchers focused on fish and generally did not assess the abundant and diverse invertebrates. The BGL was introduced at the first North American Paleontological Conference meeting in August 1969, the then curator of the University of Montana, William Melton, presented an unusual organism, which he hoped was a conodont. Conway Morris (1973) redescribed the animal as a condontophage because the anatomical position of the conodonts components was more consistent with those ingested rather than the *in situ* anatomy of the animal. However, the fine soft-tissue preservation was evident and established the BGL as an important snapshot in the history of life.

Deposited during the latest Mississippian Serpukhovian stage, the BGL records climatic, environmental, ecological, and evolutionary changes (Hagadorn, 2002). As a Lagerstätte, it provides a rare glimpse into Earth's history with the finely preserved hard and soft-bodied marine biotas. As a plattenkalk, a micritic limestone formed via precipitation of nearly pure carbonate in the water column, the BGL accumulated as finely laminated, alternating sets of varying induration (flinz and fäule bedding), which may indicate changes in the syndepositional environment.

This project sought to elucidate the BGL benthic macroinvertebrate paleontology and syndepositional paleoenvironment by investigating the interrelated approaches of sedimentology and invertebrate paleontology. Newly acquired fossil material enabled the application of modern paleobiological analyses and sedimentological techniques, permitting the reconstruction of the environmental parameters that led to the formation of flinz and fäule laminasets.

1.2 Brief History of Exploration.— This research was conducted on the ancestral and sacred lands of many Indigenous American nations including the Blackfeet, Assiniboine, Nez Perce, Atsina, and many others as the hundreds of pictographs on the flinz sets represent diverse indigenous cultures in the ceremonial tradition dating back as much as 1,000 years (MacDonald, 2012). The University of Montana acknowledges that our Campus is in the aboriginal territories of the Salish and Kalispel people. Today, we honor the path they have always shown us in caring for this place for the generations to come.

Granville Stuart first reported occurrences of petroleum in central Montana in 1880, but drilling did not commence until 1915 (Darrow, 1956). Productive wells surround the Bear Gulch in the Heath and Tyler formations; however, it is well-known that where there is BGL outcrop, there is no oil (Aram, Personal Comment, 2013). Central Montana saw boom and bust petroleum development throughout its history, but the BGL was not revisited until renewed expansion in the post-war era of the 1950s (Darrow, 1956). Mundt (1956) formally measured the BGL, noting that it is a cryptocrystalline platy limestone, interbedded with softer, more argillaceous limestone containing few gastropods. Interestingly, he noted the upper surface of the unit could be a local unconformity. Industry revisited the area in the 1970s, facilitated by extensive well-logs, and clarified the stratigraphic relationships with renewed modeling. These well-logs of the subsurface, coupled with outcrop exploration, put to rest decades of debate surrounding the exact position of the BGL and established it as confined within the Mississippian portion of the Tyler Formation (Bottjer, 2017; Singer et al., 2019).

In 1967, a local rancher brought the first fossilized fish from the BGL into the University of Montana Geology Department and asked curator William Melton how a fish could have gotten into the rock (Williams, 1981). This began the excavation and exploration of the BGL for fossils, ultimately leading to its discovery as a world-class Konservat Lagerstätte once the findings were shared at the first North American Paleontological Convention in 1969. The University of Montana continued excavation through the 1980s, only ceasing operations with the retirement of William Melton. Richard Lund, then of the Cincinnati Museum, was invited by William Melton to identify the fish fauna, which led to a large portion of the BGL literature (Melton, 1969; Grogan and Lund, 2002).

1.3 Paleobiology.—The BGL includes numerous species of fish, cephalopods, arthropods, gastropods, brachiopods, and worms, among other taxa (Williams, 1983; Horner, 1985). Although the Bear Gulch is fascinating for the rich faunal diversity it contains, it is equally notable for the fauna that are missing. Taxa that are known to have been present and common in the Carboniferous but missing from the Bear Gulch assemblage as body fossils are: corals, bryozoans, crinoids, and trilobites (Hagadorn, 2002; Horner, 1985).

Despite these gaps in the fauna, BGL remains a highly diverse ecosystem and a premier locality to study Carboniferous biota not normally preserved elsewhere (Lund and Poplin, 1999; Hagadorn, 2002). All Paleozoic feeding types are represented, including carnivores, scavengers, filter feeders, and grazers, demonstrating that although some organisms may be absent, the BGL fauna still rivals or exceeds similar ecosystems in taxonomic diversity and trophic structure (Williams, 1981; Grogan and Lund, 2002). Due to the absence of several common Carboniferous marine invertebrates, the BGL has led researchers to suggest it was restricted with respect to the paleoenvironment (Williams, 1981; Shephard, 1993; Grogan and Lund, 2002). My research has found that with a full census of taxa, these organisms are present, for example, crinoid and trilobite components were both found in thin section but have not previously been reported (see chapter 3).

1.3.1 Fish.—Study of the Bear Gulch fish has spanned the entire history of collecting from the locality and includes over 113 species with an extensive body of literature (Lund, 1974, 1977a,b,c, 1980, 1982, 1983, 1984, 1985a,b, 1986a,b, 1988, 1989; Lund and Zangrel, 1974; Zidek, 1980; Lund and Melton, 1982; Di Canzio, 1985; Lowney, 1985; Lund and Poplin, 1997, 2002; Poplin and Lund, 2000, 2002). The vertebrate fossils of the basin include both Chondrichthyans and Osteichthyes (Hagadorn, 2002). Among them, Osteichthyes, especially coelacanths, are the most common and Chondrichthyans are the most diverse (Hagadorn, 2002; Lund and Poplin, 1999). Full growth series of coelacanths are present from larva stage to maturity, allowing extrapolation of life histories (Hagadorn, 2002).

1.3.2 Mollusca.—While receiving little attention compared to fish, several members of the Mollusca have been described from the BGL. McRoberts and Stanley (1989) described bivalves attached in life position to macroalgae. Cephalopods are the most common organism (5 to 120 mm) and include both straight and coiled forms. They are found on all bedding planes and are abundant throughout the section, although species distribution varies across the basin (Horner, 1985). Mapes (1987) and Landman and Davis (1988) both discussed the locally abundant cephalopods as indicators of open marine conditions. Due to the fine soft tissue preservation, the BGL contains some of the oldest Coleoid fossils, leading Klug et al, (2019) to examine

Coleoidea beargulchensis to investigate the evolution of conch internalization. Mollusks are of particular taphonomic interest as they are only preserved as external molds; all mollusk shell material absent (Hagadorn, 2002).

1.3.3 Arthropods.—After cephalopods, arthropods are the next most common invertebrate in the assemblage, including; ostracodes, phyllocarids, concavicarids, palaeostomatopods, eumalacostracans (Factor and Feldman,1985; Schram and Horner,1978; Schram 1979a). Specimens of *Palaeolimulus*, although rare, have been described by Schram (1979b). Trilobites are absent as articulated body fossils.

1.3.4 Brachiopoda.—According to Lutz-Garihan (1979), brachiopods from BGL are less diverse than other Carboniferous fauna, based on the limited material available at the time. Chapter 3 describes new findings with regards to brachiopods.

1.3.5 Porifera.—The sponge fauna from the BGL, according to Rigby (1979), contain hexactinellids, Belemnospongia, Arborispongia, dictyosponges, and calcarea.

1.3.6 Echinodermata.—Welch (1984) described the seastar *Lepidastella* and ophiuroids in the original dissolved aragonite.

1.3.7 Worms.—A diverse assortment of worms, including nemertines, polychaetes, and nematodes have been preserved as molds and casts, color staining, and original organic material.

Remarkable preservation includes jaws, denticles, gut contents, and soft tissues (Hagadorn, 2002; Schram, 1979b).

1.3.8 Problematica.—The BGL contains several phylogenetically uncertain fossils, as even the enigmatic organism first described at the 1969 NAPC meeting, *Typhloesus wellsi* (Melton and Scott, 1973) is no longer considered a conodont animal, and its phylogenetic relationship remains unclear (Conway Morris, 1990). Although conodont elements and apparatuses are present in the BGL contained within the gut of the conodontophage (Melton and Scott, 1973; Purnell, 1993), fully articulated body fossils of a conodont animal have yet to be found. Conulariids, with holdfasts, and Sphenothallus have also been described (Babcock and Feldmann, 1986; Van Iten, et al. 1992).

1.4 Taphonomy.—It has been hypothesized that the BGL is a classic obrution deposit with rapid burial in anaerobic fine-grained sediments with restricted bioturbation, which sequestered soft tissues from decay and scavengers (Hagadorn, 2002; Thomas, 2004). Fine preservation of whole-body fossils includes chitinous, cartilaginous, and phosphatic material (Feldman et al., 1994; Williams, 1983; Thomas, 2004). Organs, gut contents, veins, and other soft-tissue structures have also been described in detail (Lund and Poplin, 1999). As the basin was shallow, warm, and maintained oxygenated bottom waters, rapid burial is considered by many to be the dominant mechanism of preservation because, exposed to the water column, the carcasses would have quickly decayed or been scavenged (Hagadorn, 2002).

Specimens are typically preserved laterally between laminations of limestone, although algal fronds, sponges, some large cephalopod, and fish cross laminations are believed to have been deposited during times of low sedimentation rates (Hagadorn, 2002). The majority of fossils are articulate and complete, indicating that there was minimal time between death and burial with little transport (Feldman et al., 1994; Hagadorn, 2002; Thomas, 2004). There is fragmentary and rare scavenged material in the deposit, demonstrating variable preservation in the basin with rock type (Williams 1981; Horner, 1985). Changes in preservation may reflect changes in sediment supply or local variations in depositional environment (Thomas, 2004; Hagadorn, 2002; Williams, 1983). Thomas (2004) further investigated the taphonomy (primarily of fishes) in the BGL and found that phosphatization only occurred in fish scales and bone (Thomas, 2004). She also found the BGL to be too clay poor for preservation by interactions between the clay minerals and bacteria and suggests rapid replacement or carbonization was the preservation mechanism of nonmineralized tissues.

*1.5 Geology.—*The BGL crops out over 5 km^2 in Fergus County, Montana about 30 km northeast of the Big Snowy Mountains and 35 km southeast of Lewistown, Montana (Conway Morris, 1990; Melton, 1969). The outcrop area is approximately 85 km^2 with an estimated maximum thickness of 30 m (Feldman et al., 1994; Grogan and Lund, 2002). The BGL dates to the Serpukhovian, latest Mississippian, supported by dating of cephalopod sutures, conodonts, palynomorphs, and the fish assemblages (Feldman et al.1994; Mapes, 1987; Cox, 1986; Williams, 1983; Scott, 1973; Norby, 1976). The top contact is with the upper Tyler Formation, but the lower contacts are obscured by slumping, downcutting of the fluvial processes of the Tyler Formation, and overgrowth. Where exposed, the BGL grades into the organic-rich, platy shale of the lower Tyler Formation (Williams 1983; Bottjer 1993).

The BGL comprises a rhythmically alternating sequence of massive cryptocrystalline nonfissile units (flinz) with friable argillaceous laminasets (fäule) (Williams, 1983). Williams (1983) found that the lithology and nearly pure carbonate mineralogy was similar to the flinz and fäule style of bedding found in the Mid-Jurassic Solnhofen plattenkalk of Germany and adopted this lexicon for the BGL (Hemleben and Swinburne, 1991). There is no known modern analog for this type of plattenkalk deposition, but it is presumed that conditions were shallow embayments (Williams, 1983). Depositional models for BGL developed for the BGL ranged from a near-shore shoal to a relatively far-from-shore marine bay (Shepard, 1993; Lund et al., 2002). Reconstructions have placed it 12° north of the equator during the late Mississippian (Lund et al., 1993). Lund et al. (2002) consider the paleoclimate to have been arid with seasonal monsoons, but Williams (1983) points to *Lepidodendron* logs as evidence for a continually tropical environment.

The BGL represents a transgressive sequence within the Big Snowy Trough that trends east-west between the Cordilleran Miogeosyncline and the Williston Basin to the east (Williams, 1983). The basin is predominately marine with some freshwater inputs along the margins resulting in potentially seasonal brackish conditions in at least some portions of the basin (Feldman et al, 1994; Horner, 1985). Grogan and Lund (2002) have disputed this interpretation of the basin and interpret the shales as brackish water and the limestone lens as a pocket of deeper water. Presence of benthic organisms indicates oxygenated bottom waters, and the absence of wave structures or other erosional structures suggests that the limestone was laid down in calm waters (Hagadorn, 2002; Williams, 1983). The absence of bioturbation may indicate anoxic conditions within the sediment at the time of deposition or rapid lithification of sediments (Williams, 1983).

Williams (1983) postulated that sedimentation was continuous as the basin filled, indicating that the modern thickness of the section accurately represents water depth. Allowing for compaction, the basin was shallow (water depth ≤ 30 m) and gently sloped to the margins, thinning to a shoreline (Hagadorn, 2002; Lund and Poplin, 1999; Williams, 1983).

Although the deposit is known for exquisite preservation and a diversity of fauna that rivals that of the Burgess Shale, limited work has been conducted and many questions remain on the deposition of the flinz and fäule laminasets and invertebrate paleontology (Williams, 1983; Hagadorn 2002; Thomas, 2004).

This dissertation aimed to elucidate the true occurrence of all fossil materials within the BGL, regardless of quality, to investigate invertebrate paleontology. An interdisciplinary approach was applied, including invertebrate paleontology, sedimentology, and limited preliminary geochemistry to understand the formation of the flinz and fäule laminasets of the BGL plattenkalk. The following primary research questions concerning the paleontology and environmental characteristics of the BGL were addressed:

1. What is the composition of the benthic macroinvertebrate community in the BGL?
2. What are the lithologic differences and depositional processes involved in the flinz and fäule laminasets formation?
3. Does the benthic macroinvertebrate community change relative to lithology and environmental conditions (i.e. do flinz and fäule laminasets have different fossil assemblages)?

This systematic interdisciplinary investigation, with a new unbiased research collection, has provided a robust snapshot of this important lagerstätte and the syndepositional processes that led to the formation of the flinz and fäule laminasets.

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CHAPTER 2 – ANATOMY OF THE BOOK CANYON CONGLOMERATE: A SEQUENCE BOUNDARY AT THE TOP OF THE BEAR GULCH LIMESTONE IN THE BIG SNOWY TROUGH

AMY E. SINGER, GEORGE STANLEY, NANCY W. HINMAN

Singer, A., Stanley, G.D., and Hinman, N.W., 2019, Anatomy of the Book Canyon conglomerate: A sequence boundary at the top of the Bear Gulch Limestone in the Big Snowy Trough: Facies, v. 65(19). https://doi.org/10.1007/s10347-019-0557-4

2.1 - Abstract

The Serpukhovian Book Canyon Conglomerate is a newly recognized limestone conglomerate in central Montana. It overlies and contains clasts of the Bear Gulch Limestone, a plattenkalk deposit yielding amazing paleontological detail. The Book Canyon conglomerate is up to 2 meters thick, markedly lensoid, and laterally discontinuous in its outcrop for a distance of 2 km but likely extends beyond the study area. Well logs and cores indicate its presence in the subsurface between the underlying Bear Gulch Limestone and overlying Tyler Formation. This conglomerate provides new information regarding the transition of the marine-dominated Bear Gulch Limestone (Serpukhovian) to the overlying fluvial Tyler Formation (Morrowan). The Book Canyon conglomerate is interpreted as a product of subaerial/fluvial erosion of the Bear Gulch Limestone further supported by the additional discovery of a semi-arid paleosol formed on the floodplain of the conglomerate channel. Features of the Book Canyon Conglomerate include lateral bars, thalweg, and floodplain paleosol deposits.

Freshwater exposure and channelized fluvial erosion early in the post-depositional history of the Bear Gulch Limestone explains variations in the contacts between units that contribute to the debate concerning stratigraphic relationships. Further analysis of unconformities and fauna at the base and top of the unit clarifies the Bear Gulch Limestone's position in time, and its relationship to the Heath and Tyler formations.

2.2 - Introduction

The Late Mississippian, Serpukhovian Stage Bear Gulch Limestone (BGL) of central Montana is a plattenkalk -- a finely laminated micritic limestone often associated with high-resolution fossil preservation, but with no modern depositional analog (Barthel et al., 1990; Williams, 1983). The unit is known for fine preservation of soft and hard tissues in fish, worms, and arthropods. Other well-preserved fossils include sponges, algae, brachiopods, bivalves, and cephalopods. Although the BGL is known for exquisite preservation and diverse fauna, relatively few published works have elucidated the depositional history of this unit, including the draining of the shallow epicontinental seaway and transition to the fluvial Tyler Formation (Shepard, 1993a; Lavering, 2014; Hagadorn 2002).

Depositional models suggested that BGL environments range from a near-shore shoal to a relatively far-from-shore marine bay within the Big Snowy Trough (Shepard 1993b; Lund et al. 2012). These models attempt to explain the finely laminated, unbioturbated, rhythmic laminasets of the BGL where massive heavily bioturbated carbonate would be the norm for rocks of this age (Figures 1, 2, and 3). Grogan and Lund (2002) place central Montana 12^{O} north of the equator (Figures 1, 2, and 3) and interpret the laminasets as the result of an arid climate with seasonal monsoons.

There have been several conflicting hypotheses concerning the stratigraphic position of the BGL (Cox 1986; Lund et al. 1993; Shepard 1993b; Williams 1983). Grogan and Lund (2002) argue that the BGL biota, specifically the cephalopods, conodonts, and palynomorphs, are most similar to Mississippian forms and hence should be part of the Mississippian Heath Formation. Lund's extensive work on BGL's diverse and abundant fish fauna date the BGL to latest Mississippian. Stratigraphic relationships in the subsurface from both well logs and core place the BGL within the Tyler Formation (Bottjer 2017; Aram 1993a). This confirms extensive earlier oil industry literature based on field mapping at the surface. The Tyler formation lacks dateable fossils so Shepard (1993b) suggested moving the Pennsylvanian boundary beneath the widespread Amsden Formation, placing the underlying Tyler within the latest Mississippian. Recent core work by Bottjer (2017) confirms this interpretation of the Mississippian-Pennsylvanian boundary and identifies a sequence boundary between the Heath and lower Tyler. For the purposes of this paper, the BGL is contained within the Tyler Formation, following the stratigraphy of Maughan (1967), Shepard (1993b), and Bottjer (2017). The BGL is thus of Serpukhovian age, placing the Mississippian-Pennsylvanian boundary within the upper Tyler Formation.

2.2.1 - Geologic setting

The study area is in Fergus County, Montana, about 30 km northeast of the Big Snowy Mountains and 35 km southeast of Lewistown, Montana (Figure 1; Williams 1983; Conway Morris 1985). The BGL outcrops along the Potter Creek Dome and can be accessed in adjacent canyons. Outcrops in these canyons vary in thickness from a few meters to approximately 15 m. The limestone was deposited within the Big Snowy Trough, possibly associated with a Precambrian aulacogen that connected the Big Snowy Basin to the east with the open ocean to the west (Figure 2; Shepard 1993b). During the Serpukhovian, the Big Snowy Trough experienced large eustatic fluctuations, causing the depositional environment in the basin to vary (Shepard 1993b). Near the end of the Serpukhovian, global sea level dropped and faulting in the tectonically active Big Snowy Trough drained the seaway and developed a fully fluvial environment (Aram 1993b; Shepard 1993b).

The BGL consists of nearly horizontal laminasets — beds composed of multiple laminae with shared attributes. The laminasets alternate between clayey, micritic laminasets (fäule) and massive silty micritic laminasets (flinz) similar to the Jurassic Solnhofen Limestone (Figure 3; Williams 1983; Munnecke et al. 2008). The difference between the two BGL laminaset styles appears to be the degree of weathering, fossil content, and thickness. Flinz laminasets are resistant and fäule laminasets are friable. Alternating laminasets in the BGL are thought to reflect episodic microturbitity currents that helped preserve the fossils (Grogan and Lund 2002); alternatively, they may record cycles, such as tides or seasons (Hagadorn 2002), or contour currents (Isaacson personal communication 2018).

Throughout Bear Gulch time, the laminasets change in thickness, periodicity, friability and induration (Figure 3). Although individual laminae are strikingly similar, and the extent of outcrop weathering features in their appearance, the laminasets in lower parts of the section are much thicker and their periodicity more regular (Figure 3). Herein, we refer to the lower part of the section as Book Coulee BGL and the upper part of the section, which has been the focus of most of the existing research and collected fossils, as Classic BGL. The characteristics of the Book Coulee BGL and Classic BGL laminasets are distinctive in the field, yet the two laminasets are related by laminae scale features and grade into each other throughout the section (Figure 3). The fäule laminasets of Book Coulee BGL and the Classic BGL are poorly cemented and easily break into individual laminae. Book Canyon BGL flinz laminasets also break into individual laminae, but the competent individual lamina are nearly identical to lamina within the well-cemented flinz laminasets of the Classic BGL. Both flinz and fäule fall between mudstone and wackestone, with flinz containing slightly higher carbonate concentrations (Figure 4).

In 2013, we found a previously unknown conglomerate, including intraformational BGL flinz clasts, capping the classic BGL flinz and fäule laminasets and in contact with the basal Tyler sandstone conglomerate (Figure 4). The same conglomerate was found at the tops of every measured section within the Book Canyon field area (Figure 1). Several sites were sampled and showed variation across the field area. Inclined beds are evident in the thicker exposures at S1 and S2. The conglomerate also was observed, but not measured, at other sites within the field area, including lower reaches of Miller Canyon near the confluence with Rose Canyon. Williams (1981) reports a conglomerate and a conglomerate approximately 2 meters thick with clasts of Bear Gulch Limestone was also identified east of US route 87 (Lund personal communication 2017), but these outcrops are currently inaccessible and not available for this study.

2.2.2 - Conglomerates

Conglomerates and breccias can form by a number of processes, but the lithological characteristics are indicative of the depositional environment (Table 1). Characteristics that are indicative of deposition also include, but are not limited to, rounding, sorting, clast size, whether the conglomerate is clast- or matrix- supported (fabric), lithology, and bedding (Flügel 2002).

2.3 - **Methods**

Stratigraphic sections were measured at the millimeter scale along coulees that cut across the BGL. Sedimentary attributes recorded include but were not limited to:

- Grain size
- Laminaset/lamina thickness
- Sedimentary structures (ripples, cross-stratification, and soft sediment deformation)
- Ichnofauna (type)
- Bioturbation intensity

BGL laminasets were defined as either flinz or fäule, determined in the field by resistance to weathering. The detailed stratigraphic measurement and the microfacies analysis of the corresponding rock samples enabled a thorough geologic description of the BGL. The conglomerate beds were measured and hand samples collected from several sites in the study area.

2.4 - Description

A carbonate conglomerate containing BGL clasts has been identified at the top of every measured section, in contact with both underlying laminated BGL and the overlying Tyler Formation (Figure 1, 4). The thickest accumulation of the conglomerate was found in the southernmost exposure of the conglomerate at Outcrop S1 (Figure 5). The conglomerate thins to the north, east, and west with changes in bedding and clast size, but consistent lithologies (Figure 1, 5, 6, 7, and 9). A single site in the northern exposure is brecciated with distinct lithological characteristics relative to the conglomerates (Figure 8). Descriptions of the individual samples have been summarized in Table 2.

2.5 - Discussion

The Tyler Formation was a meandering alluvial valley-fill within the Big Snowy Trough. It was interpreted to have drained to the east (Shephard 1993a). Multiple regressive erosional events occur below and above the BGL (Foster 1956; Shephard 1993b). The lower Tyler channels cut into the Heath Formation (Shephard 1993a). The BGL represents a brief marine invasion between the deposition of the lower and upper Tyler Formations. The upper Tyler Formation then cuts into the BGL; in some places, all the way through the unit into the Heath Formation (Bottjer 2017; Foster 1956). This explains the difficulty in stratigraphic placement, as the BGL overlies both the Heath Formation and Tyler Formation at different locations, both at the surface and in the subsurface. Although no contact with the Heath was found in this study, multiple contacts with the basal sandstone conglomerates of the Tyler Formation were located.

Based on the criteria outlined in Tables 1, the Book Canyon conglomerate likely formed in a fluvial and interfluvial environment (Table 3). This is further supported by the numerous black limestone pebbles included in the conglomerate (Figure 6, 7). Black limestone pebbles form as a result of exposure of marine limestone to meteoric water (Flügel 2009). In the conglomerates of the field area, all the components of a single stream channel are present: a lateral bar, a thalweg, and a floodplain paleosol (Figure 10, 11).

Outcrop S1, containing the largest clasts or dropstones and poorly sorted thicker beds, probably represents the thalweg of the stream cutting across the lithified marine BGL. S2 and S3, with finer truncating beds and smaller, better-sorted clasts, are lateral accretionary bars. The clast size and composition of N5 indicate a single fluvially transported bed deposited on the exposed classic BGL (Figure 10, Table 1). N4 samples stand out as distinct and were evaluated based upon brecciation mechanisms (Table 2) rather than conglomerate (Table 1).

Based on the criteria outlined in Table 1, the brecciated N4 samples are a paleosol (Table 3; Figure 7; Flügel 2009). Limestone clasts formed in situ as a part of soil processes of a semi-arid climate. The chert cement is also a primary product in semi-arid soils. The silica likely comes from the Tyler sands or from silicate phases in the BGL. Solution-collapse also fits most of the evidence, but does not explain the strong horizontal bedding, nor is there any nearby anhydrite (Flügel 2009).

The fluvial-formed Book Canyon conglomerate in outcrop confirms Aram (1993b)’s hypothesis of an erosional relationship between lower Tyler, BGL, and upper Tyler, which is further supported by Bottjer (2017). It represents channels cutting through the BGL during the deposition of the Tyler, due to deepening and shallowing of the trough. The trough was controlled by periodic reactivation of faulting from the failed Precambrian aulacogen (Aram 1993b; Shepard 1993b). Activity of the Proterozoic aulacogen faults would control local base level, although global sea level is also known to be in flux during this time (Aram 1993b).

2.6 - Conclusions

The BGL presents several stratigraphic problems:

- The BGL varies in thickness both in outcrop and the subsurface.
- Post-depositional slumps from ongoing stream cutting make lateral relationships and mapping of individual laminasets difficult.
- Unconformities occur above, below, and lateral to the BGL.
- There is much disagreement in the literature regarding its stratigraphic placement.

Widespread fracturing and slumping of the BGL into the softer shales below has resulted in inconsistencies in outcrop observations, necessitating greater subsurface study not available to earlier workers. Recent cores have become available, increasing the field area of the BGL in the subsurface (Bottjer 2017). Modern stratigraphic techniques applied to outcrop descriptions and continued core work by petroleum geologists continue to clarify and define these stratigraphic relationships. The sequence boundary between the Heath and lower Tyler is regionally clear in both outcrop and core (Bottjer 2017).

Local interfingering with the Heath due to cutting by both upper and lower Tyler, and modern slumping, have complicated outcrop-based studies in the past. This outcrop study of the Book Canyon Conglomerate is supported by core work by Bottjer (2017), well-log analysis by Aram (1993b), and early mapping studies (Maughan 1967) that place the BGL within the Tyler Formation. Occurrence of the conglomerate beyond the field area has been suggested by other workers both in outcrop and the subsurface (Bottjer 2017; Lund personal communication 2017; Aram personal communication 2014; Williams 1981). The conglomerate may explain an anomalous signal observed in the electrical log data interpreted by Aram (1993a). This distinctive signal is widespread throughout the subsurface where BGL occurs (Aram personal communication 2014).

The Book Canyon conglomerate represents a sequence boundary in outcrop between the basal Tyler Formation and the close of BGL, as the fully marine processes of the BGL transition to the channelized alluvium of the upper Tyler (Figure 9, 10, 11, and 12). The conglomerate's contact with the sandstone conglomerates at the base of the lower Tyler is evidence of fluvial cutting and represents a sequence boundary between the marine BGL and fluvial lower Tyler (Figure 12). This relationship in outcrop confirms core and well log work that places the BGL within the Tyler Formation (Figure 12).

2.7 - Acknowledgements

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2.8 - FIGURES

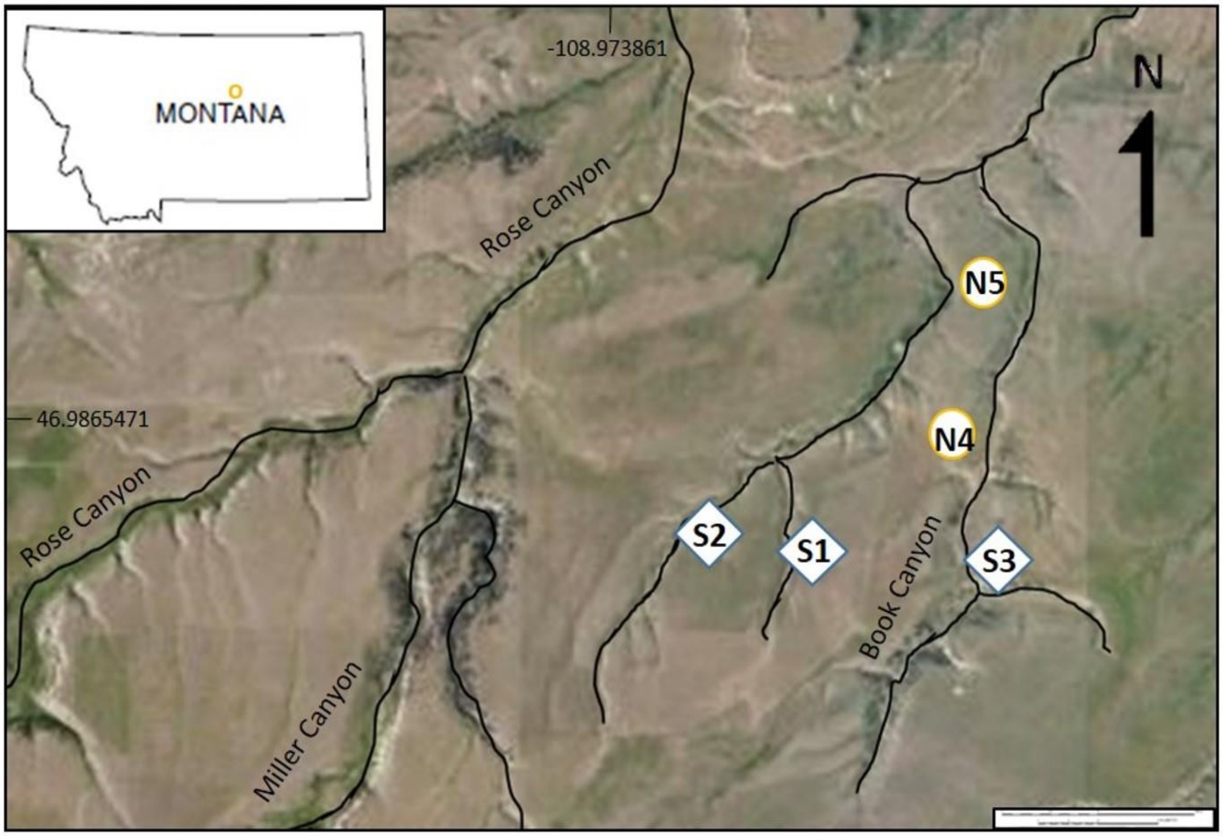


Fig. 1. Locality map of Bear Gulch Limestone (BGL). BGL outcrops in canyons that transect the unit north of the Snowy Mountains in central Montana. This study focused on specimens collected from the Book Canyon drainage. Northern (N) and southern (S) samples differ in composition. (Modified from Harris Corp., Earthstar Geographics LLC 2016).

Fig. 2. Paleomap of Bear Gulch Limestone (BGL) showing its location within the Big Snowy Trough, probably a Precambrian aulacogen, near the equator during the late Mississippian. As global sea level fell and tectonic activity reactivated, the trough emptied and developed a fully fluvial depositional environment (Modified from Blakey 2015).

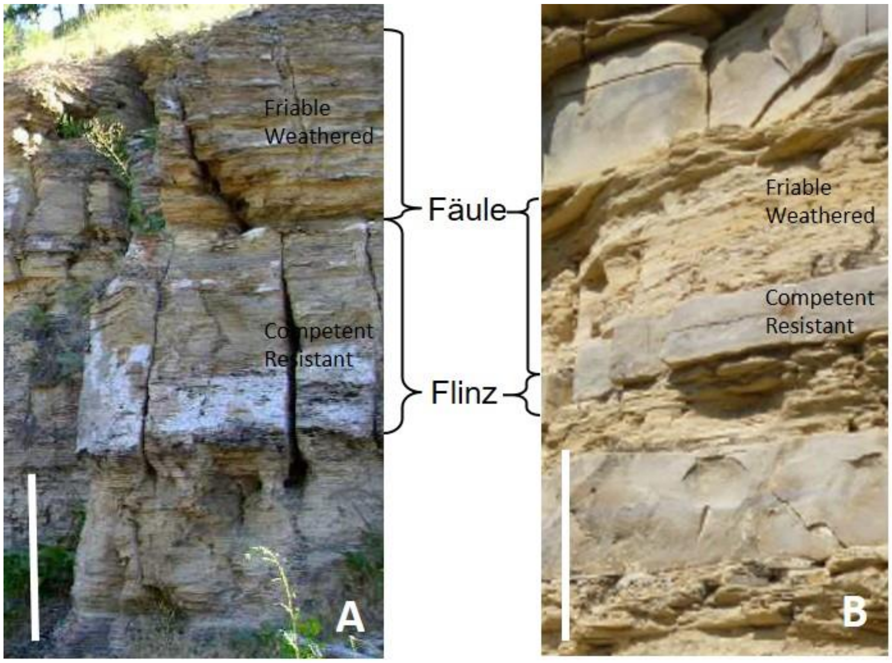


Fig. 3. (A) Meter scale Book Coulee type with regular periodicity in Book Coulee (scale bar represents 1 m) and (B) Classic Bear Gulch in Miller Canyon with irregular periodicity (scale bar represents 10 cm). A and B demonstrate similar changes between flinz and fäule laminasets in thickness, friability and induration. The flinz sets of the Classic Bear Gulch type, where laminae are very well cemented, are exceptions. The two streams are approximately 2 km apart.

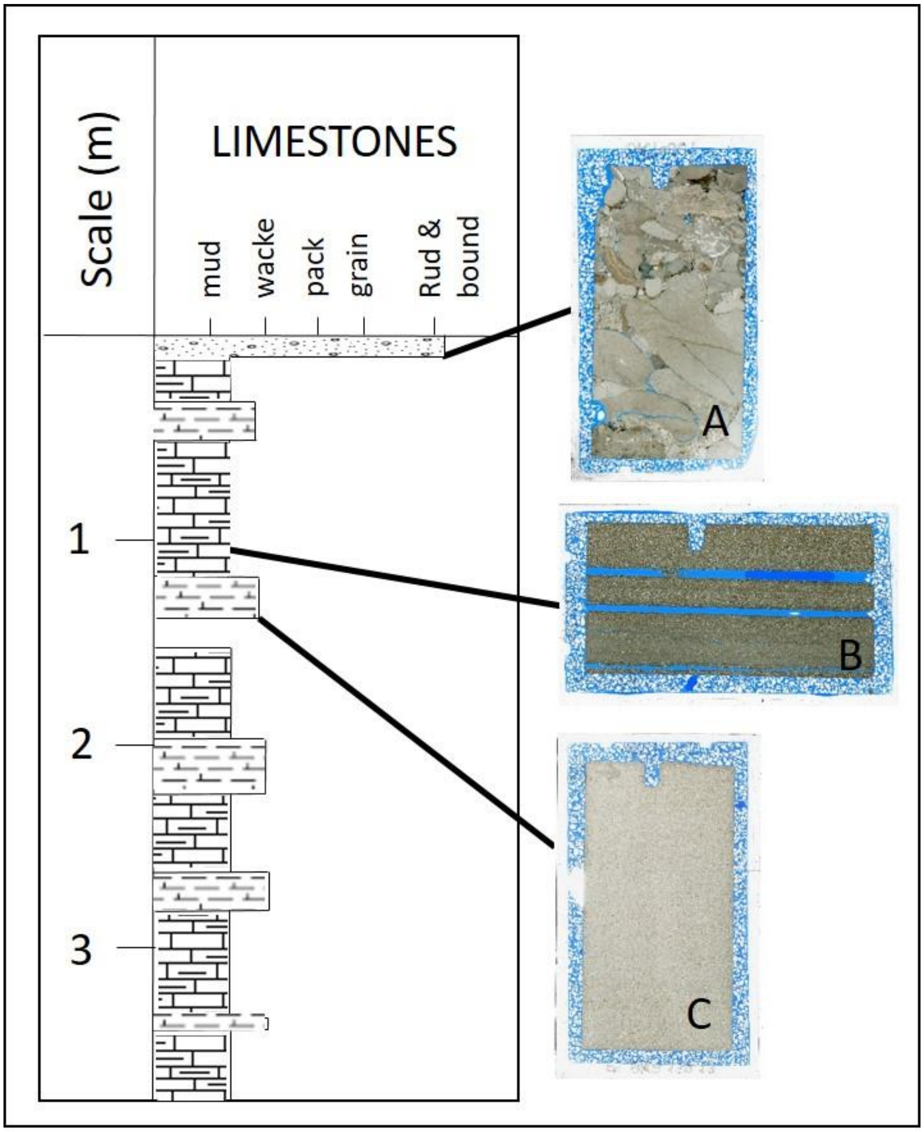
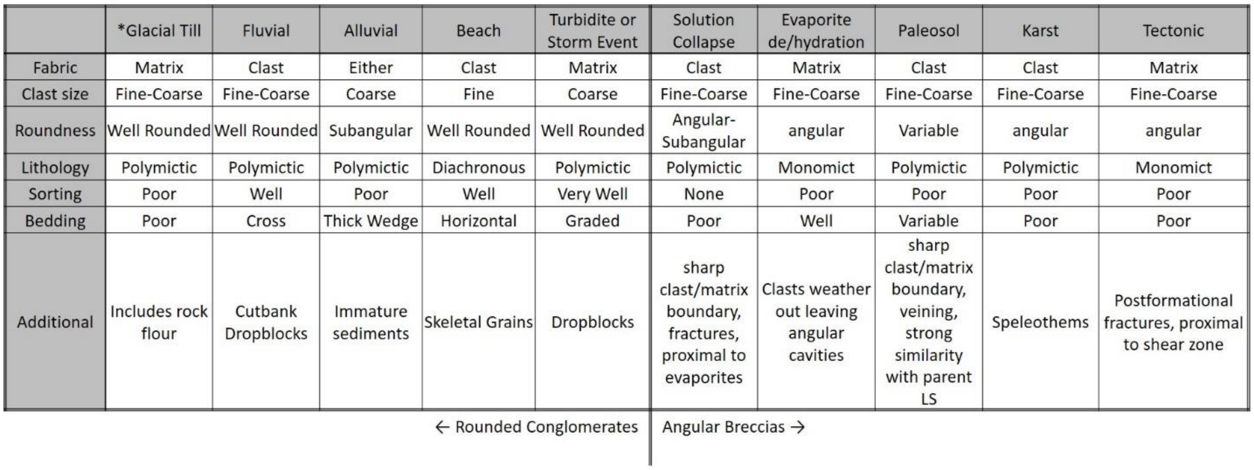


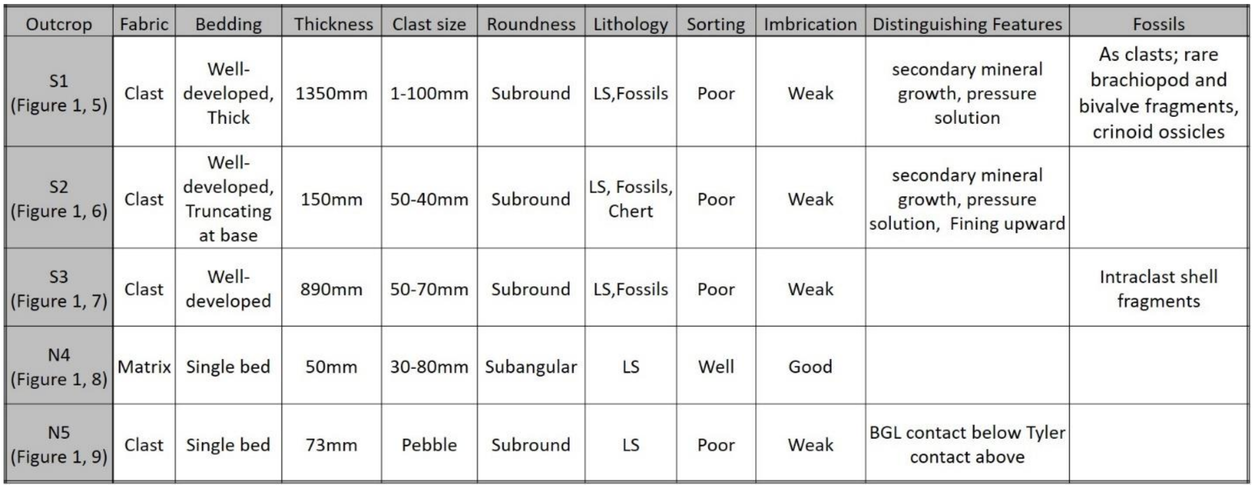
Fig. 4. Partial stratigraphic column with a thin section of the Book Canyon conglomerate (A). Note the inclusion of BGL flinz clasts in the conglomerate with small amounts of chert and fossil material. Fäule (B) and flinz (C) are included for reference. Thin sections are mounted to standard 27.0 x 46.0 mm petrographic slides.



	*Glacial Till	Fluvial	Alluvial	Beach	Turbidite or Storm Event	Solution Collapse	Evaporite de/hydration	Paleosol	Karst	Tectonic
Fabric	Matrix	Clast	Either	Clast	Matrix	Clast	Matrix	Clast	Clast	Matrix
Clast size	Fine-Coarse	Fine-Coarse	Coarse	Fine	Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse
Roundness	Well Rounded	Well Rounded	Subangular	Well Rounded	Well Rounded	Angular-Subangular	angular	Variable	angular	angular
Lithology	Polymictic	Polymictic	Polymictic	Diachronous	Polymictic	Polymictic	Monomict	Polymictic	Polymictic	Monomict
Sorting	Poor	Well	Poor	Well	Very Well	None	Poor	Poor	Poor	Poor
Bedding	Poor	Cross	Thick Wedge	Horizontal	Graded	Poor	Well	Variable	Poor	Poor
Additional	Includes rock flour	Cutbank Dropblocks	Immature sediments	Skeletal Grains	Dropblocks	sharp clast/matrix boundary, fractures, proximal to evaporites	Clasts weather out leaving angular cavities	sharp clast/matrix boundary, veining, strong similarity with parent LS	Speleothems	Postformational fractures, proximal to shear zone

← Rounded Conglomerates | Angular Breccias →

Table 1: Environments that can lead to the formation of conglomerates and breccias and their characteristics. Even though a paleolatitude of 12˚ north of the equator likely excludes *glacial processes, till is included in the table for comparison.



Outcrop	Fabric	Bedding	Thickness	Clast size	Roundness	Lithology	Sorting	Imbrication	Distinguishing Features	Fossils
S1 (Figure 1, 5)	Clast	Well-developed, Thick	1350mm	1-100mm	Subround	LS,Fossils	Poor	Weak	secondary mineral growth, pressure solution	As clasts; rare brachiopod and bivalve fragments, crinoid ossicles
S2 (Figure 1, 6)	Clast	Well-developed, Truncating at base	150mm	50-40mm	Subround	LS, Fossils, Chert	Poor	Weak	secondary mineral growth, pressure solution, Fining upward	
S3 (Figure 1, 7)	Clast	Well-developed	890mm	50-70mm	Subround	LS,Fossils	Poor	Weak		Intraclast shell fragments
N4 (Figure 1, 8)	Matrix	Single bed	50mm	30-80mm	Subangular	LS	Well	Good		
N5 (Figure 1, 9)	Clast	Single bed	73mm	Pebble	Subround	LS	Poor	Weak	BGL contact below Tyler contact above	

Table 2: Summary of the measured outcrops characteristics. Note N4, and to a lesser degree N5, have distinct characteristics from the rest of the outcrops in the field area.

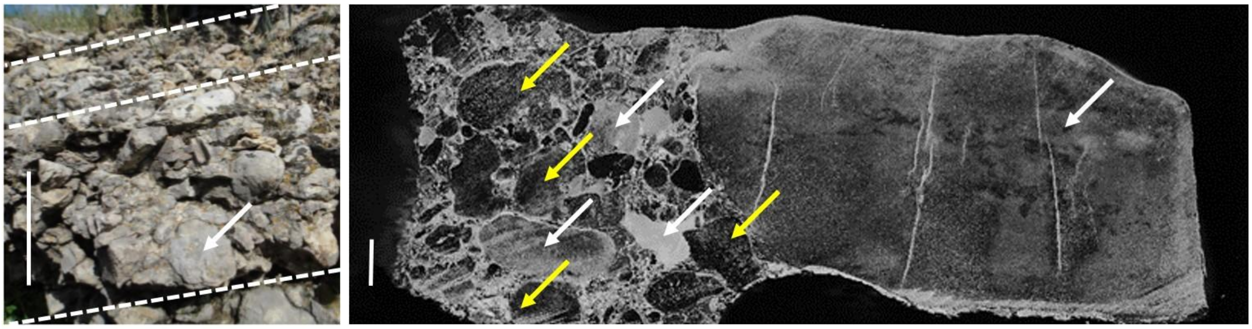


Fig. 5. Outcrop S1 contained multiple beds of the conglomerate. The beds are poorly sorted with weak imbrication. It is clast-supported with a lime-mud matrix. Some clasts show pressure solution. Clasts are predominantly limestone, including some flinz laminasets. Overall, fossils are rare outside of limestone clasts. White arrows indicate BGL flinz clasts and yellow arrows indicate BGL clasts that have turned black.

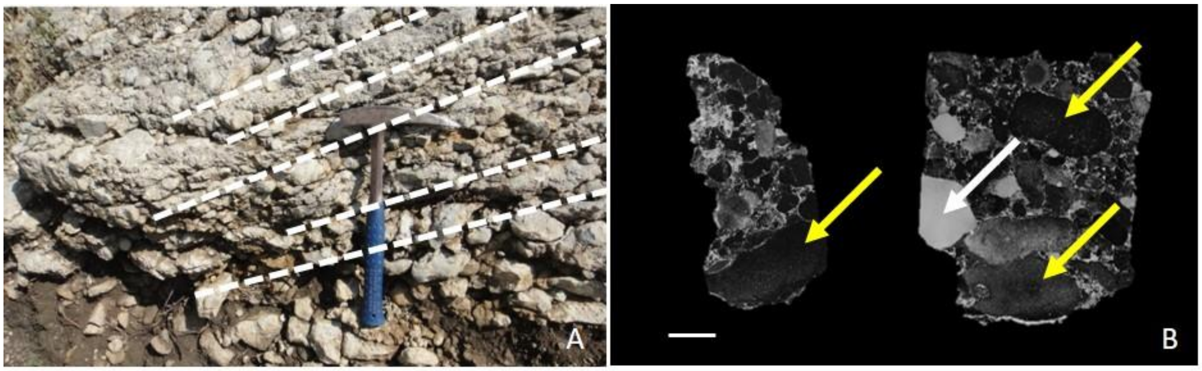


Fig. 6. Clasts range from 0.5 mm to 7 mm. Fossils are rare outside of limestone clasts. Iron staining of carbonate cement with predominantly limestone clasts, including some flinz laminasets (white arrows). Minor amounts of chert present. Pressure solution is well developed in several clasts. Yellow arrows indicate BGL clasts that have turned black. Scale bar is 5 mm. Note change in dip of beds (A).

Fig. 7. Clasts range from 0.5 mm to 7.0 mm. Overall, fossils are confined to the clasts and rarely found in the enclosing matrix. Carbonate cement with predominantly limestone clasts, including some flinz laminasets. Note change in bed and clast size from base to top of the outcrop. Scale bar is 10 cm.

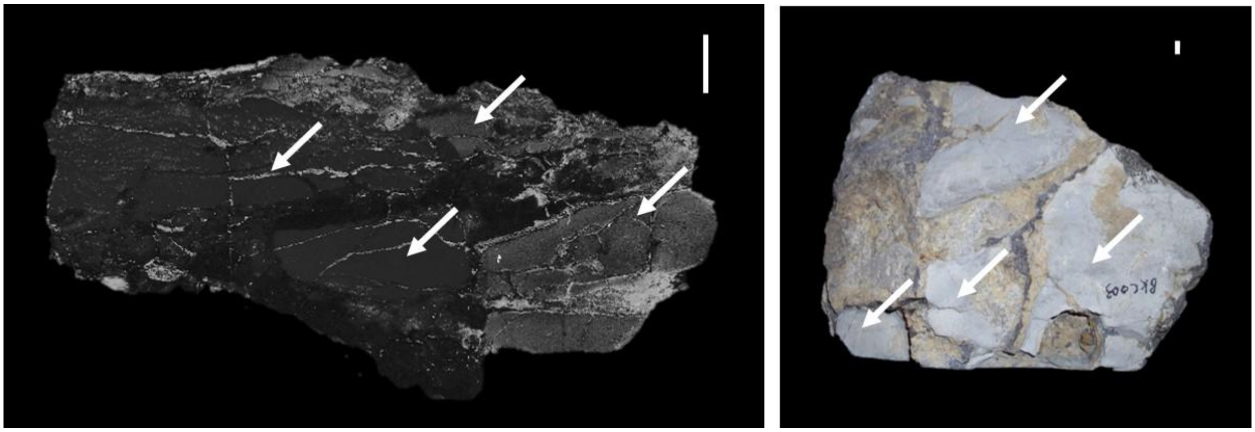


Fig. 8. Detail of top of sample N4 (right). Note subangularity of limestone clasts. Detail of polished cut (left) shows good imbrication of large subangular clasts. White arrows indicate limestone clasts.

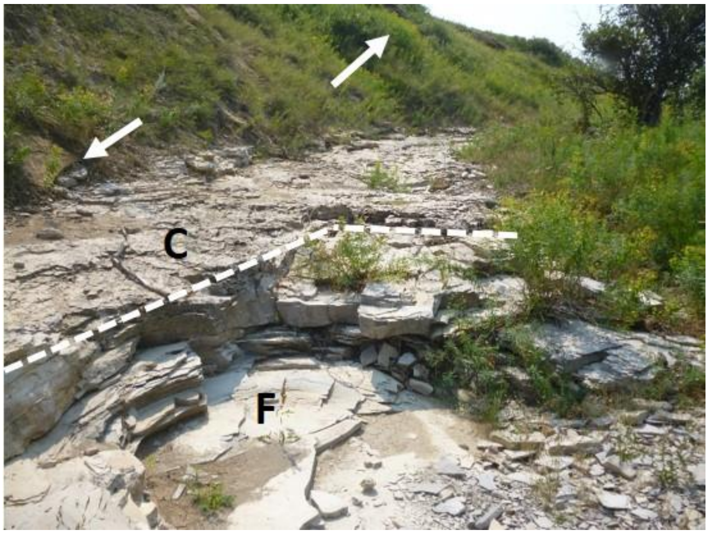


Fig. 9. Streambed with a single bed of a pebble conglomerate (C) in contact with Classic BGL flinz and fäule laminasets (F). Arrows indicate basal Tyler sands.

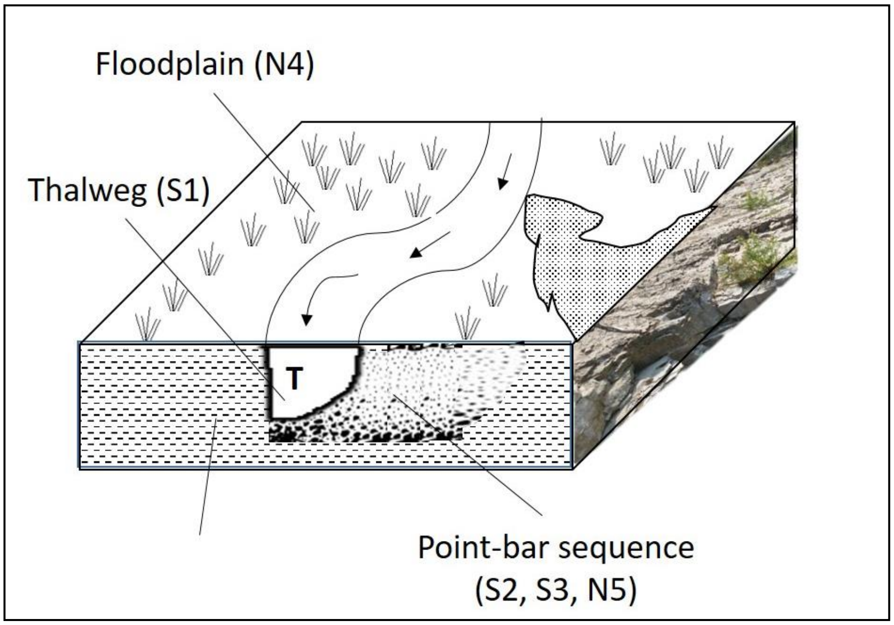


Fig. 10. Model fluvial environment that formed the Book Canyon conglomerate as it cut through BGL. S1 formed in the thalweg, whereas S2, S3, and N5 represent stages of a lateral accretionary bar. N4 varied distinctly from all other samples, as a paleosol formed in situ on the floodplain.

	*Glacial Till	Fluvial	Alluvial	Beach	Turbidite or Storm Event	BGL South	BGL North	Solution Collapse	Evaporite de/hydration	Paleosol	Karst	Tectonic
Fabric	Matrix	Clast	Either	Clast	Matrix	Clast	Matrix	Clast	Matrix	Clast	Clast	Matrix
Clast size	Fine-Coarse	Fine-Coarse	Coarse	Fine	Coarse	Fine-Coarse	Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse	Fine-Coarse
Roundness	Well Rounded	Well Rounded	Subangular	Well Rounded	Well Rounded	Round	Sub-angular	Angular-Subangular	angular	Variable	angular	angular
Lithology	Polymictic	Polymictic	Polymictic	Diachronous	Polymictic	Polymictic	Polymictic	Polymictic	Monomict	Polymictic	Polymictic	Monomict
Sorting	Poor	Well	Poor	Well	Very Well	Poor	Poor	None	Poor	Poor	Poor	Poor
Bedding	Poor	Cross	Thick Wedge	Horizontal	Graded	Cross	Strong Horizontal	Poor	Well	Variable	Poor	Poor
Additional	Includes rock flour	Cutbank Dropblocks	Immature sediments	Skeletal Grains	Dropblocks	Dropblocks	strong similarity with parent LS	sharp clast/matrix boundary, fractures, proximal to evaporites	Clasts weather out leaving angular cavities	sharp clast/matrix boundary, veining, strong similarity with parent LS	Speleothems	Postformational fractures, proximal to shear zone

Table 3. Table 1 with shared characteristics of the various conglomerate-forming environments. BGL South samples highlighted in yellow and BGL North samples in blue. BGL South shares the most characteristics with a fluvial system. BGL North samples did not form by mechanical processes, but rather in soil processes. The remaining environments can be eliminated due to the lack of shared characteristics.

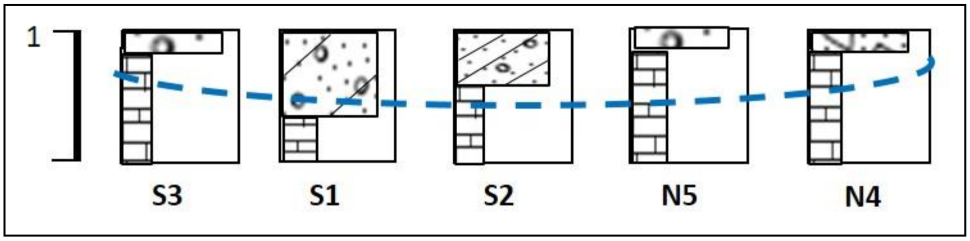


Fig. 11. Conglomerates were found at the top of all accessible coulees and canyons. Characteristics of the conglomerates changed from northern to southern sights (Figure 1). Notably, clast size and roundness changed from well-rounded in the southern samples, S1-S3, to subangular in the northernmost sample, N4. Only the S1-type conglomerate was found in lateral exposure with changes in bedding thickness, dip, and clast size. These five sample localities describe a streamcut, in cross-section, indicated by the blue dashed line. S2 formed in the

thalweg, whereas S4 represents a lateral accretionary bar. As a paleosol formed in situ on the floodplain N4 varied distinctly from all other samples.

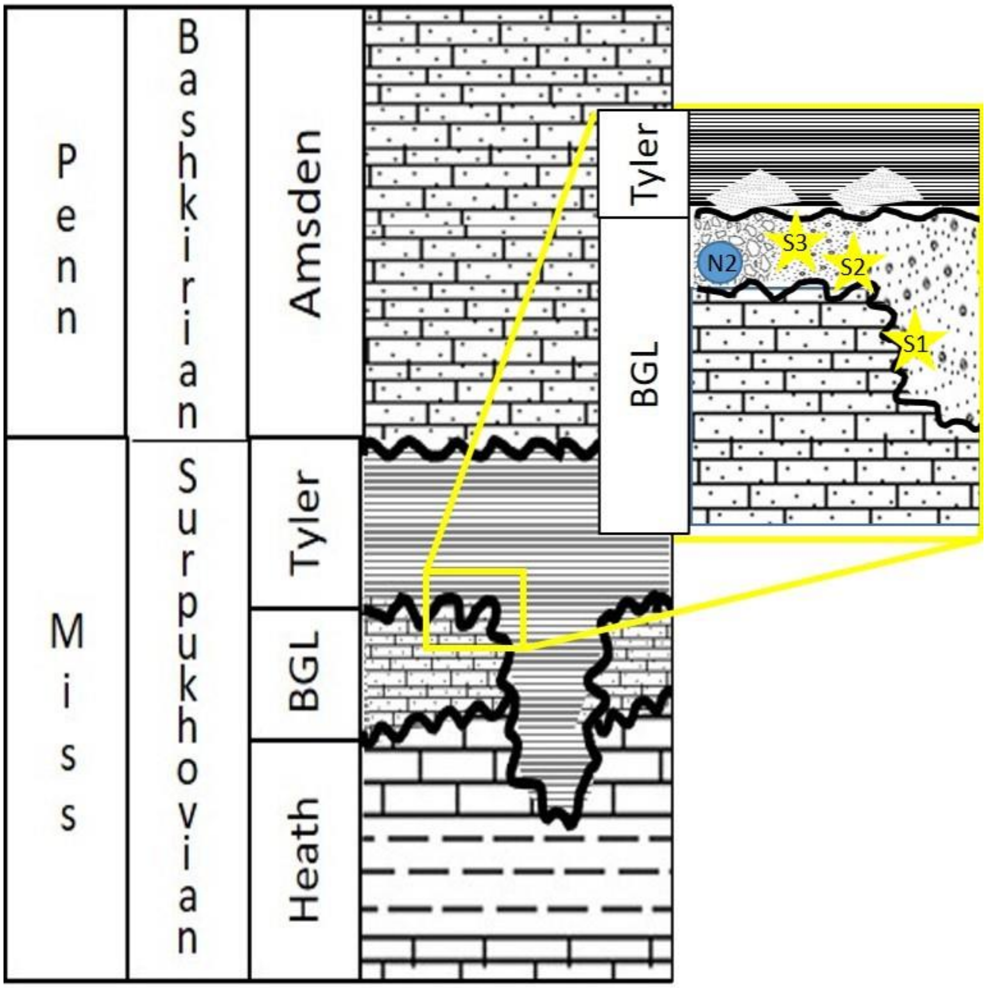


Fig. 12. Proposed stratigraphic relationships based on outcrop and subsurface data. Sequence boundaries between the Tyler and the Heath, the Tyler and the Amsden, and the cutting of the Tyler through the BGL to the Heath are represented by heavy lines. Conglomerate samples represent a stream channel capturing the transition from the marine BGL to the fluvial Tyler Formation. The Tyler is placed within the latest Mississippian as indicated by Bottjer (2017) and Shepard (1993).

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CHAPTER 3 –

Microfacies of the Bear Gulch Limestone

Amy E. Singer, Jonathan Patrick Warnock, Nancy W. Hinman, Pamela Lavering

ABSTRACT.—The Bear Gulch Limestone is a shallow, low-energy, cryptocrystalline carbonate rock formation composed of two major lithotypes: flinz, which is high in calcite, and fäule, which has slightly higher siliciclastics. Five microfacies (three flinz, two fäule) were identified and overall indicated that the Bear Gulch shallowed over time, from a fully marine base to increasingly neomorphosed materials, suggesting meteoric influence. Facies 1 was neomorphosed flinz with no apparent lamina or fossil components; Facies 2 was laminated flinz, comprising the classic Bear Gulch cryptocrystalline, massive dolomitic limestone with visible lamina and fossil components; Facies 3 was Book Canyon flinz from the base of the unit, with highly competent laminae that break apart along bedding planes; Facies 4 was classic Bear Gulch fäule, with mm-scale friable lamina; and, Facies 5 was the Book Canyon fäule, with the highest carbon content and thinnest lamina. The Bear Gulch fauna is missing common Mississippian fossils, such as crinoids, bryozoa, and corals, possibly due to increased micrite production excluding filter feeders, although isolated clasts were found in thin sections within the flinz. SEM-EDS analyses indicated that the fäule lamina sets were elevated in Al and K, possibly indicating the presence of clay minerals; whereas flinz were relatively more abundant in Ca. The two lamina sets resulted from alternating high micrite production by planktic biotic and abiotic precipitation (flinz), with lower micrite production and marginally higher clastic input (fäule). These five microfacies further clarified the developmental context of the Bear Gulch Limestone as a marine tongue of the Tyler Formation, possibly explaining the restricted fauna.

1. Introduction

The Bear Gulch Limestone (BGL) is a Serpukhovian (Carboniferous, latest Mississippian) plattenkalk, a finely laminated micritic limestone. BGL preserves a Konservat Lagerstätte, a deposit of exceptionally preserved fossils, in Fergus County, central Montana, within the Big Snowy Trough (Figure 1). In the case of BGL, the Konservat Lagerstätte includes soft-tissue preservation (Seilacher, 1970). Outcrop data, combined with extensive core and well-log data, place the BGL stratigraphically within the Mississippian portion of the Tyler Formation (Fig. 2; Mundt, 1956; Maughan and Roberts, 1967; Aram, 1993; Shepard, 1993; Bottjer, 2019; Singer et al., 2019). The unit is known for the excellent preservation of soft-bodied and biomineralized fossils and is considered the most diverse Carboniferous fossil-fish assemblage known (Feldman et al., 1994, Hagadorn, 2002). It is also rich in well-preserved invertebrates, such as annelids, arthropods, sponges, algae, brachiopods, bivalves, and cephalopods (Feldman et al., 1994; Hagadorn, 2002; Lund et al., 2012). The mid-Carboniferous section of central Montana is considered one of the most complete ones in the world (Shepard, 1993); yet, the syndepositional processes and physiochemical parameters that led to this invaluable paleontological resource remain poorly understood (Shepard, 1993; Feldman et al., 1996; Hagadorn, 2002).

As a plattenkalk, the BGL is a finely grained micritic limestone with nearly horizontal laminasets, i.e. beds composed of multiple millimeter-scale laminae, of varying induration; Barthel et al., 1990). Borrowing from the terminology coined by Williams (1981) to describe the classic plattenkalk, the Jurassic Solnhofen limestone of Germany, the laminasets with more competent, fused lamina resistant to weathering are known as *flinz,* and the more friable, higher clay mineral content laminasets are referred to as *fäule*. The petrologic similarity of the units between the two plattenkalks does not imply a similar depositional environment; these facies form in a variety of settings, from lagoon to lacustrine (Munnecke, 1997; Hagadorn, 2002). Thus, deciphering the geologic history of a plattenkalk is complicated because the resulting rock type is not necessarily indicative of a single depositional process.

In the present study, an integrated analysis of depositional systems, ranging from bed- to platform-scale, was performed based on outcrop and thin-section data. This integrated research used a traditional microfacies study of petrologic thin sections and scanning electron microscopy (SEM) with backscatter electron (BSE) imagery and chemical analyses by energy dispersive X-ray spectroscopy (EDS). The aims of the present study were to: (1) Document facies and microfacies associations within the BGL (based mainly on petrographic and field data), (2) Infer depositional processes leading to the formation of the flinz vs fäule laminasets, and (3) Evaluate paleoclimatic and paleogeographic controls on the development of the BGL.

2. Geologic Setting

The BGL was deposited in the Big Snowy Trough, an east-west trending Precambrian aulacogen that connected the Williston Basin in the east, to the open ocean in the west (Williams, 1981; Shepard, 1993; Feldman et al., 1994). Presently it is exposed along stream cuts brought to the surface by the Potter Creek Dome and ranges in thickness up to 15 m in the field area (Fig. 1; Williams, 1981; Feldman et al., 1994). By combining new outcrop data with industry core and well-log data (Aram, 1993; Bottjer, 2017), Singer et al. (2019) established that the BGL was contained within the Tyler Formation, presently dated to latest Mississippian (Serpukhovian). This largely resolved decades of disagreement over the stratigraphy resulting from the poorly defined geologic ages for the Tyler Formation and lack of clear contacts in the field (Feldman et al., 1994; Singer et al., 2019).

Paleogeographic reconstructions place the basin at 12° north of the equator during the late Mississippian (Shepard, 1993; Grogan and Lund, 2002). Seasonal aridity and wetter periods were to be expected for this position within the tropics (Grogan and Lund, 2002). Like other plattenkalks, the BGL consists of laterally continuous, unbioturbated bedsets that alternate between massive cryptocrystalline micritic to dolomitic limestones (flinz) and argillaceous micritic laminasets (fäule; Fig. 3; Williams, 1981; Barthel et al., 1990; Feldman et al., 1994). The BGL differs from many plattenkalks in greater variability within the composition and thickness of the flinz and fäule. It also lacks any statistically resolvable pattern or rhythmicity of the alternations between the two lithologies (Feldman et al., 1994). Further, the flinz and fäule are not coupled, as thickness in one does not predict thickness in the other (Feldman et al., 1994). For example, the lower portions of the section take on longer, more regular period laminasets that are referred to as the Book Canyon BGL; whereas higher in the section the laminasets are more irregular, higher frequency referred to as the Classic BGL (Fig. 3; Singer et al. 2019).

The syndepositional processes and physiochemical conditions of the BGL remain poorly understood due to the lack of diagnostic sedimentary structures and diagenetic overprinting (Feldman et al., 1994). Several researchers have suggested models for the formation of the finely laminated, weakly bioturbated, rhythmic micritic limestone. Mundt (1956) included the BGL in the Tyler Formation but maintained a Mississippian age and interpreted the BGL as a limestone tongue of a tectonically controlled, transgressive marine incursion within the Big Snowy Trough. Williams (1983) interpreted the flinz and fäule bedding as seasonal variations within tectonically controlled *en echelon* basins, resulting in local circulation patterns and further suggesting microturbidites may have been activated. Renewed petroleum interest in the 1970s and 1980s led Aram (1993) and Shepard (1993) to construct a regional model based on hundreds of well logs, cores, and outcrop data. Aram (1993) largely agreed with Mundt (1956), pointing further to the Laramide uplift as the tectonic control for changing water depths and lithology. Shepard (1993) interpreted the unique geology and biota as the result of a sill at the mouth of the Big Snowy Trough restricting circulation with the open ocean. This sill resulted in varying estuarine conditions, ultimately limiting the fauna to only those tolerant of variable, especially low, salinities controlled by eustatic sea level changes. Lund et al. (2012) reconstructed the BGL as a small, sheltered marine bay within the Big Snowy Trough, part of a sabkha-like environment with seasonal monsoons that generated the laminasets. The study further proposed that the monsoons triggered microturbidites representing the flinz laminasets; whereas the fäule were deposited via background sedimentation processes (Grogan and Lund, 2002). Feldman et al. (1994) stressed the lack of sedimentary structures to indicate currents and to the presence of fine fossil preservation. Together, these were interpreted to indicate shallow, calm waters with occasional large depositional events, without any specific processes or mechanisms for those events.

3. Methods

This study analyzed sedimentary samples from previously unexplored BGL outcrops. Collection sites were located along a transect approximately dissecting the width of the paleobasin (Figure 1). Lamina-scale sections were measured at the millimeter-scale for the ten localities to generate a composite measured section (Figure 4). Localities were named after local features: Main Miller Canyon samples (MM); the lower tributary coulee, or the Lower Miller (LM); the upper tributary, or Upper Miller (UM); and the aptly named Brach Pile (BP) for the large number of brachiopods. Concurrent with paleontological collections, petrologic samples were collected from the base, middle, and top of each measured laminaset. Thin sections were prepared by National Petrographic Services Inc. (Rosenberg, TX), and acetate peels were prepared according to the University of Georgia, Athens Stratigraphic Lab procedures for petrographic and SEM analyses (https://strata.uga.edu/).

Microscopic analyses were carried out via petrographic study of 33 thin sections and 20 acetate peels/polished slices on an AmScope Petrographic microscope equipped with a Sony a6000 camera at the University of Montana (UMont). Petrographic microscopy of acetate peels and polished slices was carried out at UMont to identify fabric components and sedimentary structures. A ThermoScientific PrismaE Scanning Electron Microscope (SEM), equipped with a ThermoScientific Pathfinder EDS UltraDry 60M and a ThermoScientific Pathfinder EBSD Quasor 2 System, was used for higher resolution observations of uncoated thin sections for diagnostic fabric components, sedimentary structures, and chemical analyses. EDS was used for major and minor elemental chemistry distribution of sediments, and BSE was used to evaluate grain-by-grain mineral boundaries and orientation. SEM, EDS, and BSE were performed by Jonathan Patrick Warnock at Indiana University of Pennsylvania.

4. Results

The descriptions of Folk (1959) have been employed to classify the fabrics and structures of the BGL. Although typically applied to coarser grained carbonates, this classification system introduced useful terminology; namely, *micrite* consists of grains < 4 μm, and *spar* describes all optically clear grains of any size. *Microspar* refers to those ranging from 4–15 μm.

4.1 Flinz.—Flinz lamina sets were categorized as wackestone according to Dunham's classification and contained an abundance of neomorphosed calcite but lacked any current indicators, such as ripple marks or within lamina grading. These lamina sets fell broadly into two categories: nearly pure carbonate wackestones and those with increasing amounts of opaque materials (organics). The pure carbonate wackestones did not display clear lamina (as did the rest of the BGL) and occurred in the upper portions of the Classic BGL. Silt-sized grains were subangular, with rare fossil fragments and an average lamina thickness of 8 mm. Further, the carbonate wackestones contained the highest levels of Ca (Figs. 5 and 10; Table 2).

In the lower portions of the Classic BGL, the flinz became more micritic, with higher contents of kerogen and other opaque materials. Fossil fragments, larger and more common, and lamina are weakly developed. Neomorphic calcite was clay-to-silt sized and subangular (Fig. 6).

The flinz laminasets of the Book Canyon BGL also fell into the wackestone category, albeit with greater amounts of fossil components (predominantly shell fragments), silt-sized grains, and dolomite rhombs with minimal evidence of neomorphism. Grains were sub-rounded and elongated with well-developed, fine lamina averaging 5 mm thick.

4.2 Fäule.—Fäule laminasets fell into two categories: Classic BGL and Book Canyon BGL fäule. Classic BGL fäule laminasets were limey mudstone, with an average lamina thickness of 5 mm. Book Canyon fäule consisted of organic-rich mudstone, with very fine lamina averaging 2 mm thick and clay sized grains. Both categories of fäule consisted of well-developed, easily split, lamina that appeared weakly graded.

Fäule rarely contained current indicators, which were only apparent in the upper portions of the Classic BGL. Grading within lamina was rare overall and more common in the Classic BGL.

4.3 Components.—Both flinz and fäule facies contained microspar, occurring both as cement and neomorphosed crystals. The amount and type of microspar varied across the study area and by lithology, with flinz generally containing significantly more and larger spar than fäule bedsets.

Peloids, pellets, or intraclasts of micrite were ubiquitous throughout the BGL. They were often compacted and elongated, forming lamina in some cases, especially those samples high in “organic materials”, which included any biogenic nonmineral components, such as kerogen. Peloids in the BGL were often opaque under planar light and could have formed biogenically (e.g., fecal peloids) or abiotically as coherent rip-up carbonate mud. Peloids were most common in fäule bedsets and often formed lamina with poor contacts.

Dolomite rhombs were ubiquitous but never occurred in frequencies > 10%. Numerous specimens from the flinz bedsets showed evidence of recalcification or dedolomitization (Flügel, 2010). These specimens often had rhomb-shaped pores with no mineral content and were partial dolomite and calcite, in some cases completely replaced by calcite or filled with organic matter (Fig. 9). Porosity was low in the BGL samples (≤ 10%), and the pores were not connected (i.e. the rocks were impermeable).

Fossil components were frequently shell fragments from brachiopods, bivalves, and ostracods. Spar was frequently associated with crinoid stem pieces. Body fossils of trilobites, as with crinoids, were absent from the BGL; however, components such as the classic shepherd hook, did occur in thin sections.

SEM-EDS was consistent with unpublished XRD results from previous theses (Williams, 1981; Radar, 2013; Lavering, 2014; Johnson, 2015) defining the BGL as a highly calcitic limestone with minor amounts of dolomite, quartz, and organics. Flinz were more Ca-rich, and fäule had Al and K, possibly indicating the presence of clay minerals. Transects across laminated specimens alternated between Ca-rich and Ca-poorer laminae, but this pattern was not observed in the microsparic neomorphosed flinz. A continuous line scan with SEM-EDS revealed that the laminated flinz alternated between enriched Ca and Si laminae, compared to the purer flinz that lacked optically apparent laminations, which showed no such variation (Fig. 11). According to EDS data, flinz laminasets from the Book Canyon BGL also contained more silica than the flinz samples from the Classic BGL lithology. SEM-EDS data indicated that fäule generally was enriched in Al, whereas flinz were enriched in Ca.

5. Discussion

5.1 Facies definition.— Five facies were identified based on petrology and geochemical analyses summarized in Table 3:

Facies 1 Microsparic (Flügel, 2010) Neomorphosed Flinz Facies: This facies is located at the top of the measured section and is considered part of the Classic BGL Flinz. It is composed of a calcareous packstone, with homogenous silt-size subangular grains present. Laminae were rare-to-absent and contained < 1% pore space. Rare stylolites cutting across bedding planes were the only sedimentary structures observed. Optical petrology revealed a dominantly calcitic rock, with an average of 10% dolomite, 1% quartz, and rare pyrite (Table 1). SEM-EDS confirmed higher Ca than all other facies (Table 2). Rare micritic remnants of fossil materials were present (Figure 5, Table 3).

Facies 2 Laminated Flinz Facies: This facies is found high in the measured section. It is considered to be part of the Classic BGL flinz. It is composed of a calcareous packestone with homongenous silt-sized subangular grains present. The grains were smaller and displayed less neomorphism than Facies 1. Laminae were apparent. Stylolites were restricted to lamina planes and filled with bitumen/kerogen. Weak-to-no grading was present within lamina. In addition to calcite, rare pyrite was observed. SEM-EDS analyses indicated minor chemical changes relative to Facies 1 (Fig. 10; Table 2). In Facies 2, SEM-EDS transects had alternating Ca- and Si-rich laminae with a increased variability in atomic percentages and thickness than was observed in Facies 1 (Fig. 5, 6, and 10). Fossil components included occasional shell fragments and weakly neomorphosed crinoid components (Table 3).

Facies 3 Book Canyon Flinz Facies: This facies is found low in the measured section and is not considered part of the classic BGL flinz. Facies 3 is composed of a calcareous/dolomitic wackestone containing sub-rounded, elongated, silt-to-medium size sand grains and dolomite rhombs. It is thinly laminated (5–25 mm thick) with weak-to-no grading present within the lamina. SEM-EDS analyses confirmed higher concentrations of Si and C (Fig. 7, Table 2) relative to Facies 1 and 2. Additionally, higher micrite and organic matter contents were observed in Facies 3 compared to Facies 1 and 2 (Table 1). Crinoid components and abundant shell fragments were present. Rare shell fragments are identifiable to Phyla.

Facies 4 Classic BGL Fäule: This facies is located high in the measured section. It is considered to be a calcareous/dolomitic mudstone. Laminations were present and had irregular thickness, with no grading (Fig. 8). Kerogen-filled stylolites existed along lamination partings. Ripples were present but rare in this facies. Pores were observed in this facies and porosity constituted < 10% of the rock volume in thin section. The pores are interpreted to have occurred as the result of the dissolution of dolomite (Fig. 8). While this facies is composed predominantly of calcite and organics, calcite grains with dolomite rinds were present and may indicate dedolomization due to meteoric exposure (Fig. 8; Flügel, 2010). Furthermore, pyrite was rare and framboidal. SEM-EDS analyses indicated higher concentrations of Al and K compared to the flinz facies (1-3), possibly from clay minerals (Table 2). Fossil components were rare and included trilobites, crinoids, and shell fragments (Table 3).

Facies 5 Book Canyon Fäule: This facies is found low in the measured section and composed of organic-rich wackestone/packestone containing silt-to-very-fine sand-sized grains. Lamina varied from 0.5–5 mm, with weak grading apparent in a few laminae. Pores were present and contained organic matter (bitumen or kerogen). SEM-EDS analyses showed higher levels of Si and C relative to Facies 4 (Table 2). Locally abundant shell fragments, rare trilobites, and crinoid components were observed in thin section (Fig. 9; Table 3).

5.2 Facies interpretation.—

The BGL likely formed in a shallow, low-energy environment with high sedimentation rates (Williams, 1981; Feldman et al., 1994). Carbonate mud was likely produced *in situ* as a by-product of algal photosynthesis and inorganic precipitation from the water column (Williams, 1981; Riding et al., 2019). Algal photosynthesis restricts micrite production to the photic zone and lack of current indicators means it was not transported but deposited *in situ*. Calcareous algae of the Carboniferous included Dasycladacea and Solenoporacea, but neither was found in the BGL (Williams, 1981; Riding et al., 2019). Microbially sourced micrite was unlikely to leave any evidence to differentiate it from inorganic whitings (Flügel, 2010). The lack of current indicators observed in this study throughout the BGL (outside the uppermost fäule beds with ripple marks), paired with exceptional preservation, points to micrite settling out of the water column in a shallow low-energy environment (Williams, 1981; Feldman et al, 1994; Flügel, 2010).

Micrite production by planktic cyanobacteria and inorganic precipitation would form carbonate-mud rain, burying anything on the seafloor without disturbance (Feldman et al., 1994). During photosynthesis cyanobacteria preferentially use dissolved CO_2 as their carbon source. If CO_2 becomes limited, as it was during the Carboniferous, the cyanobacteria can switch to bicarbonate (HCO_3-) as a source (Riding et al., 2019). This switch to bicarbonate requires conversion within the microbial cells to CO_2, which releases hydroxide (OH-) and in turn increases pH in the water close to the cell (Riding et al., 2019). This localized pH increase encourages $CaCO_3$ precipitation and as a result small $CaCO_3$ crystals nucleate on or near the cell wall (Riding et al., 2019). Periodically the outer cell wall is shed together with its associated crust of $CaCO_3$ crystals and resembles marine ‘snow’ as it drifts down and ends up as micrite on the seafloor (Riding et al., 2019). This is a likely mechanism for micrite production in the BGL given the microcrystalline fabric of the limestone. Microbial carbonates were more abundant during the Mississippian, which has been interpreted by some to indicate that the seawater carbonate saturation state (SWSS) was elevated (Riding et al., 2019). The SWSS must be elevated for calcification to occur and the BGL may have experienced an elevated SWSS that favored high micrite production in the water column by cyanobacteria.

Exceptional fossil preservation, such as that seen in the BGL, requires that dead organisms be preserved rapidly to avoid decay of soft tissues. Typically this occurs by either rapid burial or deposition in anoxic sediments. It is unclear if the rate of micrite production in the water column would be sufficient to preserve fossils by obrution, therefore unhospitable bottom waters likely protected the material from scavenging before burial. Anoxia is a likely mechanism to explain the exceptional preservation of the BGL.

The BGL has been assumed to be low oxygen and low salinity due to the absence of corals, bryozoans and articulated crinoids (Melton, 1968). The presence of pyrite observed in Facies 1 through 4 provides support for at least periodic anoxia in the bottom waters and/or sediments of the BGL. Kerogen, observed in both of the fäule facies, further suggests anoxia. None of the fossil fishes interpreted as benthic were restricted to any single area of the BGL, suggesting that bottom waters and any potential anoxia were fairly homogenous across the BLG (Feldman et al., 1994). Additional evidence for the potential homogeneity of BLG bottom waters comes from Williams (1981) and Shepard (1994), who suggested that the bottom waters at the time of BGL deposition had low oxygen due to poor circulation, citing the differences between the BGL and the surrounding black shales of the Tyler/Heath. If the BGL waters regularly interacted with an open marine system, circulation would have been good. They further cite the lack of scavenging, major current features, minimal levels of decomposition and transport throughout much of the BGL as evidence for restricted circulation resulting in anoxia (Williams, 1981; Shepard, 1994).

Alternative explanations for the absence of these taxa can be considered. These organisms all require a narrow window of near-normal salinities, so salinity could have been a factor leading to their ecological exclusion from the BGL. Williams (1981) noted the presence of acanthodians, indicating freshwater to brackish conditions, especially in the fäule laminasets. Furthermore, these absent taxa also require clear waters for feeding, so these same organisms may simply have been excluded because micrite production made the water too cloudy (Flügel, 2010).

While the middle and upper water column were dominated by microbial micrite production, anoxic bottom waters seem to be common to all facies of the BGL. Pyrite was found in four of the described facies, and kerogen or other preserved organic matter was found in all five. With the exception of some ripple marks in Facies 5, current indicators are missing from the deposit, supporting a low energy, anoxic, setting. Despite this similarity, however, differences in sedimentology indicating environmental changes can be seen between individual flinz and fäule facies and between flinz and fäule overall.

Facies 1 contains well-developed neomorphism, suggesting the BLG was significantly altered by meteoric waters soon after deposition. Meteoric alteration of the syndepositional calcite, possibly from aragonitic needles or microcrystalline planktic precipitation, to larger microsparic, aggrading neomorphic calcite in Facies 1, obscured or eliminated laminations (Fig. 5). Furthermore, shallow burial resulted in weak pressure solution that promoted stylolites that crossed laminations (Fig. 5). Microsparite was the product of meteoric recrystallization of laminated micrite (Flügel, 2010).

In contrast, the laminations of Facies 2 are still apparent, meaning this facies experienced less neomorphism and meteoric influence. Laminations alternate from more to less Ca-rich, perhaps indicating fluctuations in terrestrial influence due to fluctuations in climate (Fig. 11). Fossil components were most abundant in Facies 2. Crinoid stem pieces, notably missing as whole body fossils, were common implying that these crinoids were either scavenged, decomposed, or transported before burial (Fig. 6). This likely means that Facies 2 represents the most marine conditions. Further, Facies 2 also contains kerogen-filled stylolites, that were restricted to lamina partings, implying less common or less intense periods of anoxia. Because kerogen is only seen at lamina partings, rather than throughout the lamina, anoxia sufficient to preserve organic matter was present only seasonally in the time between deposition of neighboring laminations.

The final flinz facies, Facies 3, contrasts with the other two, especially in mineralogy. Facies 3, Book Canyon Flinz, was enriched in Si, indicating terrestrial influence. Furthermore, the rarity of fossil components in, and low stratigraphic position of Facies 3 possibly indicate an early transitional brackish setting of the BGL.

Fäule facies were distinct from flinz, with higher concentrations of Si and reduced micrite content (Table 1, 2, and 3). Facies 4, Classic BGL fäule, had the highest porosity due to the dissolution of dolomite rhombs. When not completely dissolved, they were in the process of dissolution with calcitic centers and dolomitic rinds, possibly indicating meteoric alteration, i.e. alteration by an increase in precipitation-derived freshwater to the site (Fig. 8). Laminations were clear in hand samples and thin sections, implying anoxia as discussed above, although with irregular thickness and rhythmicity, which likely indicates variability in microbial production of micrite (Fig. 8). Facies 5, Book Canyon fäule, only differed from Facies 4 in that it displayed more regular thickness of the lamina (Fig. 9), implying more consistent biogenic micrite production. Fäule represented times of reduced micritic production from the water column relative to flinz time. This may be due to changes in temperature, salinity, water depth, precipitation, and other parameters that influence the SWSS (Riding et al., 2019). Higher siliciclastic input is a consequence of increased transport of silica-rich sediment to the site with freshwater input. The meteoric influence implied by the dissolution of calcite rhombs supports increased meteoric precipitation, rain, leading to increased terrestrial input to the BGL system.

The fäule laminasets were likely all influenced by increased terrestrial sedimentation, and current indicators do occur in the uppermost portions of the Classic BGL fäule. There are no other indications of sediment transport. Grading was rarely observed and poorly developed, fossils did not orient in a preferential direction, and fish fossils were generally articulated and well preserved with no indication of transport. These data further deflate the turbidite or contourite deposition model. The microcrystalline nature and nearly pure composition of the sediments all indicated deposition from the water column in a shallow, low-energy environment. Such environments are typically near enough to shore to experience terrestrial influence.

Taken together, these facies reveal a system alternating between elevated micrite production (flinz) in a shallow basin and higher clastic input (fäule) in a less biologically productive shallow basin. Considering the distribution of these facies in stratigraphic order, long-term trends in the presence/absence of these facies reveal a shallowing of water depth over time, consequent with an increase in meteoric water and terrestrial input. These stratigraphic differences reveal a change in the controls on flinz versus fäule sedimentation in the lowermost portions of the section, composed of Facies 3 (flinz) and 5 (fäule). As discussed above, Facies 3 represents a fairly shallow water setting, with terrestrial influence bringing in freshwater and siliceous sediment. Facies 5 represents a deeper water setting, but still within the photic zone, as evidenced by the deposition of laminations with regular periodicity. Therefore, sea level change was the primary control on the deposition of flinz versus fäule during the early stages of BGL development.

In contrast, the upper portions of the measured section contain flinz Facies 1 and 2 as well as Facies 4 (fäule). Facies 1 and 2 differ in that Facies 1 shows meteoric water influence whereas Facies 2 is more marine. This implies a climatic control on BLG sedimentation, i.e. the presence of increased precipitation leading to Facies 1 deposition and reduced precipitation leading to Facies 2 deposition. Facies 4 also is notably influenced by meteoric water. Therefore, this facies is also interpreted as being controlled by climatic factors. As such, sediment variability between flinz and fäule during the early stage of deposition of the BGL is controlled by sea level shifts, while variability in sediments deposited later is controlled by climatic variability, i.e. meteoric rain input to the BGL system. Terrestrial influence to the BGL culminates in a fluvial system of the upper Tyler Formation overriding the BGL, ending marine deposition of micrite (Singer et al., 2019).

6. Conclusions

The BGL was a shallow restricted basin, not unlike a lagoon, alternating between times of high carbonate mud production from the water column by planktic cyanobacterial photosynthesis or inorganic processes (flinz), with more clay mineral-rich accumulations (fäule). The flinz represents higher inputs of planktic micrite; whereas the fäule represents increased terrestrial input to the marine shallows and intertidal depths. Early BGL, the regular meter-scale Book Canyon style deposition (Facies 3 and 5), was controlled by sea level and likely experienced more marine conditions. The later period of deposition, Classic BGL (Facies 1, 2, and 4), recorded local control by increasingly unstable climate or weather, as reflected by irregular thickness with no discernable pattern (Feldman et al., 1994).

The following conclusions were drawn from the present research: (1) Book Canyon beds, Facies 3 and 5, developed under fully marine conditions in a deeper water-stable setting controlled by global eustacy. Rich in organic matter, the sequence was deposited in a stratified water body with at least intermittent anoxic conditions that preserved fossils and kerogen; (2) Classic BLG, comprising Facies 1, 2, and 4, represents the increasingly unstable conditions driven by variable influence of freshwater neomorphism. Irregular cyclicity may point to an increasingly unstable climate; (3) Water column precipitation by inorganic and organic (microbial) processes supplied micrite; (4) The flinz and fäule represented times of high and relatively depressed micrite input, respectively, with the latter corresponding to a minor increased input of siliciclastics as well.

7 Acknowledgements

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Figures, Tables, & Captions

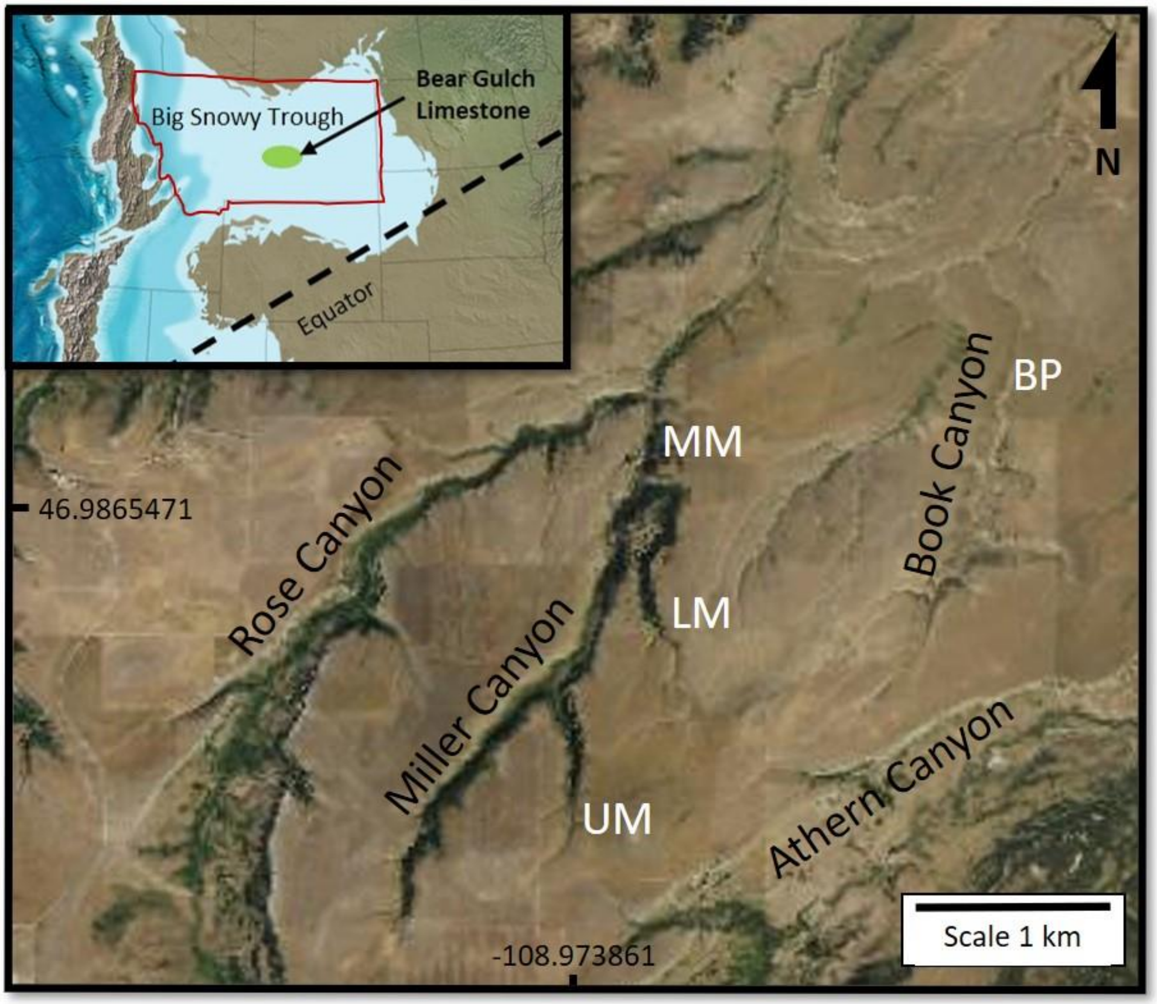


Figure 1. Bear Gulch field area and collecting sites as named by locals: UM, Upper Miller; LM, Lower Miller; MM, Main Miller; BP, Book Canyon. (Inset) BGL location within the Big Snowy Trough in central Montana. Equator during the Serpukhovian is interpreted to be at 12° N, after Singer et al. (2019). Note: Miller and Book Canyon are local designations for these unnamed streams.

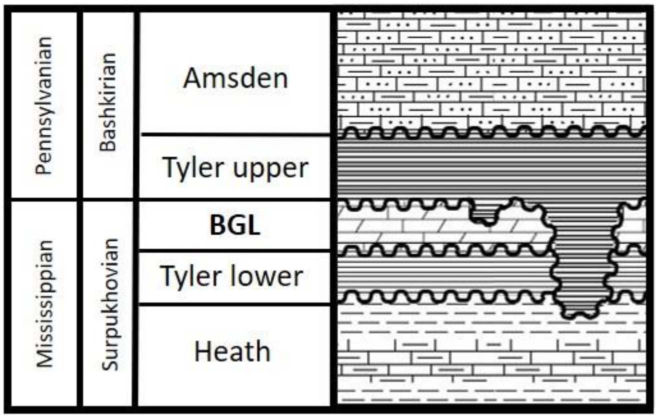


Figure 2. Simplified stratigraphic relationships of the mid-Carboniferous system of the Big Snowy Trough. BGL is a lens contained within the Tyler Formation, which is split into the lower and upper members. The upper member of the Tyler Formation has cut through the BGL, the lower Tyler, and into the Heath Formation in some areas, thus making stratigraphic relationships difficult to determine.

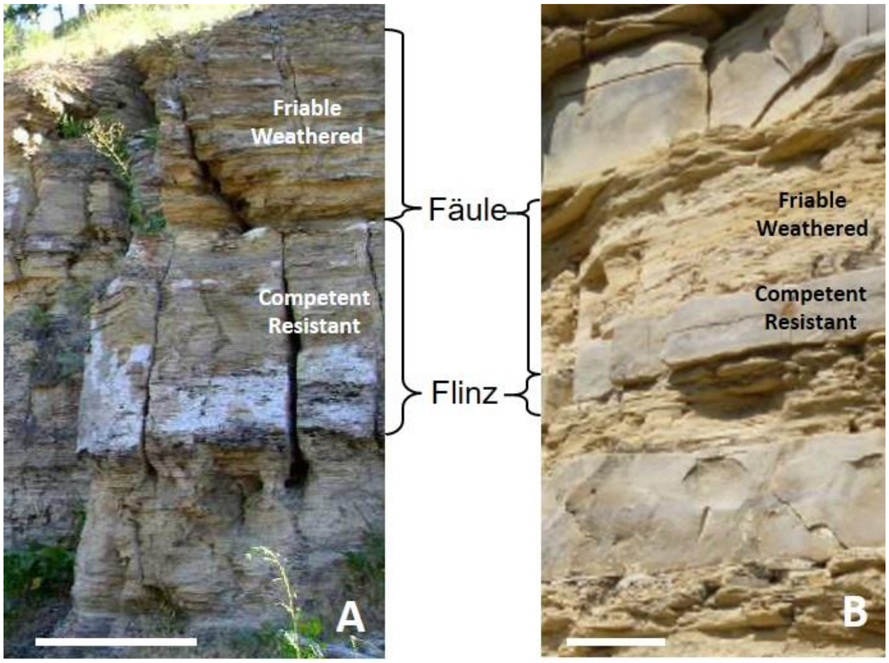


Figure 3. Images of Book Canyon and Classic BGL flinz and fäule lamina sets: (**1**) Meter-scale Book Canyon-type, with regular periodicity (scale bar = 1 m*)*; (**2**) Classic BGL in Miller Canyon, with irregular periodicity (scale bar = 10 cm*).* 1 and 2 are ~2 km apart.

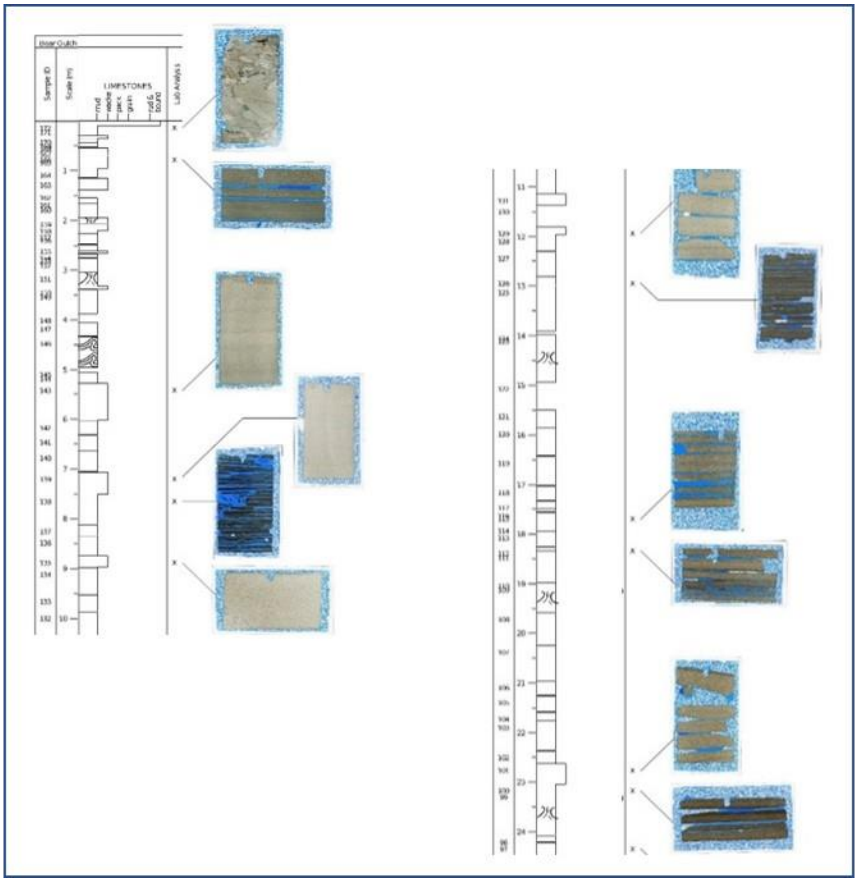


Figure 4. Composite sections of BGL, with correlated positions of representative thin sections taken for petrology and SEM-EDS. Note changes in lamina competence from the base (Book Canyon lithotype), compared to those in the upper half of the section (Classic BGL lithotype). Most notable are the observable changes in the flinz, with the loss of clear lamination and organic matter.

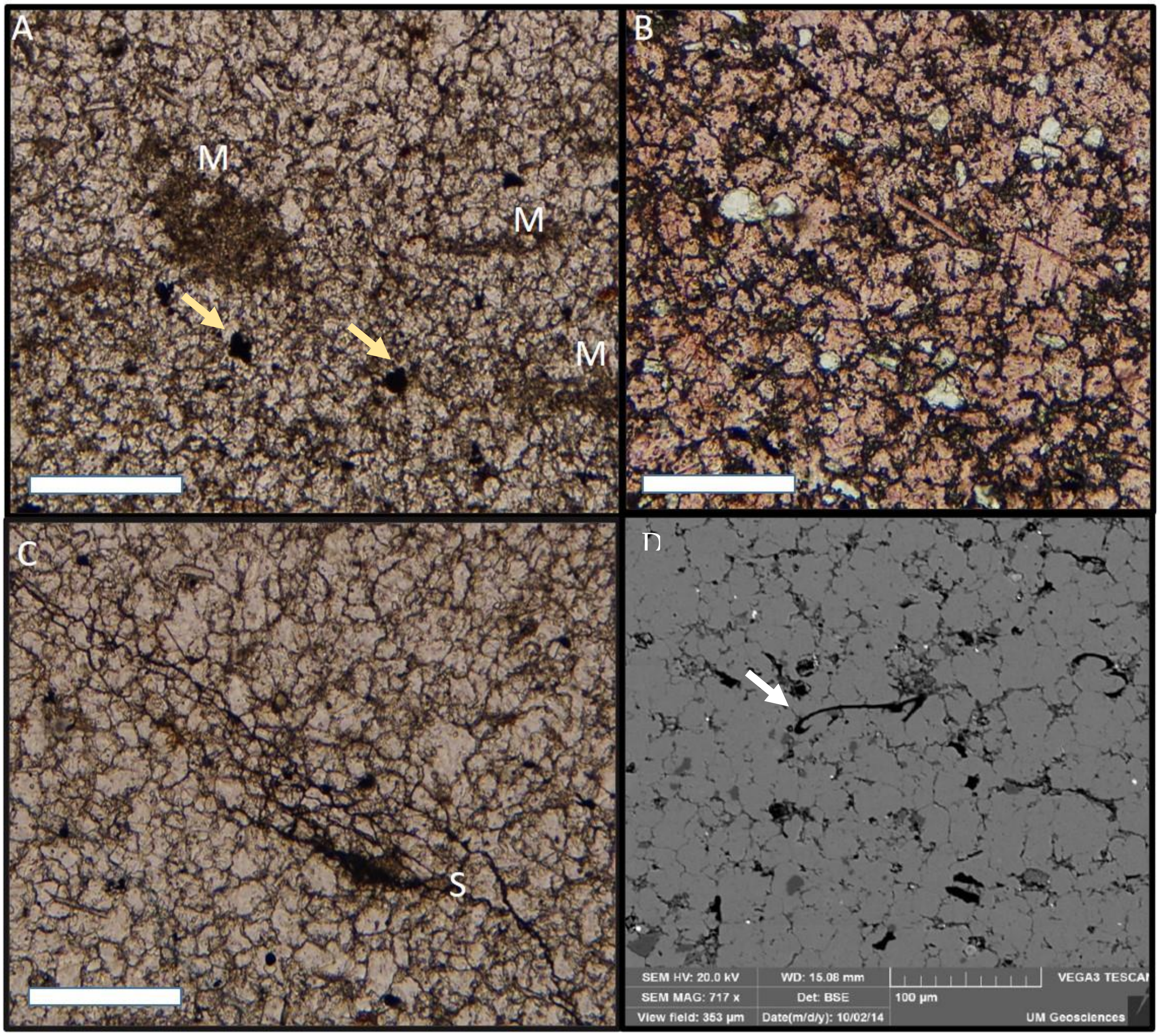


Figure 5. Facies 1 photomicrographs and BSE image showing microsparite and neomorphosed Classic BGL flinz for which laminae were no longer visible in hand samples. Aggrading neomorphism altered the original mineralogy, and consumed smaller grains consistent with meteoric exposure (Flügel, 2010). Pore space generated by dissolved dolomite rhombs was filled with kerogen (yellow arrows). *M* is the micritic remnant of a fossil. (**A**) *S*, stylolite across bedding plane (**C**); (**B**) is stained with alizarin red S, and (**D**) SEM-BSE shows the porosity from dissolution of fossil shell center of image (white arrow). Petrographic scale bars in (**A–C**) are 0.5 mm.

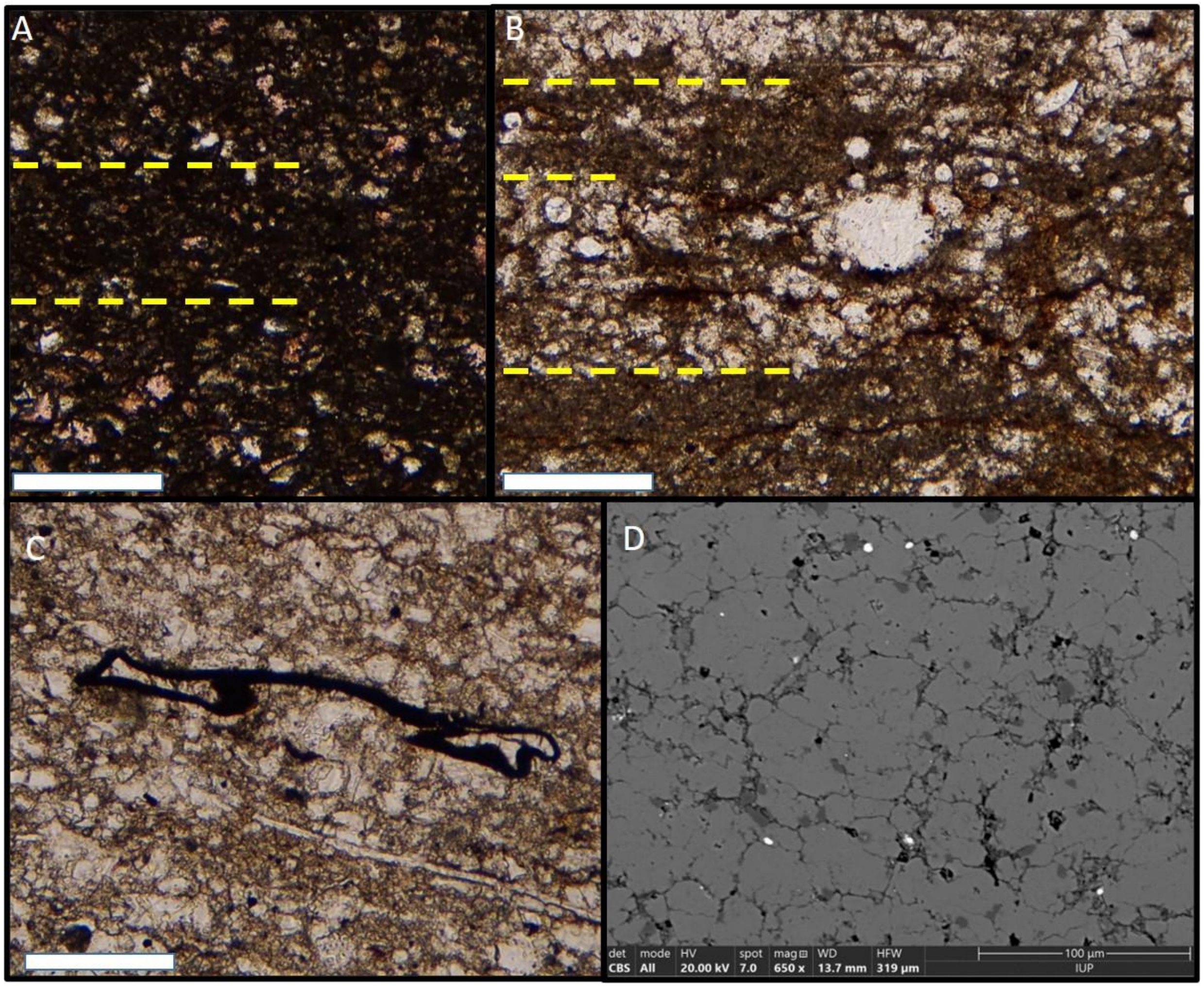


Figure 6. Photomicrographs and BSE image of Facies 2, Classic BGL laminated flinz showing lamina, some of which are deformed. Even when laminae were less apparent (C), horizontality was strong, and neomorphism moderate. Organic components included kerogen, crinoid components, trilobites, and shell fragments. (**A**) is stained alizarin red S. (**D**) is SEM-BSE displaying similar features as Facies 1, but includes pyrite and quartz. Fossils were most common in the laminated Flinz. Petrographic scale bar is 0.5 mm.

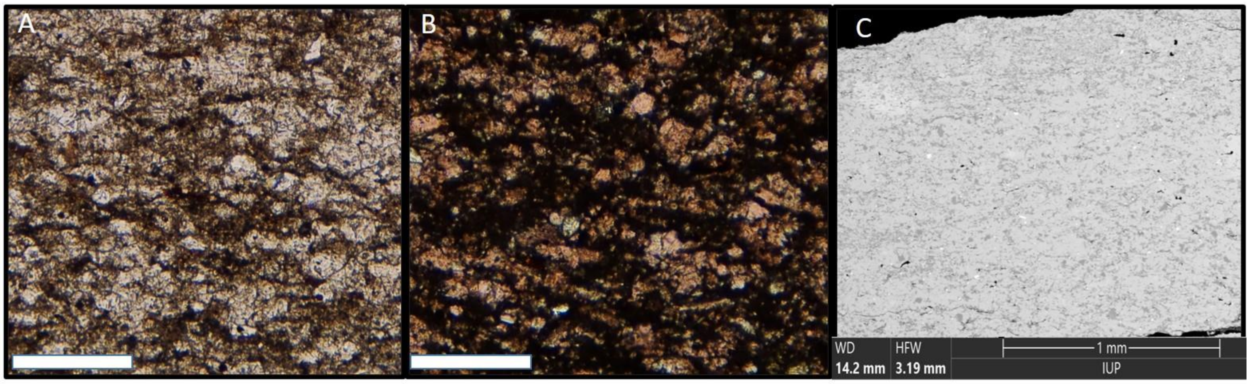


Figure 7. Facies 3, Book Canyon flinz. Some recalcification was present, but laminae were still apparent, and fossils identifiable. This facies was characterized by higher concentrations of micrite and organics. Crinoid components and rare shell fragments were also identifiable. (**B**) is stained with alizarin red S, and (**C**) is the SEM-BSE displaying the smaller grain size and orientation. Scale bar for (**A**, **B**) is 0.5 mm.

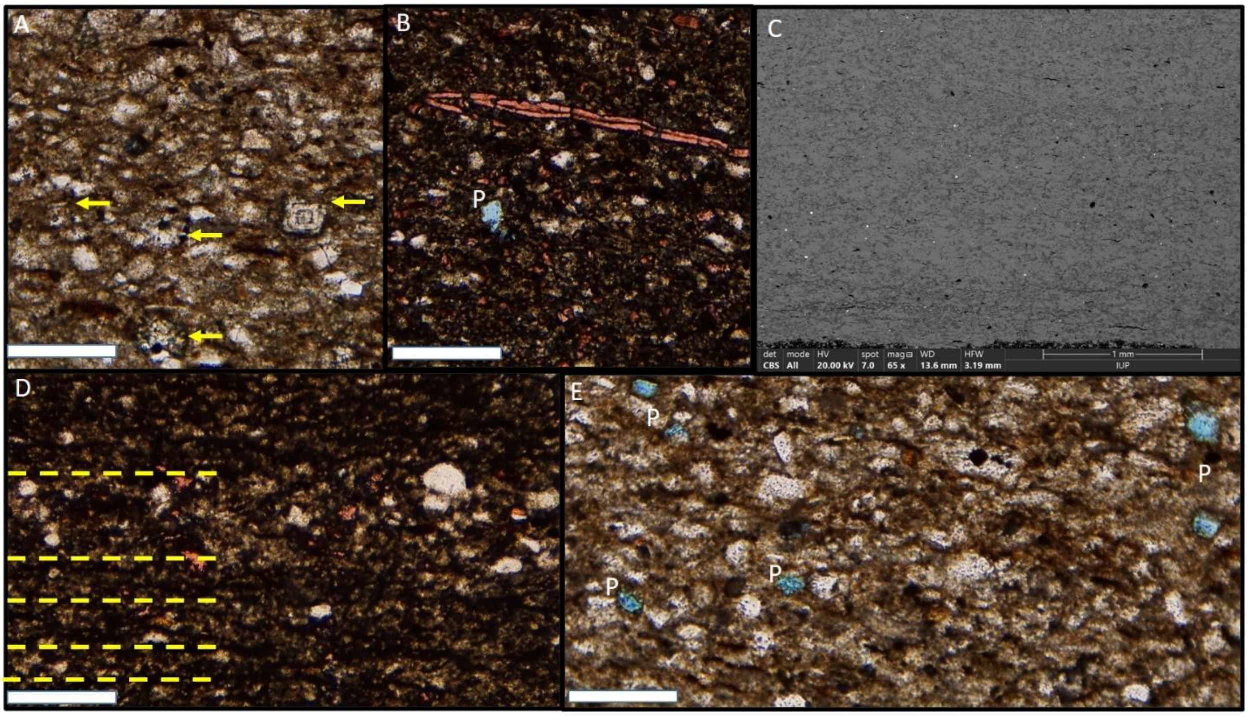


Figure 8. Facies 4, Classic BGL fäule. (**D**) Strongly laminated, but with irregular lamina thickness. (**B**, **E**) *P* indicates pore space due to the dissolution of dolomite. (**A)** Yellow arrows

indicate remnant dolomite rinds with calcite cores. Rare fossils, including shell fragments, and abundant organic matter. (**C**) shows SEM-BSE (note the small grain size). Scale bars in photomicrographs (**A, B, D, E**) are 0.5 mm.

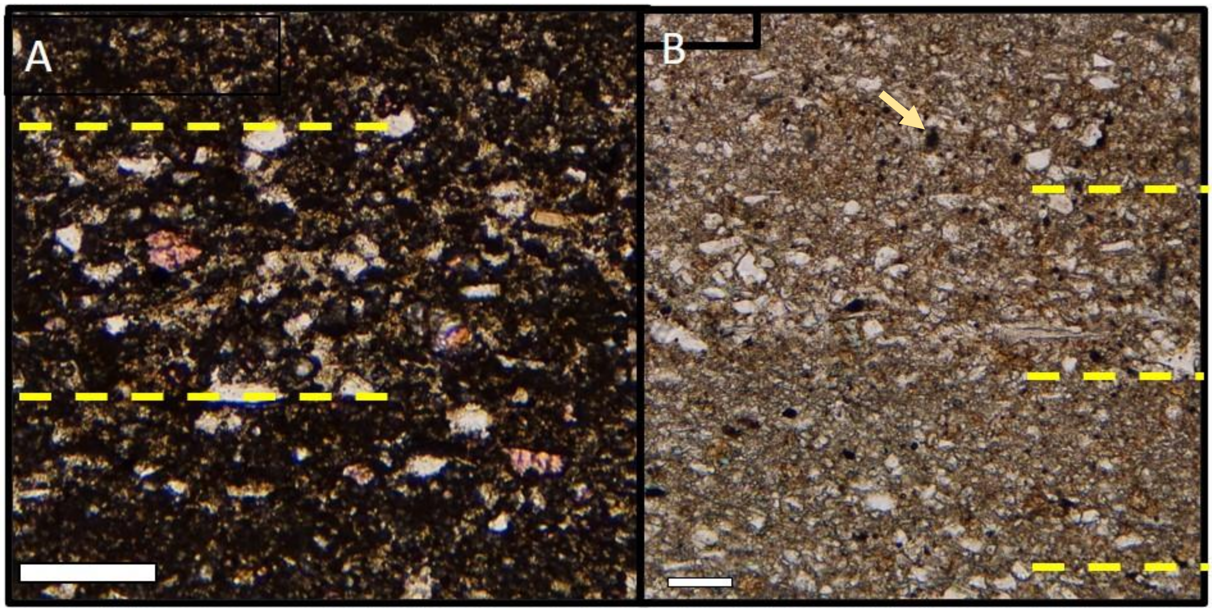


Figure 9. Photomicrographs of Facies 5, Book Canyon fäule, showing well-developed lamina with consistent thickness. Rhomb-shaped pores are smaller and filled with organic matter (arrow). (**A**) Plain light photomicrograph with alizarin red stain, and (**B**) Plain light photomicrograph. Scale bar is 0.5 mm

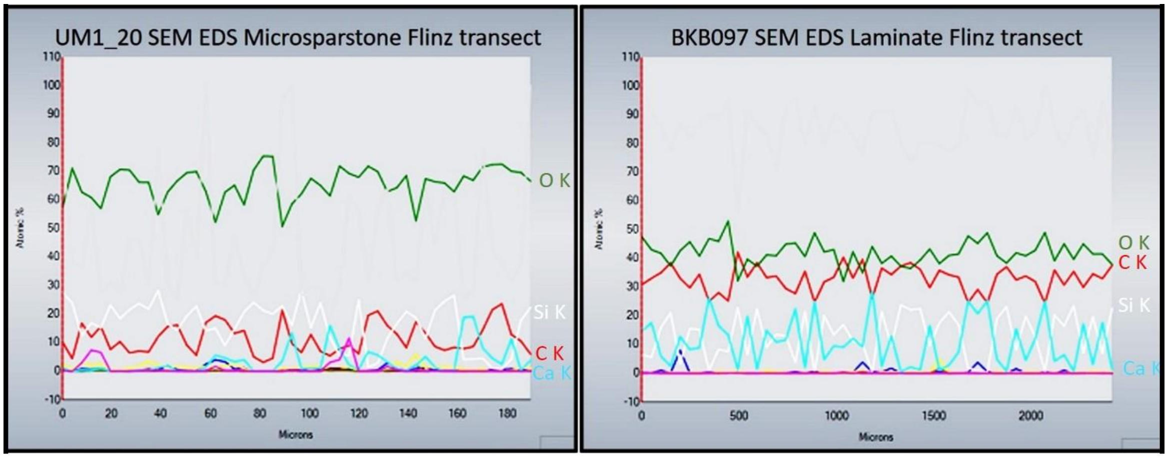


Figure 10. SEM-EDS continuous line scan across Facies 2 Laminated flinz (BKB097) and Facies 1 Microsparstone (UM1_20). Facies 2 maintained greater amounts of C, Si, and Ca. Note that Ca and Si appeared to alternate with lamination. Facies 1 lacked apparent laminations and had a more irregular distribution of elements. Although there appears some remnant of the laminations chemically, no clear pattern emerged in samples from Facies 1.

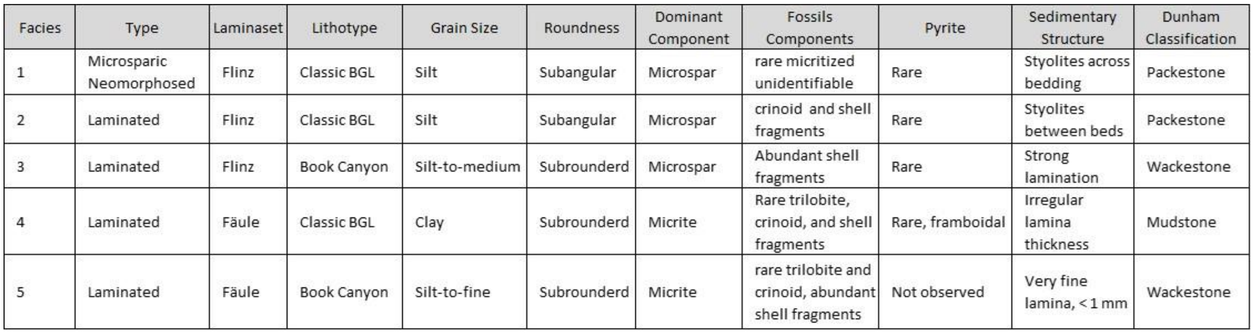
Table 1. Composition of the BGL facies by percent of thin section surface area.

Facies	Lithology	%Dolomite	%Quartz	%Micrite	%Microspar	%Opaques	%Pellets	%Fossil
Neomorphed	Flinz	4.50	1.00	17.50	58.50	13.00	1.50	4.00
Laminated	Flinz	4.60	1.00	31.00	41.00	8.00	2.20	12.20
Book Canyon	Flinz	3.00	1.00	25.00	50.00	10.00	1.00	10.00
Total	Total Flinz mean	4.56	1.00	25.00	48.78	10.22	1.89	8.56
Classic	Fäule	9.75	3.50	37.13	30.63	9.00	3.88	5.50
Book Canyon	Fäule	7.00	2.00	45.00	30.00	10.00	4.00	2.00
Total	Total Fäule mean	9.20	3.20	38.70	30.50	9.20	3.90	4.80

Table 2. Elemental Composition by atomic percent of the BGL facies determined by SEM-EDS.

Facies	Lithology	Al K	Ca K	C K	Fe K	K K	Mg K	O K	Si K	S K
Neomorphed	Flinz	0.52	6.78	19.86	0.26	0.11	0.49	67.51	4.38	0.20
Laminated	Flinz	0.62	4.75	20.08	0.27	0.18	0.67	64.50	8.87	0.15
Book Canyon	Flinz	1.07	4.68	17.26	0.23	0.16	0.25	44.78	31.53	0.08
Total	Total Flinz mean	0.63	5.64	19.67	0.26	0.14	0.54	63.65	9.39	0.16
Classic	Fäule	0.96	2.66	19.59	0.29	0.23	0.68	62.75	12.90	0.04
Book Canyon	Fäule	0.90	4.82	20.48	0.34	0.18	0.42	63.43	9.55	0.07
Total	Total Fäule mean	0.95	3.14	19.79	0.30	0.22	0.62	62.90	12.15	0.05

Table 3: Facies Identification



Facies	Type	Laminaset	Lithotype	Grain Size	Roundness	Dominant Component	Fossils Components	Pyrite	Sedimentary Structure	Dunham Classification
1	Microsparic Neomorphosed	Flinz	Classic BGL	Silt	Subangular	Microspar	rare micritized unidentifiable	Rare	Styolites across bedding	Packestone
2	Laminated	Flinz	Classic BGL	Silt	Subangular	Microspar	crinoid and shell fragments	Rare	Styolites between beds	Packestone
3	Laminated	Flinz	Book Canyon	Silt-to-medium	Subrounderd	Microspar	Abundant shell fragments	Rare	Strong lamination	Wackestone
4	Laminated	Fäule	Classic BGL	Clay	Subrounderd	Micrite	Rare trilobite, crinoid, and shell fragments	Rare, framboidal	Irregular lamina thickness	Mudstone
5	Laminated	Fäule	Book Canyon	Silt-to-fine	Subrounderd	Micrite	rare trilobite and crinoid, abundant shell fragments	Not observed	Very fine lamina, < 1 mm	Wackestone

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CHAPTER 4 –

Invertebrate paleontology of the late Mississippian Bear Gulch Limestone, central Montana

Amy E. Singer, Roy Plotnick, Nancy W. Hinman

ABSTRACT.—The mid-Carboniferous (Mississippian, Serpukhovian) Bear Gulch Limestone of central Montana remains one of the least-studied Konservat Lagerstätte. It records a time of rapid climate change during the latest Mississippian, and although extensive research has been carried out on the fish fauna and crustaceans, little is known about the diversity of other invertebrates. The present work provides the first report of excavations in the Bear Gulch Limestone undertaken with the purpose of a complete, lamina-level survey of the stratigraphic occurrences of invertebrates. A standardized collection protocol was established to generate an occurrence distribution with respect to lithology, within and between outcrops. The flinz (extremely pure limestone) lamina sets indicated deeper marine conditions, with abundant and diverse brachiopod faunas (including 12 new genera), nektonic cephalopods, conulariids, and hexactinellids. Fäule (interlayers with slightly lower carbonate contents and minor increases in clay minerals) lamina sets were representative of shallower, less hospitable conditions, with lower diversity and overall faunal abundance. The invertebrate assemblages indicated differing environmental conditions at the time of deposition via rhythmic variations in the micritic limestone between the two laminasets.

1. Introduction

The Bear Gulch Limestone (BGL) of central Montana is the best known Serpukhovian (Upper Mississippian) Konservat Lagerstätten, a sedimentary deposit with exceptional preservation of soft tissues in fossil (Hagadorn, 2002). These deposits provide an opportunity to study important intervals in the Earth's history, as they preserve a more detailed picture of the biodiversity than other deposits containing mostly biomineralized fossil remains (Seilacher, 1970; Muscente et al., 2017).

The BGL is a plattenkalk succession of fine-grained, largely unbioturbated flinz beds (extremely pure limestone) interlayered with fäule beds of lower carbonate content and slightly higher clay mineral content (Williams, 1983; Hagedorn, 2002; Fig. 1). Fossils are primarily preserved in the flinz beds, but isolated remains exist within the fäule beds as well. The high-fidelity preservation of the BGL has potential for understanding not only a Serpukhovian marine community but also ecological and environmental changes in species assemblages near the Mississippian-Pennsylvanian boundary. Central Montana preserves one of the most complete sections of mid-Carboniferous sequences, and the BGL preserves a marine fauna during this transition (Shephard, 1993; Singer et al., 2019). Known for its spectacular fish and important crustacean fossils, descriptions of the typically abundant and diverse Carboniferous taxa, like crinoids and solitary rugose corals, are notably absent from the BGL literature (Williams, 1983; Shepard, 1993; Hagadorn, 2002; Schram et al., 2006; Lund et al., 2012; Singer et al., 2019).

Although excavations in the BGL have spanned over four decades, they have mostly concentrated on fish fossils. A more complete understanding of the BGL fossil assemblages, including a detailed survey of invertebrates, is necessary to provide the environmental context of this important Lagerstätten. Additionally, detailed stratigraphic and locality information is missing from many of the existing BGL collections housed in museums around the world—an issue potentially creating systematic bias (Whitaker and Kimmig, 2020). In this study, a quantitative, lamina-by-lamina survey of BGL invertebrates is reported based upon extensive new excavations from three previously unexplored sites located along two canyons locally referred to as Miller Creek and Book Canyon (Fig. 1). Lower Miller (LM) and Upper Miller (UM) are located along two small tributaries to Miller Creek, and BP (Brach Pile) is located in Book Canyon. A fourth site, Main Miller (MM) was not included in this study as sampling varied from the other three sites. Additionally, invertebrate assemblages were documented with respect to lithology to elucidate the intra- and interrelationships between the flinz and fäule laminasets for compiling the first comprehensive study of fossil distribution within the BGL.

2. Geologic Setting

2.1 Overview.—The BGL of Fergus County, central Montana, was situated within the Big Snowy Trough at 12° north of the equator at the time of deposition in the mid-Carboniferous (Fig. 1; Williams, 1983; Singer et al., 2019). It is composed of unbioturbated, horizontal beds that alternate between massive silt-sized micritic limestone lamina sets (flinz) and clay-sized micritic less carbonaceous lamina sets and slightly elevated in clay minerals (fäule), similar to the Jurassic plattenkalk successions of the Solnhofen/Eichstätt area (Fig. 3; Münch, 1955; Williams, 1983; Munnecke et al., 2008). A plattenkalk is a finely bedded micritic limestone, sometimes containing high-fidelity soft-tissue fossil preservation, fine unbioturbated lamina sets, and rhythmic depositional patterns, which can record tidal, seasonal, or climatic signals

(Williams, 1983; Barthel et al., 1990; Hagadorn, 2002; Singer et al., 2019). Plattenkalks are evident globally throughout geologic history, yet there is no known modern analog, making it difficult to assign discrete environmental indicators from the geology alone (Barthel et al., 1990; Williams, 1983). The rhythmically alternating flinz and fäule laminasets are the most notable features of the BGL outcrop (Fig. 3). Flinz sets are more competent, with fused lamina, and are resistant to weathering; whereas fäule sets are friable, with a higher clay mineral content (Singer et al., 2019). The environmental signal indicated by the changing lithology is presently unknown, and various models have invoked tectonics, contour currents, and even microturbidites triggered by seasonal monsoons (Williams, 1983; Aram, 1993; Feldman et al., 1994; Grogan and Lund, 2002; Singer et al., 2019), but the absence of scours, current transport, and other current indicators makes these mechanisms unlikely. Depositional models for these limestone formations vary from back-reef lagoon environments to near-shore shoals, to far-from-coastline marine epeiric seaways (Aram, 1993; Feldman et al., 1993; Shepard, 1993; Singer et al., 2019). Based on cephalopods, conodonts, and palynomorphs, as well as regional stratigraphic relationships, the BGL is contained within the Tyler Formation and dates to the mid-Carboniferous, latest Mississippian, Serpukhovian stage (Fig. 2; Williams, 1983; Cox, 1986; Lund et al., 1993; Shepard, 1993; Bottjer, 2017; Singer et al., 2019).

2.2 Preservation.—Fossils of the BGL are usually flattened and parallel to the bedding plane, although rare large specimens may extend through more than one lamina (Feldman et al., 1994). Mollusks are preserved primarily as external molds, with all original shell material rarely maintained in exceptional specimens (Williams, 1983; McRoberts and Stanley, 1989). Brachiopods exhibit a range of preservation from original shell material to external molds.

Thomas (2004) further investigated the (primarily fish) taphonomy of the BGL and found that phosphatization occurred but only in taxa with phosphate-rich tissues., e.g. bones and scales. Fish fossils are often fully articulated with nonmineralized tissues and little-to-no evidence of transport (Feldman et al., 2004; Thomas, 2004). Thomas (2004) found the BGL to be too clay-poor, both in the flinz and fäule, to support preservation by interactions between clay minerals and bacteria, suggesting rapid replacement or carbonization as the primary preservation mechanism of the nonmineralized tissues.

3. Methods

3.1 Specimen Collection.—All samples were collected from the Classic BGL beds within the field area of Fergus County, central Montana (Fig. 1; Singer et al., 2019). Field sites formed a transect across the accessible field area, with BP located at the northeast of the field area, UM at the southwest and LM intermediate between the other two (Fig. 1). Excavations followed the sampling protocol: 1) Sampling was limited to macroscopic specimens (those that could be seen with the unaided eye, > 1 mm); (2) All macroscopic fossil materials were collected regardless of condition, including vertebrate, invertebrate, botanical, trace, and other unidentifiable materials in the field; (3) Excavations at all sites were 1 m^2, cutting down through the outcrop; and (4) Excavations examined each layer to ensure every lamina of each bedding style was observed and recorded.

All fossil-bearing materials were cataloged with field numbers, locality, laminaset, and field identification. Excavations were kept to 1 m^2square per lamina so that fossils$\cdot m^{-2}$ excavated could be calculated as a proxy for abundance. Where lamina did not easily break apart along bedding planes, as was often the case with well-cemented flinz lamina sets, the material was further broken down to cobble size using sledgehammers for examination. The microcrystalline micrite often preferentially broke conchoidally across lamina along the zone of weakness formed around fossils within the lamina set, thus increasing the number of fossils recovered.

The field collections from the present study represented five new excavations at three previously undescribed sites, with 1461 individuals identified from > 2380 m^2 of the 614 flinz and 526 fäule fossil-bearing bedding planes collected (Fig. 1, Table 1). The remaining 1240 bedding planes with no macrofossils were discarded. All fossil material is housed at the University of Montana Paleontology Center (UMPC).

3.2 Lab identification.—Once in the lab at UMPC, the material was sorted by locality and laminasets determined with the aid of a binocular microscope. Due to the friable nature of plattenkalk, breaks any further preparation beyond splitting the rocks at bedding planes was unnecessary.

Where possible, specimens were identified to the genus level (Moore and Teichert, 1953; Easton, 1962; Lutz-Garihan, 1979; Rigby, 1979). Some taxa could not be identified beyond gross morphology, such as in cases with ‘vermiform’. Poorly preserved mollusks, especially nautiloids and ammonoids, where original shell material and identifying septa had been lost, were grouped to class. In the case of nautiloids and ammonoids, a morphological characteristic was also recorded, as either “coiled” or “straight” cephalopods. Filamentous algae were recorded as rare, common, or abundant. No fully articulated fish were found in this study; thus, fragmented components were counted as presence/absence, as the number of individuals could not be determined. The phylum Echinodermata was represented by individual plate components, with no full-body fossils found; accordingly, these were counted as individuals for only one echinoid spine and one crinoid stem piece were found. Counts were made for each locality by lithology (Table 1; raw counts in Supplementary information).

3.3 Statistical analyses.—Statistical analyses of the fossil invertebrates were used to determine whether the flinz vs. fäule differed in their taxonomic composition. Diversity for the summed flinz and fäule data was calculated using Shannon's H index. Simpson's similarity index was used to test if the assemblages in the flinz shared taxa with those in the fäule and whether the fäule was a subset of the flinz. The Margalef index was calculated to test for the distribution of richness across individual taxa, Bray-Curtis and Jaccard indices were calculated to test for similarity, and Spearmen's rank correlation coefficient (rs) was calculated to test the rank order correlation of the two lithologies. Analyses of individual sites compared were not performed due to insufficient data. All statistics were performed with PAST *v*.4.05.

4. Results

4.1 All phyla.—Nearly 100 taxonomic groups were identified in the lab, including 48 invertebrate taxa, representing 11 higher taxonomic categories (Table 1). The majority of identifiable fossils were brachiopods (70% in the flinz, 40% in the fäule). In this collection, 8 of 10 genera reported by Lutz-Garihan (1979) were found and 12 additional genera of brachiopods have been identified (Table 2). initial report of brachiopods from the BGL. Terrestrial botanical materials were rare in the BGL, as only unidentifiable carbon detritus was found.

Flinz and fäule laminasets contained primarily the same organisms, but with differing abundances (Table 1). Fossils in the flinz had a higher generic richness of 38 taxa across 1406 individuals (average, 4.8 fossil components/m^2), compared to the fäule with 24 taxa across 407 individuals (average, 2.6 fossil components/m^2; Table 1). An abundant unknown organism, 'unidentified string', a single strand of what appear to be polyps connected edge to edge was found in both flinz and fäule but was more abundant in the flinz (Table 1, Fig. 6). *Sphenothallus* also more abundant in the flinz. Crinoids, echinoids, conulariids and hexactinellid sponges, were only found in the flinz laminasets. Fäule contained a reduced sponge fauna, with only Demospongiae represented (although high abundance was observed for that group).

Brachiopods were overwhelmingly the most abundant component in both lithologies and far more diverse compared to other groups and more diverse than previously reported by Lutz-Garihan (1979) (Table 2). Outside of brachiopods, the top three fossils in the flinz laminasets were the "unidentified string" > coiled cephalopods > demospongia *Teganiella sp.* (Fig. 6a; Table 1). The top three fossils outside of Brachiopoda for the fäule laminasets were *Teganiella sp.* > 'verminifera' > coiled cephalopods (Fig 6a; Table 1).

Shannon's diversity index (*H*), which accounts for the diversity of the taxa within a community, showed the fäule lamina sets to be slightly more diverse relative to the flinz (*H* of 2.61 and 2.59, respectively). Shannon's equitability (*Eh*), which accounts for the evenness of a community with respect to those species present, showed the fäule laminasets to be more evenly distributed (*Eh* = 0.57) relative to the flinz (*Eh* = 0.36). Simpson's similarity index for the flinz was 0.86 and 0.90 for the fäule. For all phyla found the Margalef index indicated that the flinz is richer (5.28) compared to the fäule (and4.08; Table 2). Simpson's similarity matrix showed the fäule to be a subset of flinz, with no unique taxon identified (Table 3). The Jaccard similarity index indicated that ~50% of the taxa overlapped between the two lithologies, and a Bray-Curtis statistic of 0.51 similarly showed there to be some difference between assemblages (Table 4). A near-zero Spearman’s *rs* suggested a weak correlation between the two lithologies, likely due to the observed difference in dominant taxon (Table 5).

4.2 Brachiopod analyses.—Brachiopods were the most abundant and diverse of all groups in both lithologies and thus were investigated as a robust subgroup better suited to defining differences between the laminasets (Figs. 6 and 7). The overall fossil differences between flinz and fäule were supported by differences in assemblage composition as well as diversity indices within the brachiopod subgroup (Table 1). Articulate brachiopods were the largest group within both the flinz and fäule, including 19 identifiable genera across 675 individuals in the flinz, compared to11 genera across 136 individuals in the fäule (Table 1). The genera of Brachiopoda in the flinz but missing from the fäule included *Derbyia, Linoproductus, Tomasina, Juresania, Eospirifer*, *Orbinaria, Atrypa,* and *Oehlertella.*

In contrast to the findings among all phyla, brachiopod Shannon’s diversity index (H) among the brachiopods, showed the flinz laminasets to be more diverse relative to the fäule (*H* = 1.95 and 1.8, respectively); however, *Eh* showed fäule laminasets more evenly distributed among the brachiopod subset compared to flinz (0.58 and 0.41, respectively). Simpson’s similarity index for brachiopods indicated an even distribution (0.76 and 0.77 for flinz and fäule, respectively; Table 2). The Margalef index indicated that the flinz laminasets were richer among the brachiopods (2.76 and 2.04 for the fäule; Table 3). The Simpson’s similarity matrix also showed the fäule to be a subset of the flinz (Table 4). The Jaccard similarity index showed that ~50% of the taxa overlapped between the two lithologies, and the Bray-Curtis index (statistic value 0.34) indicated some level of difference (Table 4). A Spearman’s *rs* of 0.766 for all taxa and 0.843 for the brachiopod subset showed there was a correlation between the two lithologies, likely due to the difference in dominant taxa. Flinz was dominated by *Ovatia sp.*, and fäule was dominated by *Lingula sp.* (Table 5). Although it was not possible to compare by site with the current dataset, a plot of abundances showed there were differences by site, with UM1 dominated by *Lingula sp.*, and BP0 maintaining a more robust rhynchonelliform brachiopod assemblage (Figure 7).

5. Discussion

The specific mechanism responsible for the differences between flinz and fäule has been a long-standing debate, with suggestions ranging from tides and seasons to turbidites (Feldman et al., 1994; Grogan and Lund, 2002; Lund et al., 2012). Williams (1983) and Aram (1992) invoked tectonics as the controller of water depth within the Big Snowy Trough, although evidence for this within the outcrop is lacking. Grogan and Lund (2002) proposed that "microturbidites" triggered by seasonal monsoons were the source of the flinz sedimentation. There is no evidence among the invertebrates to support the mechanisms of microturbidites or contour current activations as the causes of the flinz laminasets. The invertebrates, moreover the brachiopods, showed a change in water conditions, such as salinity or oxygenation, between the flinz and fäule lamina sets.

Thus, the flinz and fäule lamina sets may not represent tides or event deposition but rather, rapid climatic alterations that influenced sea level. Shephard (1992) suggested that the unusual fossil assemblages of the BGL are due to differential recruitment of taxa because of changes in circulation within the Big Snowy Trough and eustatic fluctuations. The nektonic cephalopods are in notably higher abundance in the flinz, possibly indicating greater access to the open ocean or higher oxygenation of the water column within the BGL basin. This claim is supported by the abundant and diverse rhynchonelliform brachiopods, which constituted 59% of the flinz compared to 28% of the fäule, potentially supporting near-normal marine conditions during deposition of the flinz. Although the absence of corals, bryozoans, crinoids, and echinoderms from both lithologies suggests that fully marine conditions may never have been achieved, they can also be excluded because of soft-sediments, which would have inhibited recruitment among stalked forms and inhibited filter feeding. The single echinoid and crinoid plate components found in the flinz, however, may indicate that favorable conditions were regionally located, and bioclasts such as these were only transported during flinz time.

The restricted diversity of the fäule and dominance of euryhaline Linguliform brachiopods (14% in fäule, 10 % in flinz) and demospongia (16% in fäule,6% in flinz) may indicate less hospitable water conditions such as higher temperature, non-normal salinities, or low oxygen. *Lingula sp.* is known for its ability to thrive in brackish or shallow water, poorly oxygenated estuaries, and mud flats (Clarkson, 1998). This wider environmental tolerance is also seen in Porifera, with the demospongia, found from freshwater to strictly marine habitats, also highly abundant in the fäule. Calcarea, found in fäule exclusively are restricted to the littoral zone (Brenchley and Harper, 1998). The sponge and brachiopod fauna indicated conditions were less hospitable to invertebrate life.

The brachiopod analyses provided more robust data, and the few minor discrepancies observed in between brachiopod based and whole assemblage analyses across phyla may be due to the inability to identify all specimens to the same taxonomic level. Consequently, the following discussion is restricted to brachiopod data statistical analyses. Analyses indicated that there was a difference in richness between the flinz and fäule laminasets although relatively similar diversity patterns were observed within each. With all values at 1, Simpson's similarity index confirmed that fäule is a subset of the flinz, in apparent agreement with Shephard (1993) who observed that there seemed to be little difference in recruitment. The taxa missing in the fäule were all rare in the flinz, often represented by < 5 individuals. This could be an artifact of sampling related to time-in-field or difference in the volume of flinz rock relative to fäule. Feldman et al. (1994) found no statistically significant pattern or cycle in the rhythmicity of the flinz and fäule laminasets and stressed that they were not coupled, i.e. thickness in one did not predict thickness in the next. These inconsistencies may also be an issue of taphonomy, as Thomas (2006) evaluated fossils from the flinz and not the fäule; thus, there may be a different preservation mechanism in the latter. Among the brachiopods, however, preservation appeared consistent among both lithologies, and the difference in the most abundant taxon possibly indicated an actual difference in the physiochemical conditions at the time of deposition. Flinz were overwhelmingly dominated by *Ovatia sp.*, a productid, whereas fäule were dominated by *Lingula sp.*, an inarticulate brachiopod. Coupled with the high occurrence of other shallow-water taxa, Demospongiae, calcarean, and abundant filamentous algae, fäule appeared to be confined to shallow water.

6. Conclusions

Systematic collection protocols of all fossil materials, including invertebrates and low-grade specimens, are necessary to accurately reconstruct environmental conditions at the time of deposition. Despite relatively similar diversity patterns within each lithotype, there was a marked difference in richness, where the fäule assemblage was a subset of the flinz. Those taxa missing from the fäule were rare in the flinz, possibly indicating a sampling issue; however, the Spearman's *rs* support a true difference. The invertebrates of the flinz and fäule laminasets represented differing conditions wherein the flinz conditions can support more stenohaline organisms while fäule conditions support shallow-water taxa, such as *Lingula sp.* and Calcarea, as well as other euryhaline genera, such as Demospongiae. This study shows that important environmental information lost in prior work, i.e. when invertebrates were inaccurately sampled or excluded from ecological studies, obscures the subtle differences between the flinz and the fäule. For example, this study added 12 genera of brachiopoda to the initial taxa list identified by Lutz-Garihan (1979) underrepresenting the abundance and diversity of the brachiopods, obscuring variations between the flinz and fäule laminasets that point to changes in the syndepositional environment. Additionally, isolated components of 'missing' Mississippian taxa, such as trilobite and crinoids, have now been found. Further sampling of the invertebrates may clarify the invertebrate paleoecology and specific variations between the two lithologies.

Ultimately, the following conclusions were drawn from the present research:
(1) The flinz and fäule lamina sets were different in richness; (2) There were relatively similar diversity patterns in each lithology; (3) The fäule was a subset of the flinz, and there was not a unique fauna in either lithology; (4) Brachiopoda represented the largest invertebrate group in both lithologies and are more diverse than previously reported; (5) Articulate brachiopods were more abundant and diverse in the flinz while inarticulate brachiopods were more abundant in the fäule; (6) The ranks were different, with fäule dominated by *Lingula sp.* and flinz dominated by *Ovatia sp.*; (7) Taxonomic groups within the flinz required more normal marine conditions; and, (8) Taxonomic groups within the fäule represented organisms with greater tolerance to environmentally variable conditions.

The literature and collections of BGL did not reflect the true diversity of the marine taxa in BGL and these findings show the overall fauna contains many components of more typical

Mississippian age deposits not previously reported. This improves our understanding of the BGL in the context of other Lagerstätten and fills in a critical gap near the Mississippian-Pennsylvanian boundary that addresses ecological and environmental changes. Key questions remain concerning the syndepositional physiochemical conditions, taphonomy of the invertebrates especially the mollusks, and the exact placement of the Mississippian-Pennsylvanian boundary.

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Figures, Tables, & Captions

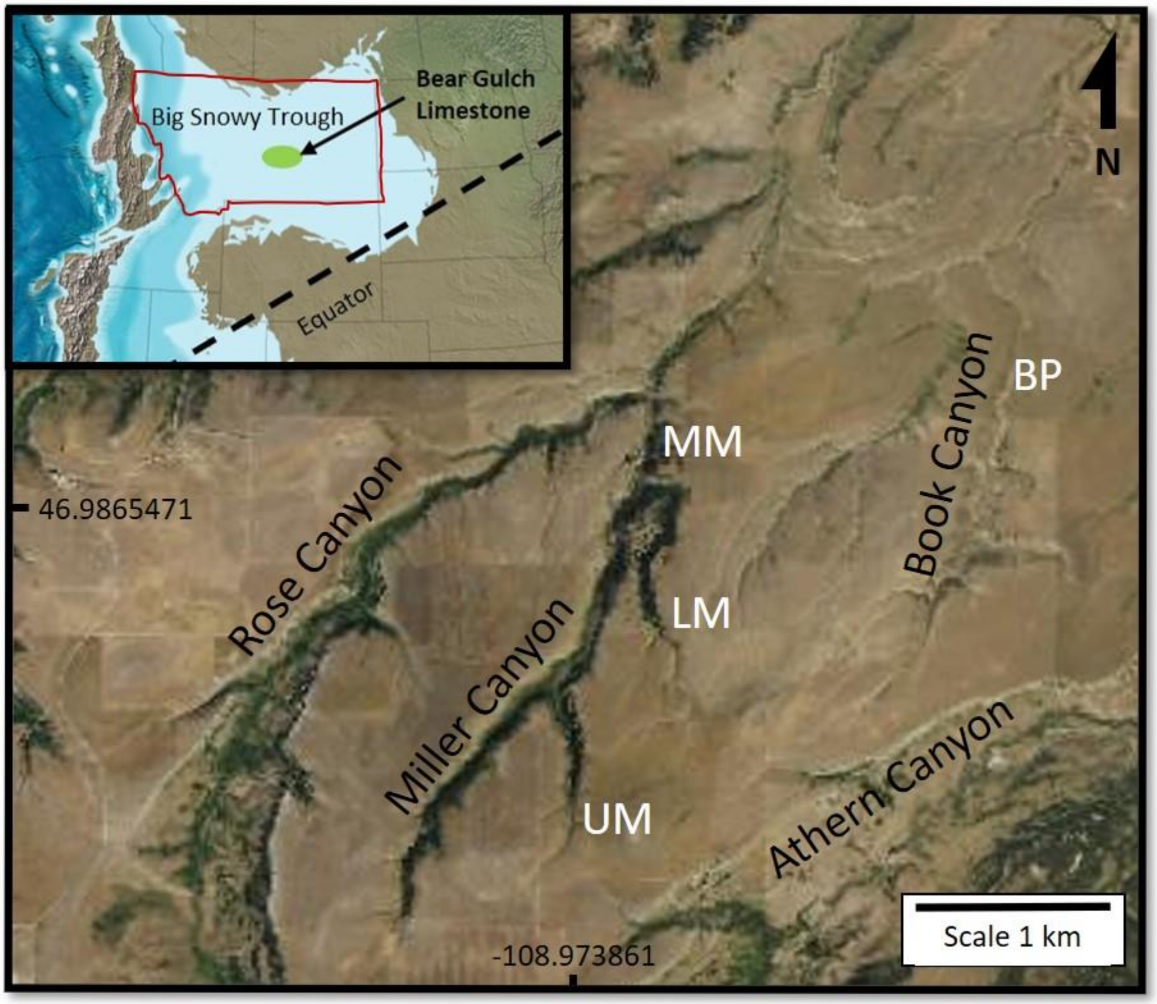


Figure 1. Bear Gulch field area and collecting sites: UM, Upper Miller; LM, Lower Miller; MM, Main Miller; BP, Book Canyon. (Inset) BGL location within the Big Snowy Trough in central Montana. Equator during the Serpukhovian is interpreted to be at 12° N, after Singer et al. (2019).

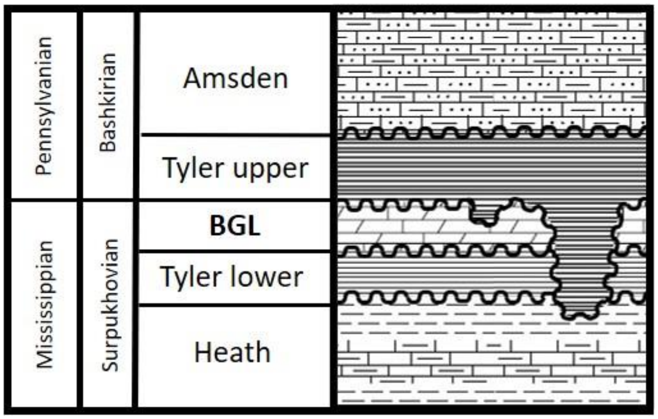


Figure 2. Stratigraphic column adapted from Singer et al. (2019). Note that in some locations, the fluvial Tyler Formation cuts through the Marine BGL into the Heath.

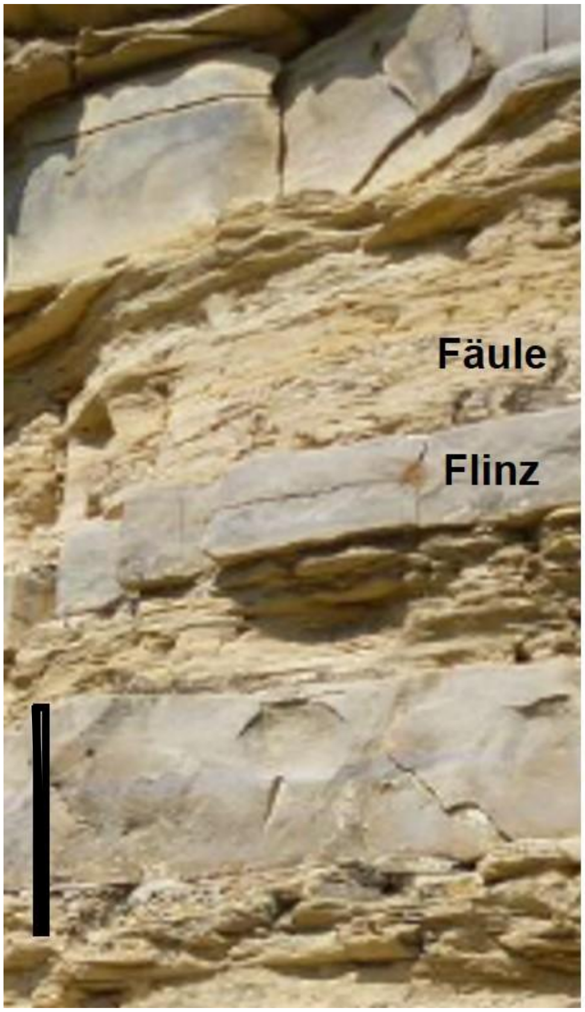


Figure 3. Classic BGL at Lower Miller (LM) field site: well-cemented flinz and friable fäule lamina sets. Fossils occur within both types. Scale bar is 10 cm.

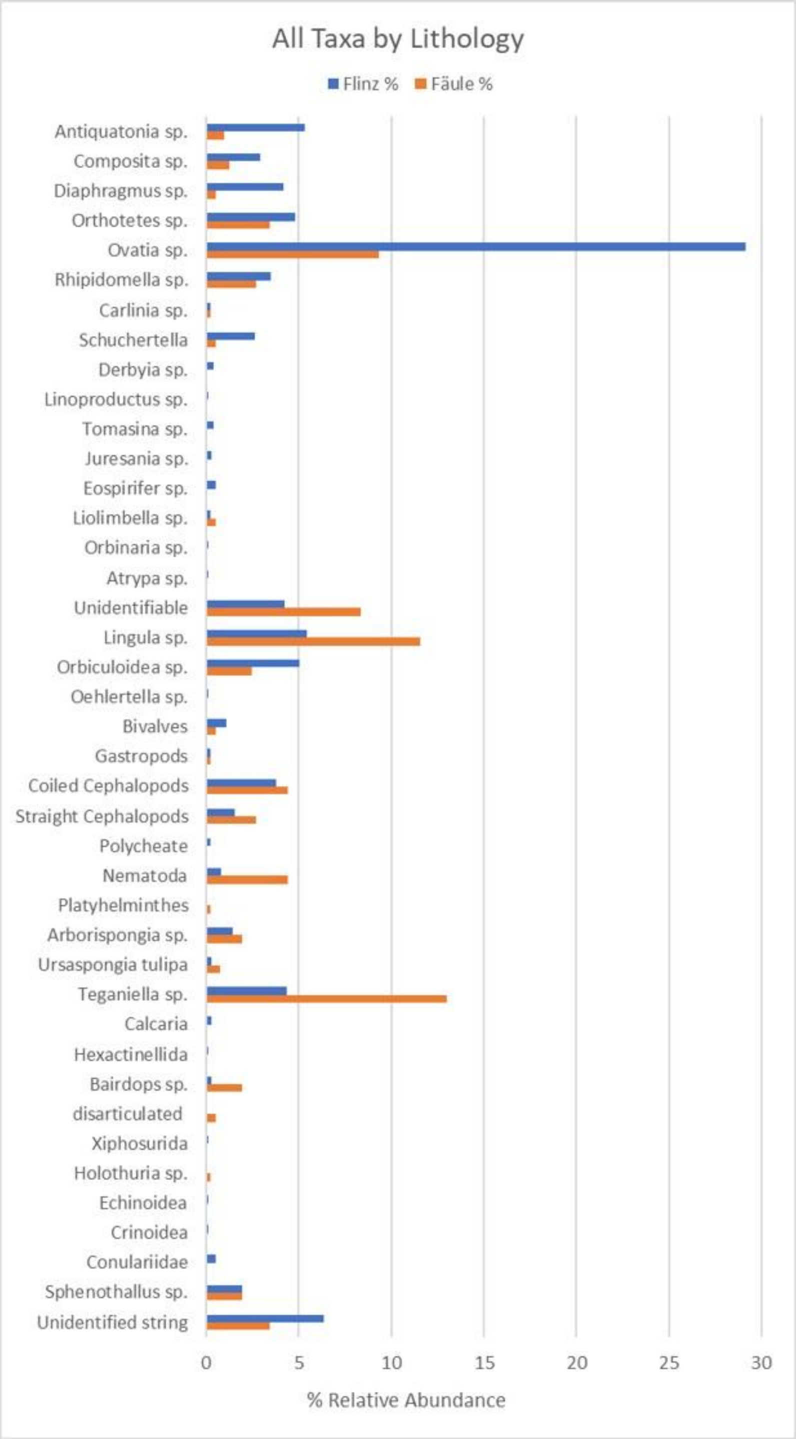


Figure 4. Percent relative abundance of all invertebrates of the BGL between the assemblages in the flinz vs fäule lamina sets.

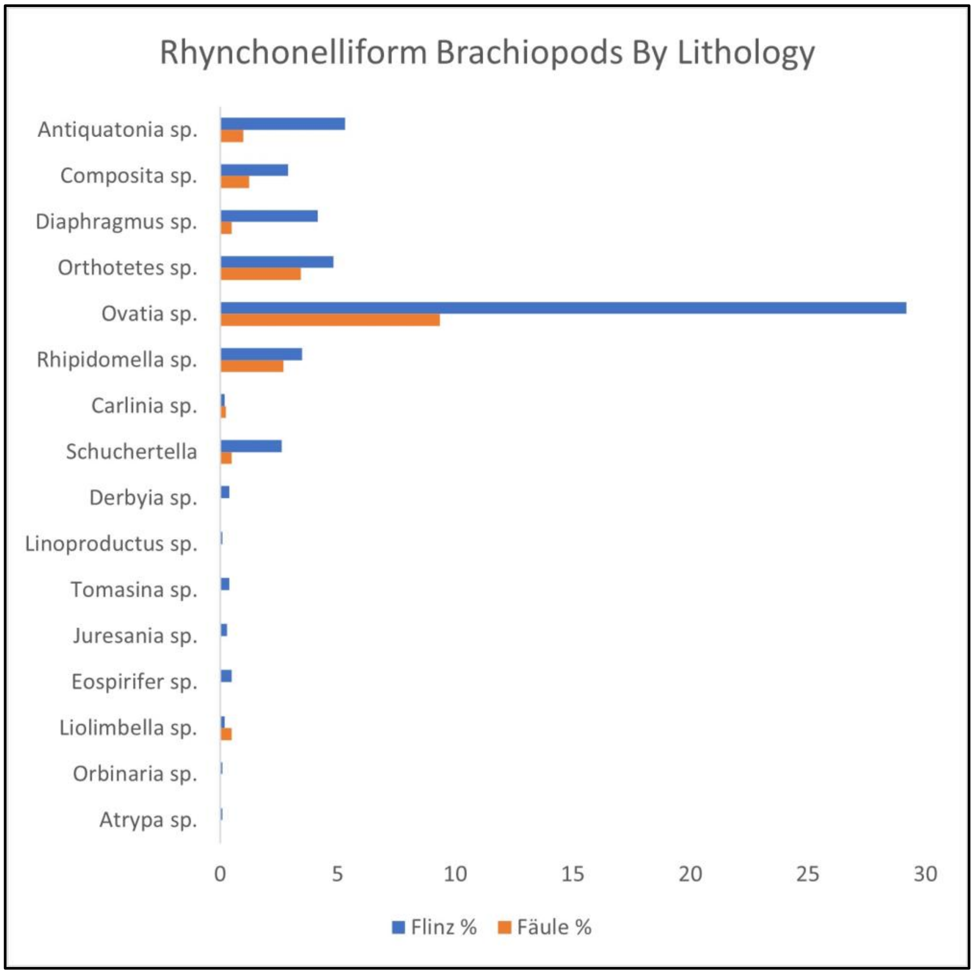


Figure 5. Percent relative abundance of rhynchonelliform brachiopod genera: of the BGL between assemblages in the flinz vs fäule lamina sets.

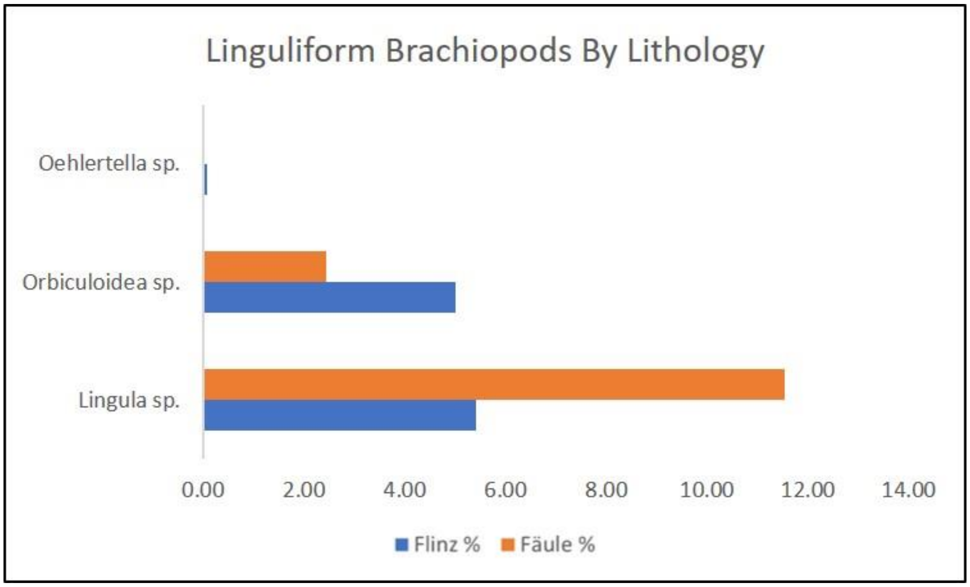


Figure 6. Percent abundance of lingulilform brachiopod genera of the BGL between assemblages in the flinz vs fäule lamina sets.

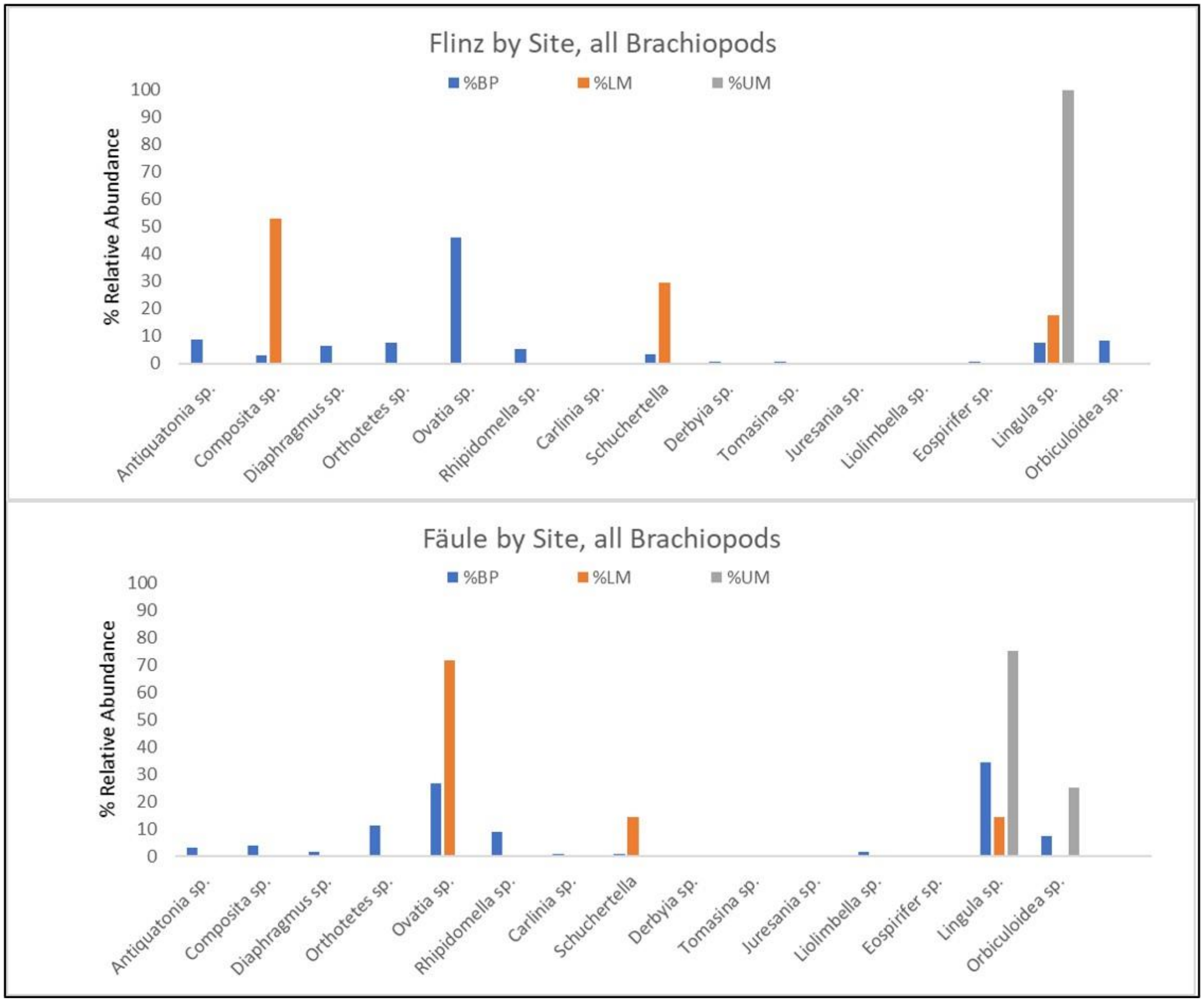


Figure 7. Brachiopod genera abundance for three novel, excavated sites: BP, LM, and UM, showing the (**1**) flinz and (**2**) fäule assemblages by site. LM and BP were more articulate-rich, and UM, near the top of the unit, was more inarticulate-rich across both lithologies. The number of individuals from UM and LM were not suitable for statistical analyses.

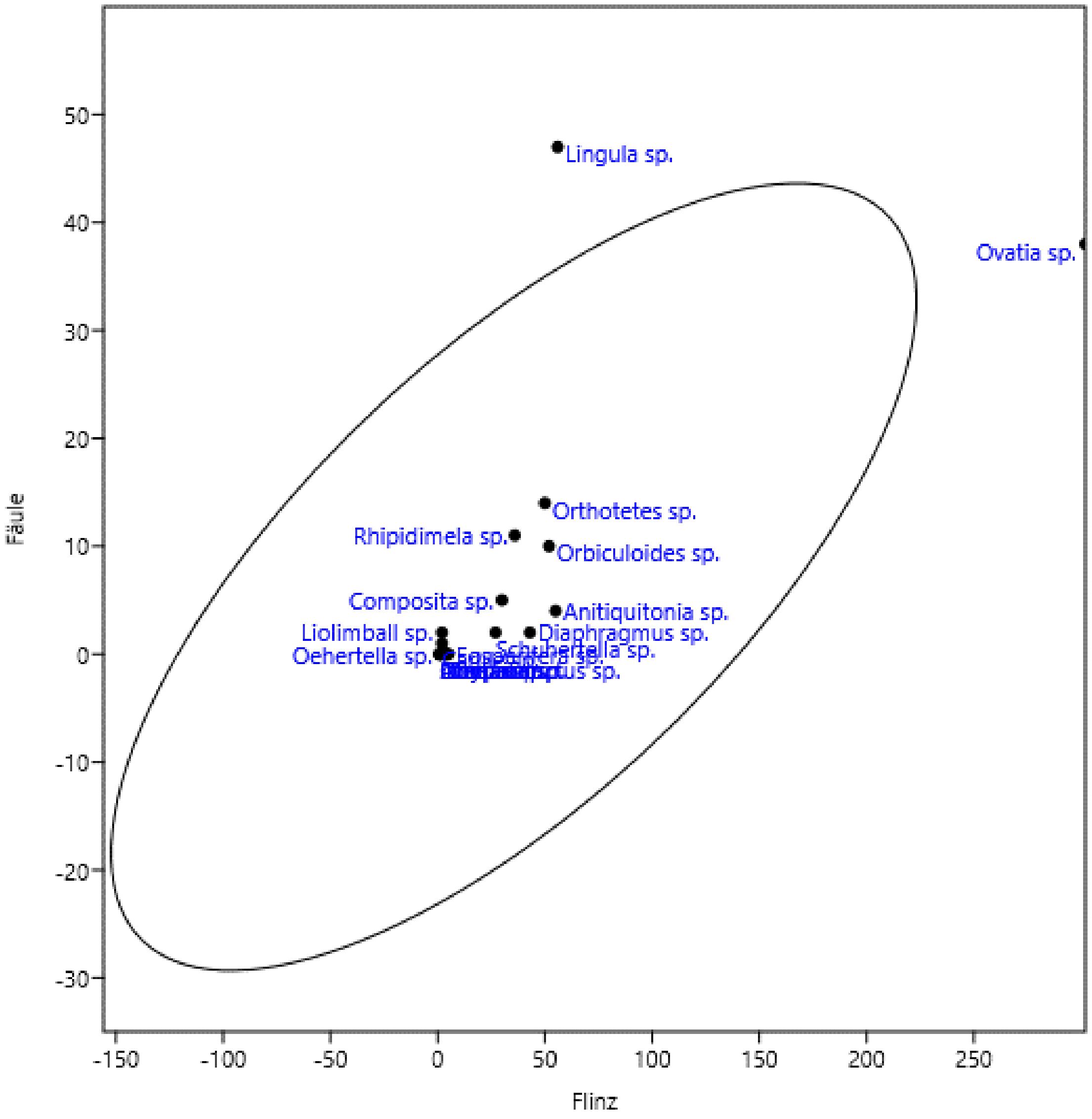


Figure 7. Bivariate plot of flinz vs fäule brachiopod counts. The 95% ellipse shows a correlation, except for the outliers.

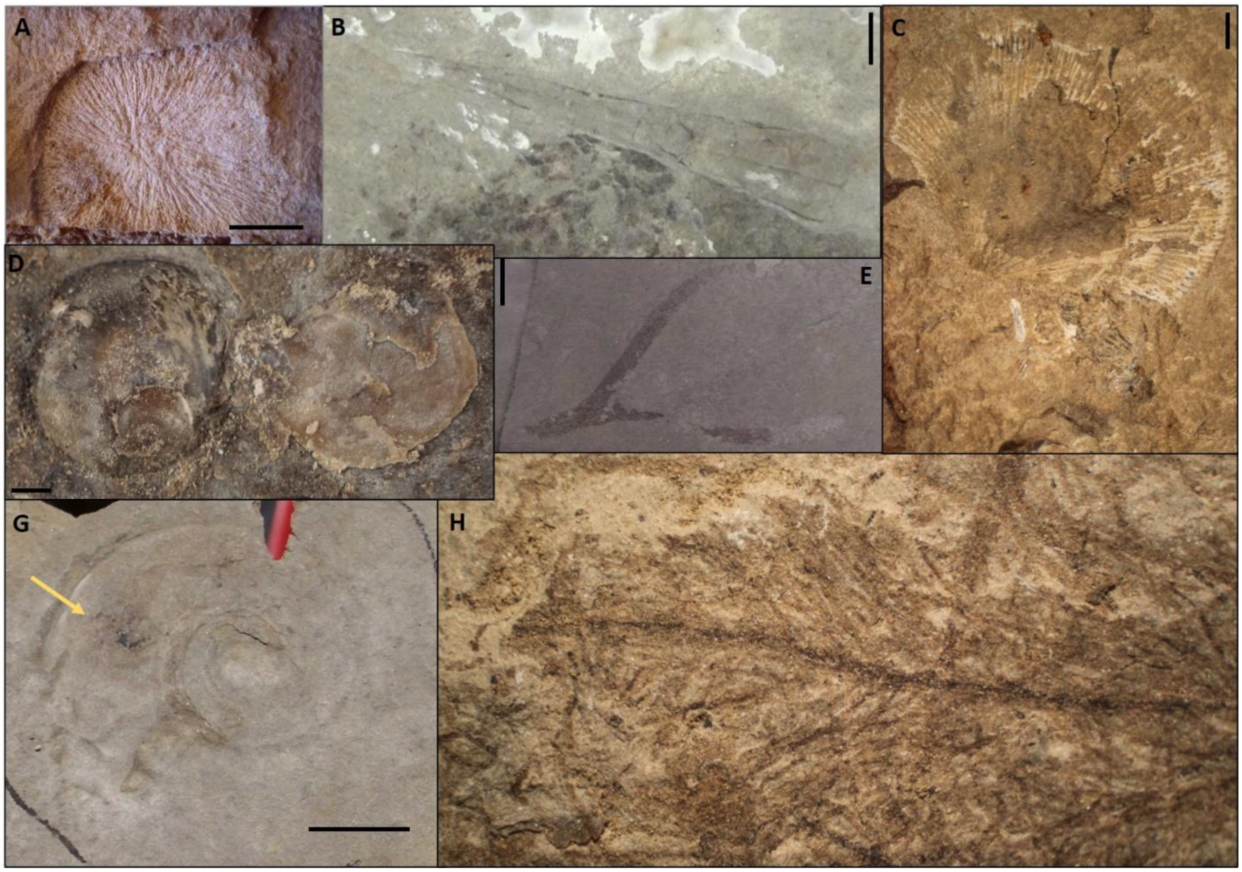


Figure 8. Fossil invertebrates of the Bear Gulch fäule lamina sets: (**A**) Porifera: Calcarea, (**B**) Straight Cephalopod, (**C**) *Antiquitonia sp.,* (**D**) Gastropoda, (**E**) Arboriospongia, (**F**) abundant string fossil, (**G**) Coiled Cephalopod, note yellow arrow indicating preserved phosphatic jaw assembly, (**H**) Filamentous algae. Scale bar is 0.5 cm

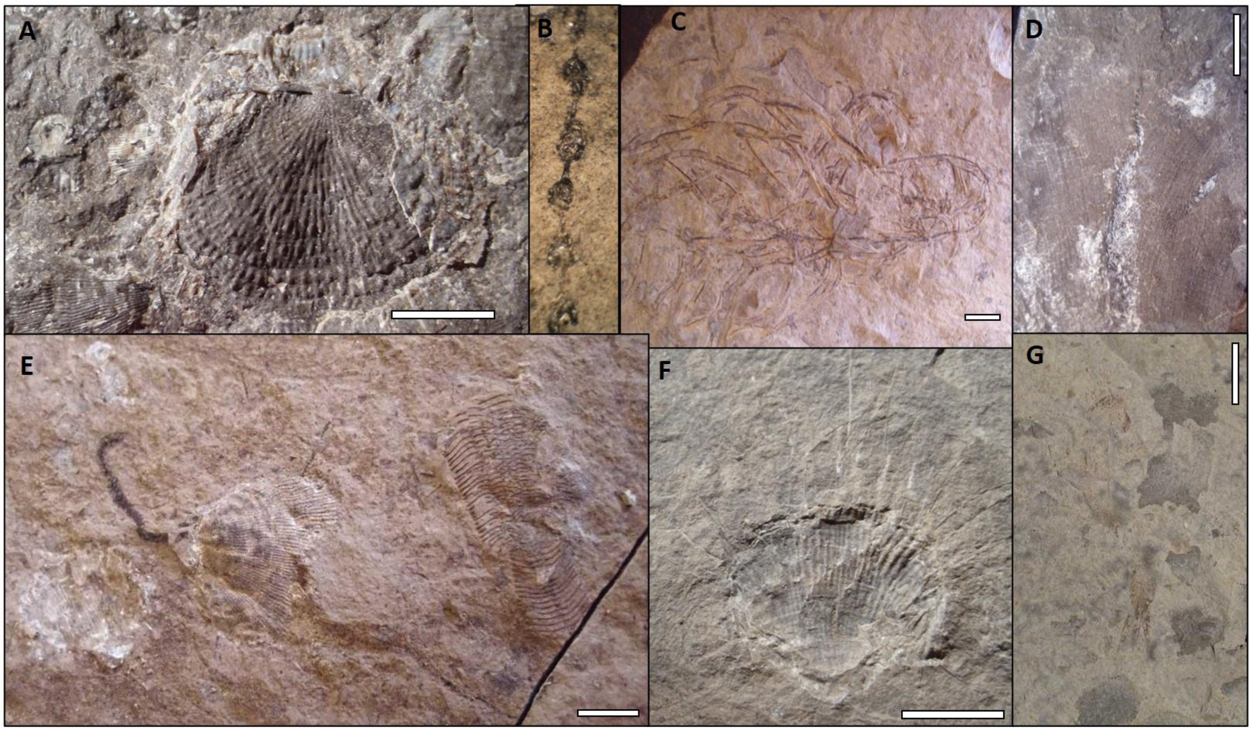
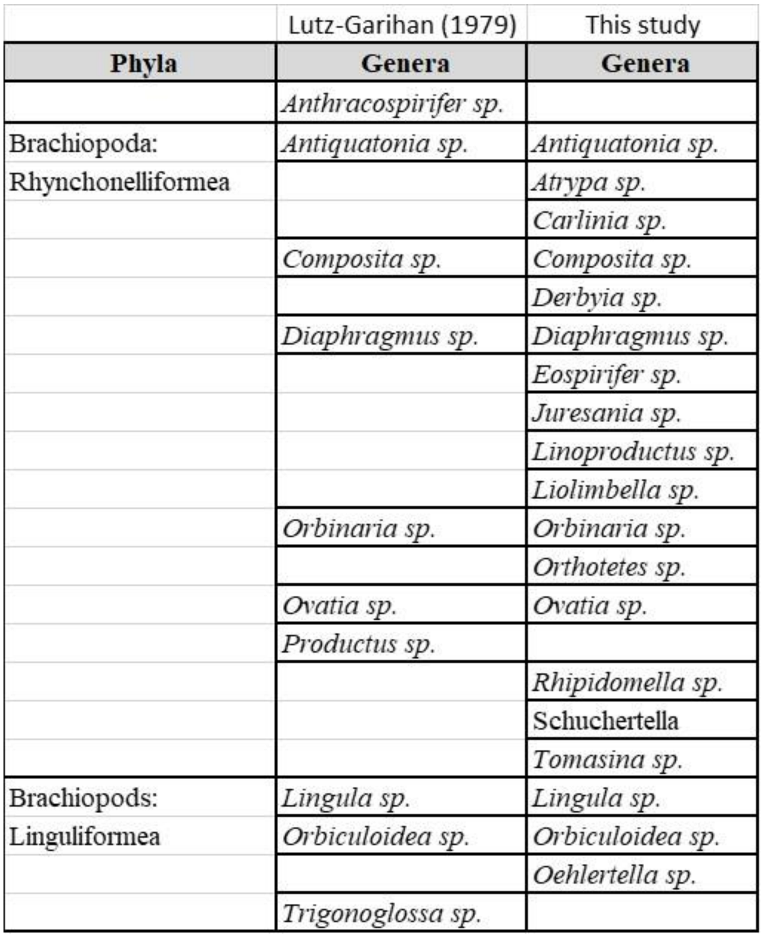


Figure 9. Fossil invertebrates of the Bear Gulch flinz laminasets: (**A**) *Antiquitonia sp.*, (**B**) *Sphenothallus*, (**C**) Slab that includes a vermiform, *Antiquitonia sp.*, conulariid, and filamentous algae, (**D**) *Ovatia sp.*, (**E**) Arthropoda. Scale bar is 0.5 mm.

Table 1. Taxonomic group abundance counts found in each lithology.

Phyla	Genera	Flinz	Flinz % of Total	Fäule	Fäule % of Total
Brachiopoda: Rhynchonelliformea	*Antiquatonia sp.*	55	5.31	4	0.98
	Composita sp.	30	2.90	5	1.23
	Diaphragmus sp.	43	4.15	2	0.49
	Orthotetes sp.	50	4.83	14	3.44
	Ovatia sp.	302	29.18	38	9.34
	Rhipidomella sp.	36	3.48	11	2.70
	Carlinia sp.	2	0.19	1	0.25
	Schuchertella	27	2.61	2	0.49
	Derbyia sp.	4	0.39	**0**	-
	Linoproductus sp.	1	0.10	**0**	-
	Tomasina sp.	4	0.39	**0**	-
	Juresania sp.	3	0.29	**0**	-
	Eospirifer sp.	5	0.48	**0**	-
	Liolimbella sp.	2	0.19	2	0.49
	Orbinaria sp.	1	0.10	**0**	-
	Atrypa sp.	1	0.10	**0**	-
	Unidentifiable	44	4.25	34	8.35
Brachiopods: Linguliformea	*Lingula sp.*	56	5.41	47	11.55
	Orbiculoidea sp.	52	5.02	10	2.46
	Oehlertella sp.	1	0.10	**0**	-
Mollusca	Bivalves	11	1.06	2	0.49
	Gastropods	2	0.19	1	0.25
	Coiled Cephalopods	39	3.77	18	4.42
	Straight Cephalopods	16	1.55	11	2.70
Verminifera	Polycheate	2	0.19	**0**	-
	Nematoda	8	0.77	18	4.42
	Platyhelminthes	**0**	-	1	0.25
Porifera: Demospongia	*Arborispongia sp.*	15	1.45	8	1.97
	Ursaspongia tulipa	3	0.29	3	0.74
	Teganiella sp.	45	4.35	53	13.02
Porifera: Calcaria	Calcaria	3	0.29	**0**	-
Porifera: Hexactinellida	Hexactinellida	1	0.10	**0**	-
Arthropoda	*Bairdops sp.*	3	0.29	8	1.97
	disarticulated	**0**	-	2	0.49
	Xiphosurida	1	0.10	**0**	-
Echinodermata	*Holothuria sp.*	**0**	-	1	0.25
	Echinoidea	1	0.10	**0**	-
	Crinoidea	1	0.10	**0**	-
Fish	Coelacanthiformes	34	3.29	42	10.32
	Placodermi	**0**	-	1	0.25
	Shark – grasper	1	0.10	1	0.25
Problematica	Conulariidae	5	0.48	**0**	-
	Sphenothallus sp.	20	1.93	8	1.97
	Unidentified string	66	6.38	14	3.44
Trace fossils	Coprolites	17	1.64	20	4.91
Botanical	Filamentous Alga	rare	-	Abundant	-
	Frond Alga	**0**	-	4	0.98
	carbonized UNID	22	2.13	21	5.16
Total fossils		1035		407	

Table 2. Brachiopod genera identified in this study compared to those previously reported.



	Lutz-Garihan (1979)	This study
Phyla	**Genera**	**Genera**
	Anthracospirifer sp.	
Brachiopoda:	*Antiquatonia sp.*	*Antiquatonia sp.*
Rhynchonelliformea		*Atrypa sp.*
		Carlinia sp.
	Composita sp.	*Composita sp.*
		Derbyia sp.
	Diaphragmus sp.	*Diaphragmus sp.*
		Eospirifer sp.
		Juresania sp.
		Linoproductus sp.
		Liolimbella sp.
	Orbinaria sp.	*Orbinaria sp.*
		Orthotetes sp.
	Ovatia sp.	*Ovatia sp.*
	Productus sp.	
		Rhipidomella sp.
		Schuchertella
		Tomasina sp.
Brachiopods:	*Lingula sp.*	*Lingula sp.*
Linguliformea	*Orbiculoidea sp.*	*Orbiculoidea sp.*
		Oehlertella sp.
	Trigonoglossa sp.	

Table 3. Diversity indices for across all taxa and brachiopods.

All Taxa	**Flinz**	**Fäule**
Taxa S	37	24
Individuals	917	282
Dominance D	0.14	0.10
Simpson 1-D	0.86	0.90
Shannon H	2.59	2.61
Margalef	5.28	4.08
Brachiopods	**Flinz**	**Fäule**
Taxa S	19	11
Individuals	675	136
Dominance D	0.24	0.22
Simpson 1-D	0.76	0.78
Shannon H	1.95	1.80
Margalef	2.76	2.04

Table 4. Similarity indices across all taxa and brachiopod subset.

All Taxa			Brachiopods		
SIMPSON	Flinz	Fäule	*SIMPSON*	Flinz	Fäule
Flinz	1.00	0.91	Flinz	1.00	1.00
Fäule	0.91	1.00	Fäule	1.00	1.00
JACCARD	Flinz	Fäule	*JACCARD*	Flinz	Fäule
Flinz	1.00	0.55	Flinz	1.00	0.58
Fäule	0.55	1.00	Fäule	0.58	1.00
BRAY-CURTIS	Flinz	Fäule	*BRAY-CURTIS*	Flinz	Fäule
Flinz	1.00	0.51	Flinz	1.00	0.34
Fäule	0.51	1.00	Fäule	0.34	1.00

Table 5. Spearman’s *rs* correlation coefficient of the ranks for all taxa and brachiopods.

All Taxa		
Spearman's rs	Flinz	Fäule
Flinz		1.37E-08
Fäule	0.76553	
Brachiopods		
Spearmans rs	Flinz	Fäule
Flinz		5.93E-06
Fäule	0.84271	

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CHAPTER 5 – SUMMARY

The Bear Gulch Limestone is a Mississippian-aged Konservat Lagerstätten that preserves soft tissues and is known for its well-studied fish fauna. However, two fundamental questions have been unresolved by previous work: what is the true occurrence of the biota, particularly the invertebrates and what variations led to the flinz and fäule laminasets? This dissertation records investigations into the BGL that aimed to resolve questions that have been outstanding for decades. A number of tools and techniques were employed to resolve these fundamental questions through an interdisciplinary approach, facilitating further research into the BGL. The BGL is a plattenkalk, a pelagically-derived micritic limestone. Plattenkalks are confounding by their very nature, and the source of micrite is a long-standing question in the field of sedimentology, necessitating traditional sedimentary techniques, as well as geochemical and paleontological analysis, to address these questions. The primary approaches of sedimentology and paleontology, in addition to limited preliminary geochemistry, were used to elucidate the environmental conditions that may have led to the development of flinz and fäule beds as well as the biota. Furthermore, paleontologic analysis considering the whole fauna of the BGL aided in environmental reconstruction.

Many questions concerning the formation of the flinz and fäule laminasets have been limited due to a lack of an interdisciplinary approach; however, the methods in this study included several techniques to provide a more robust and extensive data set to further our understanding.

Singer et al. (2019) reported an important discovery that ended the debate of the stratigraphic position of the BGL and established that it is contained within the Tyler Formation

(Chapter 2- Anatomy of the Book Canyon conglomerate: A sequence boundary at the top of the Bear Gulch Limestone in the Big Snowy Trough). The Bear Gulch Conglomerate is a sequence boundary at the base of the upper Tyler Formation (Singer et al., 2019). It is in direct contact with the sandstone conglomerate that is the base of the upper Tyler, referred to by some as the Stonehouse Canyon Member (Horner, 1979; Williams, 1983; Lund et al., 2002; Bottjer, 2017; Singer et al., 2019). The confusion over the stratigraphy and the disconnection between the paleontological literature and the industry literature led to many inconsistencies that have hindered research surrounding the depositional processes and the composition of the biota.

New paleontological collections from across the region where the BGL crops out provide insight into the environments represented by the BGL and its development through time. These new excavations quickly refuted several conventions about the BGL. For example, brachiopods were not rare as is stated in the literature but are in fact one of the largest invertebrate groups found across all lithologies and sampled localities the field area (Chapter 4; Hagadorn, 2002; Lund et al., 2012). As fossils are generally rare in plattenkalks, despite the extensive excavation, not enough fossils occurred in all taxonomic groups to allow for robust statistical analyses. The brachiopods numbered in the hundreds and were a suitable subset to explore. The resulting ecological findings utilizing only brachiopod data were consistent with tests performed on the entire invertebrate biota (Chapter 4). The invertebrate fossil assemblages of the flinz and fäule were not discrete or unique, but similar and correlated (Chapter 4).

Among the non-brachiopod invertebrate fauna, there are indications of variations in the environmental conditions that restricted the biota of fäule as opposed to flinz. The sponge fauna was different between flinz and fäule, with hexactinelliids exclusive to the flinz and a single calcarean specimen exclusive to the fäule. Demospongiae and filamentous algae were present in both but were much more abundant in the fäule. Flinz on the other hand contains more *Sphenothallus* and “unidentified string” organism. Nektonic animals appeared to be ubiquitous, with few differences between the two lithologies among fish and cephalopods (Feldman et al., 1994; Lund et al., 2012). These observations of the non-brachiopod fauna and differences in the rank order of the brachiopod biota suggest that the flinz experienced more normal seawater conditions and that the fäule received more terrestrial input and represents shallower conditions that stressed the biota.

Regional context is necessary to understand how the basin and the marine community developed within the Big Snowy Trough far from the open ocean. Prior investigations focused on the vertebrate fauna (Singer et al., 2019). Upon review of collections at the University of Montana Paleontology Center (UMPC) and inquiries at other holdings across the country, it was clear that collections are further overwhelmingly biased toward high-quality specimens, and those of unique interest to the collector. This bias is common and an area of importance for paleontological workers undertaking collections-based research (Whitaker and Kimmig, 2020). Consequently, new specimens were needed. As outlined in Chapters 3 and 4, collection protocols were used to limit collection bias to the maximum extent possible by standardizing the excavation area and collecting all material, regardless of the condition or the ability to identify the fossils in the field. These new sites yielded a research collection of over 1500 specimens.

The BGL has been referred to as an unusual deposit, not only because it is a Konservat-Lagerstätten, but because it had appeared to be missing several expected Mississippian taxa. Without an accurate census, it is unclear if this exclusion is taphonomic, ecologic, or collection based. The collection protocol used here was based upon a literature review of paleoecological collection techniques focused to eliminate collection bias. Consequently, the question of taphonomic vs. ecologic exclusion theoretically could be evaluated.

Thomas (2006) conducted limited taphonomic investigations, but the focus of the project did not address whether the flinz and the fäule represented similar or different preservation. Utilizing a number of ecological indices and statistics to analyze my research collection (Chapter 4), I showed fäule to be a subset of flinz; there were no unique taxa in fäule, and those that were absent were from the fäule are rare in flinz. This may indicate that continued collections would eventually yield a replicate biota and that there is no taphonomic difference between the two facies. However, fossils were preserved to the same quality in both lithologies. For example, mollusks are missing their shells in both lithologies and preserve as external molds. Among cephalopods in both flinz and fäule, although the shell material was lost, the phosphatic jaw material was preserved. It is therefore likely, based on observation of the biota present within the flinz and fäule, that there is no taphonomic difference between the two, and variations in the fossil populations reflect of the life assemblages. The possibility that the 'missing' Mississippian organisms, i.e. those common to other Mississippian marine deposits that are not represented in the BGL, such as crinoids, may be taphonomically excluded was beyond the scope of this research, although they are found in thin sections, which would imply that they are not taphonomically excluded. Rather, they are more likely ecologically excluded and are present regionally (Chapter 3).

Lack of clear stratigraphic relationships obscured regional processes, both tectonic and environmental, that influenced the depositional processes and history of BGL. For example, the dominant fluvial processes during deposition of the Tyler Formation may have contributed freshwater in the later stages of BGL, (Chapter 3), adding variability to the cyclicity of deposition of the flinz and fäule and early neomorphism. The fluvial processes occurring during deposition of the Tyler Formation cut across the basin-wide depositional sequence creating an incised unconformity. This explains why the stratigraphy has been difficult to resolve in outcrops, which highlights the necessity of coupling these data with subsurface data. Proprietary data showed that the conglomerate contacts the upper Tyler Formation and that the BGL is present above the lower Tyler Formation (Aram, pers. comm.; Bottjer, pers. comm.). Previously, no upper contact had been established for the BGL. The conglomerate described here not only firmly establishes the BGL as part of the Tyler Formation but suggests that it may also be the Mississippian-Pennsylvanian boundary. The M/P boundary is assumed to be in the upper Tyler but has never been found in outcrop or subsurface examinations (Bottjer, personal comment, 2019).

Findings from petrologic and sedimentologic investigations supported the findings suggested by the biota that the flinz and the fäule represent variations in the environmental conditions. The BGL periodically experienced periods of shallowing that stressed the biota resulting in the fäule laminasets. During fäule times, micrite production was depressed, the biota restricted, and terrestrial sediments entered into the BGL system. During flinz times, conditions were more favorable to marine biota and micrite production was high by both inorganic (whitings) and organic (planktonic photosynthesizing microbes) processes.

Five microfacies, three flinz and two fäule, were identified based on variation in lamination, mineralogy, limited preliminary geochemistry, and sedimentary structures. Variations in the presence of these facies within a stratigraphic progression record the history of BGL. The BGL's first incursion into the Big Snowy Trough represents a near-normal salinity marine system that gives way to a more brackish and climatically variable system capped by the conglomerate of Chapter 2 and upper Tyler Formation. Local variations could not be tested in the biota due to an extreme lack of fossils in the two upper excavations, LM and UM. Notably, this was the only locality that contained mud cracks and ripple marks, key environmental indicators, which are exclusively found in the fäule laminasets immediately below the next flinz laminaset. The lack of fossils may result from the shallowing of the water column, driven at least in part by this transition to fluvial conditions of the Tyler Formation.

Petrologically, the flinz samples of the upper locations were heavily neomorphosed by freshwater, as opposed to flinz samples lower in the unit, further supporting these conclusions. The flinz was divided into three microfacies, and the fäule into two, largely on the degree of neomorphism (Chapter 3). Facies 1 was the heavily neomorphosed flinz and qualified as a microsparite, which was the result of recrystallization due to freshwater alteration of laminated mudstones (Flügel, 2010). Facies 2 was the laminated flinz where lamina was still clear and fossil components still identifiable. Crinoid and trilobite components were most frequent in this facies and points to more normal marine conditions. Facies 3 was the Book Canyon flinz, with little-to-no alteration of the carbonate components, implying little meteoric influence. Shell fragments, as well as kerogen, were abundant due to a productive water column. Facies 4 was the Classic BGL fäule laminasets and showed evidence of meteoric alteration. Facies 5 was the Book Canyon fäule. Overall, these facies in stratigraphic order showed the BGL shallowed through time from the fully marine Book Canyon Microfacies 3 and 5, to the meteorically altered Classic BGL Microfacies 1 and 4.

No single line of evidence independently confirms the environmental syndepositional conditions of the BGL, its biota, and the flinz and fäule laminasets. But this multidisciplinary approach provided evidence that established the flinz and fäule as related but with slight variability in their environmental parameters, impacting the resident biota and the resulting lithology. Furthermore, in contrast with previous work, these conclusions are stronger by the inclusion of the entire biota, namely the sessile invertebrates, that would not have been able to move if water conditions became unhospitable. Mobile organisms, such as fish and nektonic cephalopods, may have been able to temporarily tolerate the changing conditions by moving to different areas of the basin. Sessile invertebrates lived and died in the water and sediments in which they were preserved, and thus act as a proxy of the environmental conditions of the ecosystems represented by the rocks in which they are found. Changes in the invertebrate assemblages lend support and clarify the sedimentological evidence in the microfacies investigation. The limited preliminary geochemical material presented here emphasizes the need for further investigation of the BGL in order to further understand the ecological, environmental, and climatological conditions it represents. Further excavations with a similar emphasis on reducing bias and collecting invertebrates will allow more basin-wide conclusions to be drawn and clarify the distinctions between the flinz and fäule.

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