

The geological and biological environment of the Bear Gulch Limestone (Mississippian of Montana, USA) and a model for its deposition

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ABSTRACT

The Bear Gulch Limestone (Heath Formation, Big Snowy Group, Fergus County, Montana, USA) is a Serpukhovian (upper Mississippian, Namurian E₂b) Konservat lagerstätte, deposited in the Central Montana Trough, at about 12° North latitude. It contains fossils from a productive Paleozoic marine bay including a diverse biota of fishes, invertebrates, and algae. We describe several new biofacies: an *Arborispongia*-productid, a filamentous algal and a shallow facies. The previously named central basin facies and uppermost zone are redefined. We address the issue of fossil preservation, superbly detailed for some of the fish and soft-bodied invertebrates, which cannot be accounted for by persistent anoxic bottom conditions. Select features of the fossils implicate environmental conditions causing simultaneous asphyxiation and burial of organisms. The organic-rich sediments throughout the central basin facies are rhythmically alternating microturbidites. Our analyses suggest that these microturbidites were principally generated during summer monsoonal storms by carrying sheetwash-eroded and/or resuspended sediments over a pycnocline. The cascading organic-charged sediments of the detached turbidity flows would absorb oxygen as they descended, thereby suffocating and burying animals situated below the pycnocline. Seasonal climatic variability would have provided the cycling between vertically mixed to density-stratified water column. These dynamics are likely to have promoted the high biodiversity of the bay, would have produced the rhythmic repetition of microturbidites that characterize the Bear Gulch Limestone, and provide a compelling explanation for the detailed preservation of its fossils.

KEY WORDS

Bear Gulch Limestone,
deposition,
paleoecology,
paleoclimate,
microturbidite.

RÉSUMÉ

L'environnement géologique et biologique du Calcaire de Bear Gulch (Mississippien du Montana, USA) et son modèle de dépôt.

Le Calcaire de Bear Gulch (Heath Formation, Big Snowy Group, Fergus County, Montana, USA) est un Konservat lagerstätte déposé dans le bassin du Montana Central, à environ 12° de latitude Nord. Il contient des fossiles d'une baie marine comportant un biote varié de poissons, d'invertébrés et d'algues. Nous décrivons plusieurs nouveaux biofaciès : à *Arborispongia*-productidés, à algues filamenteuses et un faciès peu profond. Le faciès précédemment nommé central du bassin et la zone supérieure sont redéfinis. Nous abordons la question de la conservation des fossiles, dont le détail est parfois très fin chez certains poissons et invertébrés à corps mou, et qui ne peut être expliquée par des conditions anoxiques persistantes sur le fond. Chez quelques fossiles, l'observation de certains caractères impliquent des conditions environnementales provoquant simultanément l'asphyxie et l'ensevelissement des organismes. Les sédiments organiques dans tout le faciès central du bassin sont des microturbidites qui alternent de manière rythmique. Nos analyses suggèrent que ces microturbidites se sont formées principalement pendant les tempêtes des moussons d'été par transport de sédiments lessivés et/ou remis en suspension au dessus d'un pycnocline. Le déferlement de sédiments, chargés en éléments organiques provenant des flux de turbidites mises en suspension, devait absorber l'oxygène au cours de leur descente, de ce fait suffoquant et ensevelissant les animaux situés au dessous du pycnocline. La variation saisonnière climatique a dû provoquer les alternances entre mélange et stratification par densité dans la colonne d'eau. C'est cette dynamique qui explique la forte biodiversité de la baie, la répétition rythmique des microturbidites qui caractérise le Calcaire de Bear Gulch. Elle fournit aussi une explication incontournable à la conservation de détails des fossiles.

MOTS CLÉS

Calcaire de Bear Gulch,
dépôt,
paléoécologie,
paléoclimat,
microturbidite.

INTRODUCTION

The Bear Gulch Limestone of Central Montana (USA) was first described as a part of the Tyler Formation (Pennsylvanian), barren of fossils and correlated with subsurface limestones farther to the east (reviewed by Nelson 1993). The fossiliferous Bear Gulch deposit was discovered through the activities of local ranchers who found fish remains while recovering ornamental building stone. This discovery initiated quarrying operations in 1968 by William Melton (Montana State University), one of the coauthors (R. L.), and their field parties and led to a stratigraphic study of the exposures by Horner (1985) and a sedimentologic study by Williams (1981, 1983).

These latter works placed the Bear Gulch Limestone within the Mississippian Heath Formation, rather than the Tyler Formation. They also demonstrated that there is no direct horizontal (layer-cake) correlation between the Bear Gulch Limestone and other limestone units to the east (the fundamental premise for designating all of these limestones as the Bear Gulch member of the Tyler Formation). Our continuing field explorations (e.g., Lund *et al.* 1993; Feldman *et al.* 1994) have substantiated Horner's and William's interpretation and so, their stratigraphic designations are adhered to here. We have expanded our database of geologic, sedimentary, and faunal and floral information and now provide a more in depth examination of the

environmental conditions influencing the deposition of the Bear Gulch Limestone.

Over the 33 years of study, the Bear Gulch Limestone has revealed a large assemblage of vertebrate and invertebrate fossils. Vertebrate faunal diversity is very high (Lund & Poplin 1999). These fossils are preserved along a spectrum that ranges from scattered scales and disarticulated skeletal elements to entire bodies including skin pigments and pigmented outlines of venous blood vessels and internal organs (Grogan & Lund 1997). Fine traces of soft tissues are also preserved in some invertebrates. Their faunal composition is unusual in that most of the shelled forms characteristic of the late Mississippian (Lutz-Garihan 1985) are conspicuously rare or absent. Preservational considerations are not a viable causative factor in this absence. In fact, this rock unit has been classified as a plattenkalke (Williams 1981, 1983) and a Konservat lagerstätte (Briggs & Gall 1990; Lund *et al.* 1993; Feldman *et al.* 1994) based on the diversity and the extraordinary preservation of soft-bodied animals and traces of vertebrate internal organs.

Classical explanations for the preservation of such diverse and high quality fossil faunas invoke persistent anoxic, dysoxic, or hypersaline bottom waters or sediments (Barthel *et al.* 1990). Yet, we find the Bear Gulch deposit reveals a bottom-living fish fauna (including a probable burrowing component) that is ubiquitous, they are found in all lithologies and throughout the basin. They demonstrate the benthic environment was inhabitable, that despite the very fine nature of the mud (Lund *et al.* 1993) this environment must have been aerobic.

Our collective analyses of field and laboratory observations indicate seasonal climatic variations that would promote high faunal diversity and quality preservation and may account for aeration of fine bottom muds. Data are compiled to present a reconstruction of the probable prevailing paleoecologic, paleoclimatic and paleocirculatory conditions in this region during the Serpukhovian; Namurian E₂b. This paper discusses how these conditions could explain the remark-

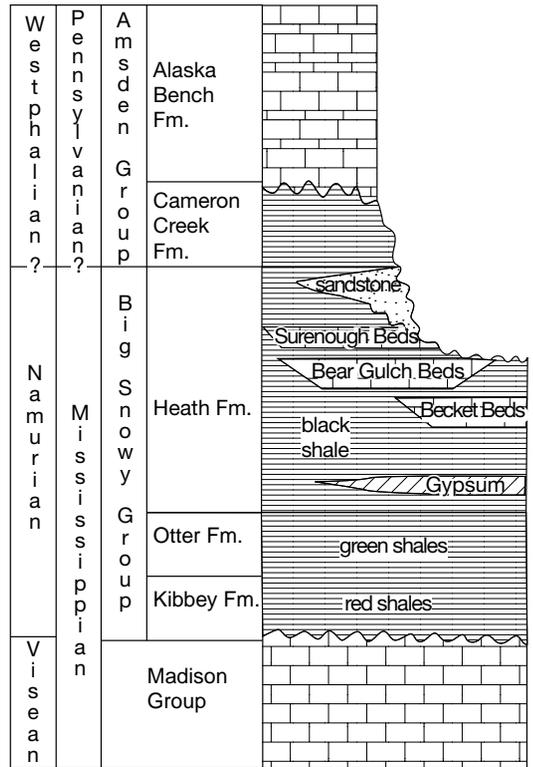


FIG. 1. — Schematic diagram of stratigraphy, modified from Williams (1983).

able features of the Bear Gulch bay; its faunal diversity and quality of fossil preservation.

MATERIALS

Information for this study has been derived from fossil quarrying operations conducted from 1968 through 2000, and from the works of Williams (1981, 1983), Horner (1985), and Feldman *et al.* (1994). Quarrying has resulted in over 5000 fish from 85 sites within and around the outcrop area of the Bear Gulch lens, and innumerable invertebrate and algal specimens. Locality and catalog data are on file at Carnegie Museum of Natural History, Pittsburgh, Pennsylvania, USA. Museum collection designations are as follows: Carnegie Museum of Natural History (CM), Royal Ontario Museum, Toronto, Ontario (ROM),

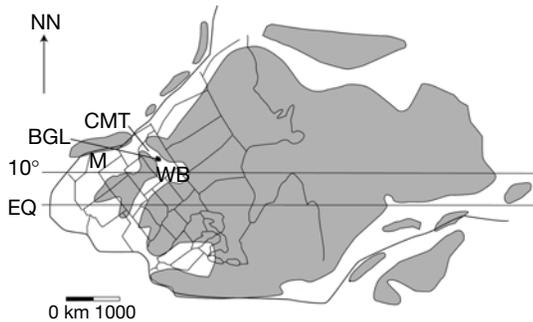


Fig. 2. — Namurian paleogeography of North America, redrawn from Witzke (1990). Emergent lands shaded; present political boundaries outlined. Abbreviations: **BGL**, Bear Gulch Limestone; **CMT**, Central Montana Trough; **EQ**, Namurian equator; **M**, miogeosyncline; **NN**, Namurian North; **WB**, Williston basin; **10°**, Namurian 10° North latitude.

University of Montana Geological Museum, Missoula, Montana, USA (MV).

GEOGRAPHIC AND GEOLOGIC SETTING OF THE BEAR GULCH LIMESTONE

Regional stratigraphy

The Bear Gulch Limestone is one of a series of limestone lenses within the Heath Formation of Montana and North Dakota that have collectively been named the Bear Gulch Limestone Member (Williams 1983; Horner 1985) or upper Heath Formation (Feldman *et al.* 1994) (Fig. 1). The Heath Formation along with the underlying Otter and Kibbey Formations are called the Big Snowy Group, are all Namurian E₂b in age (Lund *et al.* 1993), and correlate with the Serpukhovian (Riley 2000; Menning *et al.* 2000). The Kibbey Formation is a basal transgressive sandstone that lies unconformably upon karst topography at the top of the massive middle Mississippian Madison Group limestones. The Otter Formation contains littoral-zone lithologies. The Heath Formation consists of shallow marine and brackish water shales, linear channel sandstones, littoral to fresh-brackish water shales, limestone lenses representing pockets of less turbid or deeper water, and supralittoral gypsum layers.

The upper boundary of the Heath Formation in the outcrop area marks the Mississippian-

Pennsylvanian boundary. Sands within the Heath Formation and erosional features at its upper boundary indicate uplift progressing from a southerly direction and a possible source of fluvial influx from the south. Unconformably overlying the Heath Formation is the Cameron Creek Formation, consisting of soil zones, fresh-water pond deposits, and some littoral zone deposits. Above this is the Alaska Bench Limestone (Amsden group), a shallow transgressive marine unit. The entire upper Heath Formation as well as the Alaska Bench Limestone thins to zero at an apparent structural high at Forest Grove, Mt.

Stratigraphic studies show that the Chesterian was a period of brief epicontinental sea transgression upon the emergent surface at the top of the Madison Group in this region of western North America (Fig. 2) (see paleomap reconstructions at www.scotese.com and www.ucmp.berkeley.edu/geology). It resulted in the deposition of the Big Snowy Group in the Williston basin and the narrow Central Montana Trough.

The Central Montana Trough (Central Montana lineament) was an intermittently active geological feature extending from the Williston basin in the east, across Montana to the Montana-Idaho border. Surface geological mapping and oil well log data show a 160 km series of in-line limestone lenses within the Heath Formation that successively overlap one another from east to west, and demonstrate that the trough was subsiding intermittently (east to west) during the deposition of the Heath Formation (Williams 1981). The Bear Gulch Limestone is one of these lenses formed during this period of tectonic instability.

Bear Gulch stratigraphy

The fossiliferous exposures of the Bear Gulch lens are visible in outcrop over about 85 km². They measure about 14 km east-west by 10 km north-south at its widest extent along the eastern exposure line (Fig. 3). A maximum sedimentary accumulation of about 30 m is exposed near its northeastern margin. The western edge of another limestone lens, the Becket, lies underneath the eastern edge of the Bear Gulch Limestone and

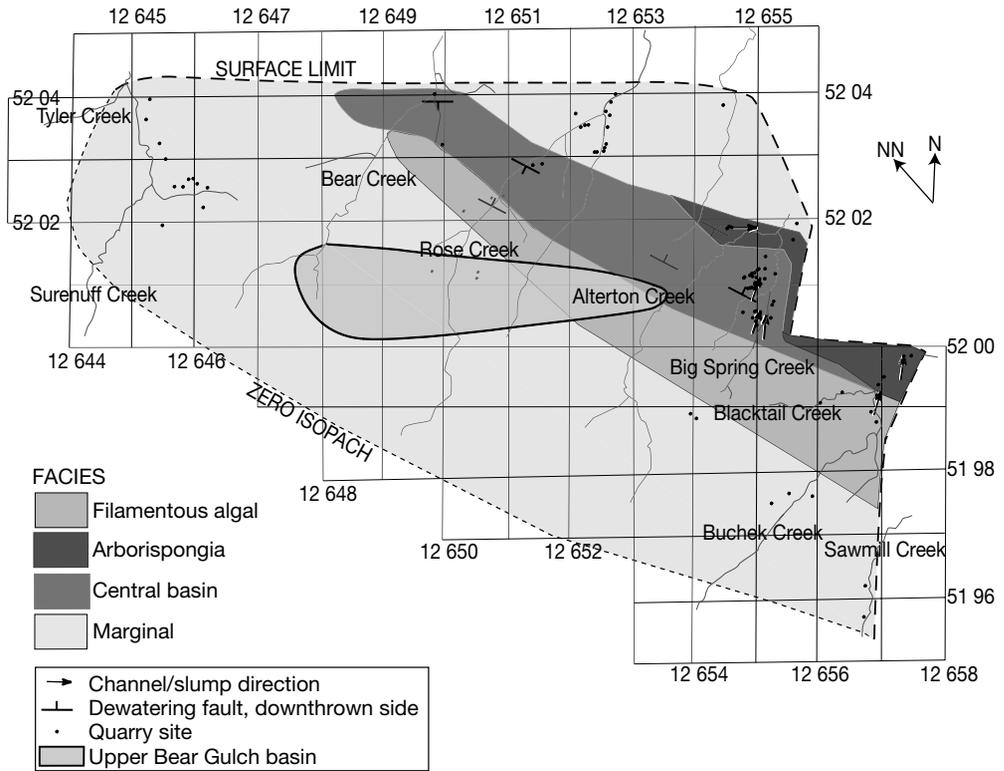


FIG. 3. — Conformation of the Bear Gulch lens, Upper Heath, Fergus County, Montana. Boundaries of the facies are approximate. The grid is in km, Universal Transverse Mercator, zone 12, from the U.S. Geological Survey Becket and Forest Grove 7 1/2' (topographic) quadrangle maps. Abbreviation: NN, Namurian North, from Witzke 1990.

extends eastward into the subsurface. Oil well log data show at least five other lenses of similar rocks below and to the east of the Becket limestone (Williams 1981). Another small lens with accompanying fossils and linear sandstones, the Surenough beds, is found above the northwestern margin of the Bear Gulch Limestone and represents the last small basin episode (Horner 1985). The tectonic activity indicated by the Heath Formation chain of basins and evidence of southern uplift supports Williams' (1981, 1983) proposed origin of the bay (Fig. 4). Yet, the common penecontemporaneous slumps that occur throughout the Bear Gulch Limestone also suggest that a series of small seismic events may also be implicated in the history of this deposit. Thus, Feldman *et al.* (1994) advanced the scenario of a number of seismic events leading to the gradual

or episodic subsidence and filling-in of a shallow bay. This view of the Paleozoic bay has been expanded through our continued studies. Field observations (1995-1997) have included the discovery of complex large-scale channeling in the east wall of southern Rose Canyon (see Fig. 3) which correlates with graded, fish-bearing beds at the top of the section in the west wall of the canyon. Similar observations (1998-2000) were made at other exposures in the more northern reaches of this canyon and Bear Canyon. We interpret these data to indicate that towards the latter stages of Bear Gulch formation and prior to the development of the Surenough Creek lens, the center of deposition of the Bear Gulch Limestone apparently shifted abruptly (paleo-) westward and was most likely due to seismic activity (Fig. 3; Upper Bear Gulch bay facies).

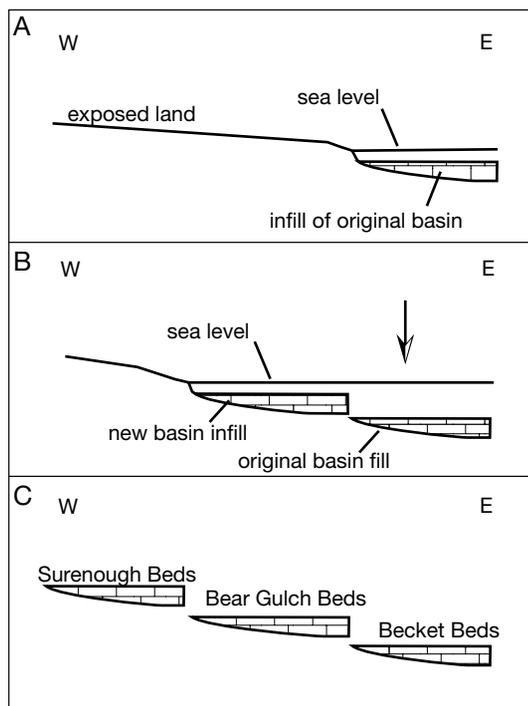


FIG. 4. — Illustration of basin formation, modified from Williams (1983); **A**, infilling of original basin to the east; **B**, subsidence of Central Montana trough (indicated by arrow) leading to drop in original basin and formation of a second basin to the west. The new basin is subject to infilling; **C**, three successive beds resulting from repeated events of subsidence and basin infilling. Abbreviations: E, east; W, west.

A GEOLOGIC/SEDIMENTARY VIEW OF THE BEAR GULCH BASIN

Sediments

The Bear Gulch is considered to be a lithographic limestone or plattenkalke (Feldman *et al.* 1994). The sediments are composed of very fine silts, lime silts, shell fragments, organic debris, and clays; silicates comprise up to 50% by volume (Williams 1981). Sedimentation in the central basin and nearby facies was in the form of rhythmically alternating sets of dark, thick, hard, fine grained, massive to graded beds and sets of lighter-colored fine laminar beds (Fig. 5); one unit of alternating light and dark beds may approach 1 m in thickness. Bed sets can be traced for at least 1 km along outcrops. There is no significant pyrite present in the sediment except for

local occurrences, such as among tightly packed *Arborispongia* Rigby, 1985 accumulations in one part of the eastern area. Occasional thin zones of small, oxidized iron-mineral nodules in the uppermost beds may also have been weathered from pyrite. Bedded cherts are common in the dense sets of the upper beds. Calcite and aragonite were mobilized away from shells in the bay center but not at the western margin. The thick, dense beds are sufficiently rich in decomposed plant matter and organic chemicals that a distinctive (oil-like) odor emanates from freshly broken surfaces. There are no obvious traces of primary evaporites within the Bear Gulch, although abundant star-shaped gypsiferous nodules disrupt the uppermost laminated beds near the northeastern margin.

Basin dimensions

Data from measured stratigraphic sections, the strike and dip of abundant dewatering micro-faults, occasional channels and foreset beds, and the orientation of the penecontemporaneous slumps and rare current-aligned features have been considered together to generate a picture of the Bear Gulch basin, its shape and flow regime (Fig. 3).

Where the uppermost layers of the Bear Gulch Limestone can be found, they are characterized by littoral and supralittoral lithologies of stromatolites, mudcracks, disrupted beds, chert beds and nodules, dolomitic nodules, and local terrestrial plant material. These are overlain in places by a 1-3 m thick conglomerate consisting of Bear Gulch clasts, and above this, by a fresh to brackish water marl in many places. To the west, the Bear Gulch Limestone thins to zero immediately south of Forest Grove, Mt., and is replaced by a zone of freshwater fish- and plant-bearing clays, shales, and a bed of dolomitic silts bearing the disrupted carcasses of large chondrichthyans, osteichthyans, and abundant acanthodians. Shortly west of this area, the lower beds of the Heath Formation contain zones with a marine upper Mississippian shelly fauna and rare vertebrate teeth and spines that have not been found within the Bear Gulch. Along its northern margin the

Bear Gulch rapidly grades into thin, dirty tan, poorly consolidated marine silts and shales. A few of the upper layers along the northern quarry sites contain considerable quantities of charcoal fragments, supporting the interpretation that these outcrops were very near shore and that charcoal blew in from on-shore fires to the north (similar conditions have been reported for the Devonian fish-bearing deposits of Miguasha, Quebec; H.-P. Schultze pers. comm. to R. L.).

The exposed eastern margin is characterized by series of complex structures. High-energy facies-fossils and associated bars flank foreset beds of a small prograding delta that indicate a principal outlet (the basin mouth) at the northeastern corner (Williams 1981). Less than 1 km to the southwest, the thickest part of the sequence is found. Both slope and current indicators demonstrate that on the west side of the bar the basin floor declines to the north. Channel and slope directions converge upon the bay opening from the southwest, west, and west-northwest. Dewatering faults further delineate a principal basin axis that extended, roughly northwest to southeast, for a minimum of 7 km. (The basin axis can be seen in section in the north wall of Atherton Gulch). Dense brachiopod, sponge, and annelid worm zones, and indications of a separate (presumably tidal) inlet are found along the southernmost aspect of this eastern margin. Articulated crinoid evidence in this area suggests that open water (i.e. stable marine) conditions existed in close proximity to the inlet. The remainder of the eastern Bear Gulch margin passes into the subsurface and many sedimentological features suggest there is no significant subsurface extension.

Basally, the Bear Gulch Limestone grades into irregularly bedded, often peloidal dark gray to black shales.

Facies: lithographic and biologic

The initial sedimentary depositional model of Williams (1981, 1983) defined four lithofacies; marly (upper beds), marginal, basin-slope, and basin facies. Subsequent field investigations have provided extensive biological and ecological data

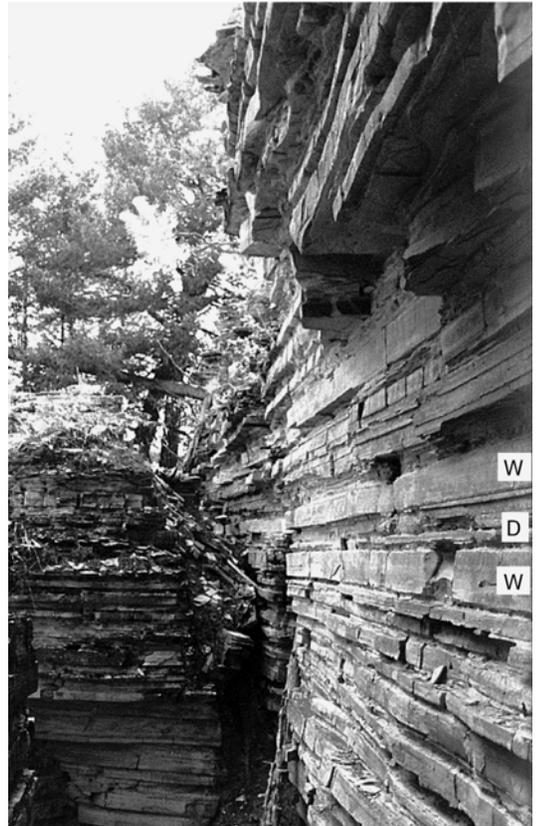


FIG. 5. — Outcrop of central basin facies, showing rhythmic alternation of dense and laminar beds. Abbreviations: **W**, wet season deposits; **D**, dry season deposits.

for inclusion in the model and so, require its refinement. We introduce three newly defined biofacies: 1) an *Arborispongia*-productid facies; 2) a filamentous algal facies; and 3) a shallow facies. Williams' marginal facies, central basin facies and the uppermost zones are redefined. The location and extent of these facies are illustrated (Fig. 3).

The central basin facies is characterized by the highest diversity of fish (Lund & Poplin 1999), by mobile and nektonic invertebrates, very limited amounts of algae (principally filamentous or narrow-fronded), and the nearly total absence of sessile benthic invertebrates. Fossil preservation in the central basin ranges from poor to superb. A rhythmic sedimentological unit in the central basin of the Bear Gulch Limestone consists of a

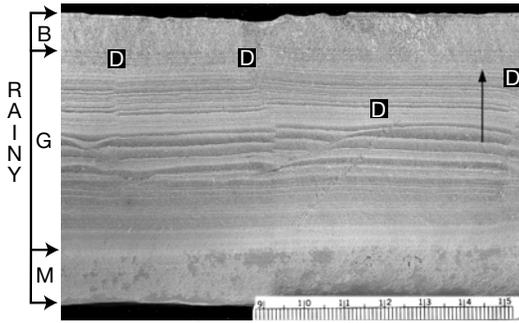


FIG. 6. — Rainy season component of central basin facies sedimentary unit. Polished section of beds from the central basin facies. Arrow indicates up; scale in cm. Abbreviations: **D**, dewatering fault; **B**, bioturbated zone; **G**, graded, laminar beds; **M**, massive non-graded bed.

dark gray, dense, poorly fissile to massive subunit and a light tan to yellow, laminar, fissile subunit. Organizationally, one complete sedimentological unit is comprised of a dense basal zone and a series of laminar beds (Fig. 5). The dense subunit consists of a thin basal zone, a zone of massive non-bedded to very irregularly bedded sediment, an upper zone containing several graded laminae, and not infrequently, a thin heavily bioturbated or unbedded uppermost zone (Fig. 6). The dense layer is succeeded by thin laminar beds of well-sorted sediments that vary from light gray below through tan to light yellow, and then to gray-brown at the base of the next dense bed. Organic drapes blanket individual graded beds, and very little scouring of underlying laminae is found. Williams (1983) speculated the massive beds might reflect periods in which turbidity currents flowed frequently, the laminae resulting from seasonal currents in a quieter period. We now extend her interpretation and propose that most of the dense subunits in the central basin facies are somewhat reminiscent of a Bouma sequence (as described by Kennett 1982), a deep-sea pattern of turbidite sedimentation.

An *Arborispongia*-productid facies occurs to the north of the central basin facies and along the eastern margin, as well as locally in the uppermost beds. It is characterized by dense stands of an arborescent sponge (*Arborispongia*) (Fig. 7E) frequently serving as the substrate for spiny artic-

ulate brachiopods, bivalve molluscs, and conulariids (Babcock & Feldman 1986). Many algal forms are evident. Of these, both calcareous and non-calcareous dasyclad algae are common, as well as an alga closely resembling the modern *Valonia* Agardh, 1823 (Fig. 7E, F, H). Diverse shrimp and worms, an unbranched species of *Sphenothallus* Hill, 1978 (Hill pers. comm. to R. L.), crinoids, branching bryozoans, and diverse fishes are also part of this habitat (Figs 7; 8). Sediments are predominantly light tan to light gray and laminar bedded, with some micro-turbidites. Preservation ranges from poor to excellent.

A filamentous algal facies lies south of the central basin facies. It is characterized by abundant algal filaments (Fig. 7H) accompanied by very small spiny productid brachiopods in all lithologies. A branched (colonial) species of *Sphenothallus* Hill, 1978 is also relatively common (Fig. 7G). Laminar to irregularly bedded sediments are tan to dark brown with the dense limestones being dark gray to black and very rich in organic material; lower in calcium carbonate and higher in terrigenous clastics than the rocks of the central basin facies. Graded microturbidites are less common than in the central basin facies, these are light gray in color and less rich in organic material. Preservation ranges from disturbed and dispersed skeletal elements to good, but specimens are predominantly less well preserved.

The marginal facies is characterized by black, irregularly bedded to occasionally laminar, bioturbated rocks in which original plant cuticle and the calcium carbonate of shells often remain. Sediments of the marginal facies are lower in calcium carbonate and particularly lower in micrite, and high in peloids and organic materials (Williams 1981). Vertebrates and shrimps are rarely preserved intact and when intact are usually disturbed; gastropods, which are very rare in other facies, are regularly present here. The acanthodian *Acanthodes lundii* Zedek, 1980, considered an indicator of brackish water conditions, is common in the western marginal beds. Large spiny productid brachiopods associated with concentrations of filamentous algae are most com-

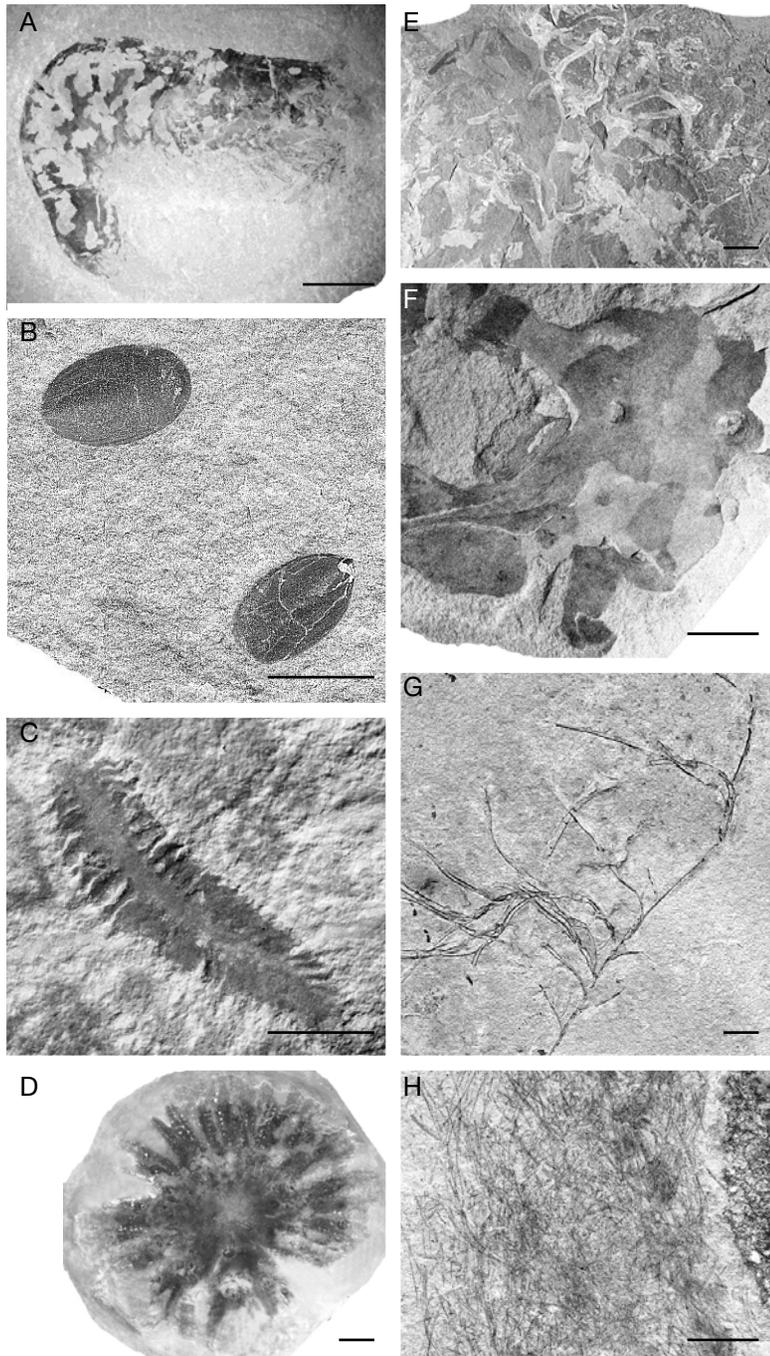


FIG. 7. — Invertebrate and algal fossils; **A**, *Aenigmocaris* Schram, 1979; **B**, lingula; **C**, segmented worm; **D**, *Lepidasterella* Welch, 1984; **E**, *Arborispongia* Rigby, 1985; **F**, sea-lettuce-like algae; **G**, *Sphenothallus* Hall, 1978; **H**, fine filamentous algae. All housed (currently uncatalogued) at the Royal Ontario Museum. Scale bars: 1 cm.

mon in the northern marginal facies and the *Arborispongia* facies.

The upper zone, or shallow facies of the Bear Gulch Limestone is characterized by whitish, tan to yellow beds, local relief surfaces with layers containing algal laminae and stromatolites, chert laminae and nodules, and star-shaped gypsiferous nodules in the softer laminated beds. Calcium carbonate may not be totally absent from skeletal materials. Cherts can imply fluvial silica in solution being precipitated upon contact with marine water, or shallow water solution and redeposition of biogenic silica from sponge spicules and diatoms (Williams 1981). Abundant *Arborispongia* communities, conulariids, large spiny productid and other articulate brachiopods, bivalved molluscs, stony bryozoans, some crinoids, and a branching species of *Sphenothallus* characterize the biota. Larval and juvenile fish as well as small shrimp are common. The upper facies is similar to the *Arborispongia* facies in faunal content and ecological significance but it is not localized to the eastern margin. The shallow facies caps the Bear Gulch lens across its much of its area of outcrop. It represents the final phase of shallowing and filling of the bay, starting from wider access to higher energy marine water and progressing to shoal conditions.

A limited variety of terrestrial leaves has been found in the uppermost zone, immediately below a conglomerate composed of Bear Gulch Limestone fragments and a superposed thick marl zone or marly facies. Ostracod shells have been found associated with the marl (Williams 1981). The conglomerate and marl are true intraformational deposits, manifesting the change in environment from that of the marine Bear Gulch lens to that of the terrestrial Cameron Creek Formation.

Sedimentological trends across the facies

A few gross, basin-wide sedimentological trends (first noted by Williams 1983, and further expanded by observations of subsequent field seasons) provide evidence of a dynamic link between the defined facies. There is a strong gradient from darker sediments with higher organic content

marginally to those with very low organic content in the central basin facies. There is a stability gradient of skeletal calcium carbonate; it ranges from being present (but altered) in the southern and western marginal facies to being totally absent in the central basin. Silts decrease relative to carbonates from the marginal to the central basin facies, as do peloids. Iron and manganese mineralization of vertebrate skeletal tissues is highest in the southeast, and decreases northward.

As noted above, there also is a significant trend in the distribution, nature, and sequence of micro-turbidites. In transects from the marginal to the central basin facies the rhythmically varying lithological units become divisible into more conspicuous subunits. Classical graded micro-turbidite laminae are concentrated in the central basin axis. The proportion of these beds to the lower, darker, more organic-rich, massively bedded rocks increases into the basin axis where they constitute the middle and lower portions of each central basin facies sedimentary unit. These data were especially significant to reconstructing the paleocirculation of the basin and the deposition of its sediments. They also provided insight into the means by which excellent fossil preservation could be achieved.

A BIOLOGICAL VIEW OF THE BEAR GULCH BASIN

The fauna of the Bear Gulch Limestone essentially contains marine fossils; fresh-water macro-fossils are extremely rare (Zidek 1980; Horner & Lund 1985). All biotic evidence points to a highly productive Paleozoic bay and a complex ecosystem.

Plant and fungal spores and acritarchs are found in the shallow water and marginal facies (Stucke pers. comm.). Algal filaments and large quantities of unidentified plant debris are observed in virtually every layer. Yet, there is some preferential localization among the different types of algae (apparently reflective of the hydrodynamic and nutrient regimes). Calcareous and non-calcareous dasyclad algae, and other undescribed attached algae, are most common in the *Arborispongia* facies to the north of the axis, while the abundant

filamentous algae are concentrated south of the axis. Worms, crustaceans, and cephalopods were abundant (Schram & Horner 1978; Schram 1979a, b; Factor & Feldmann 1985; Landman & Davis 1988). The fish fauna was diverse and the size distribution of recovered fish fossils is comparable to that of a small, shallow, modern bay (reviewed in Lund 1990). Preservation of the biofacies reveals life assemblages in place and, like the algae, demonstrates habitat selection for most of the sponge, invertebrate and vertebrate species (Lund *et al.* 1993; Lund & Poplin 1999). This includes fine scale habitat selection between ecomorphologically similar or “sibling” species of actinopterygians (Staropoli 1993) and species- or life stage-based patchiness among select resident fish (Lund 1990; Lund *et al.* 1993). A large component of migratory, vagrant, and opportunistic, fish species (Lund 1990) is also indicated. Collectively, these features are consistent with that of a productive modern marine or estuarine bay, particularly one with seasonal characteristics. Unlike today’s marine or estuarine bays, however, there is no appreciable evidence that any sessile benthic invertebrate actually lived on the sediment in the central basin facies. Small spiny productid brachiopods are commonly found in the filamentous algal facies, the large ones accompany filamentous algae and *Arborispongia*. Diverse other sessile invertebrates are often found attached to *Arborispongia* but have also been found attached to cephalopod shells and, in one instance, to a submerged log which was preserved in the central basin facies. Some contribute to flotsam assemblages (McRoberts & Stanley 1989) analogous to the modern *Sargassum* Agardh, 1820 assemblages but based on filamentous or fronded algae rather than seaweed. We find it also significant that several invertebrate faunal elements typical of the upper Mississippian are conspicuously absent or have extremely localized occurrences. These benthic forms include corals, attached echinoderms, foraminifera, ostracods, and stony bryozoans. Yet the central basin and adjacent environments were not necessarily inhospitable, for bottom- and burrow-dwelling fish have been routinely identi-

fied. These data suggest to us that unfavorable turbidity conditions may have been responsible for such a selective distribution.

PRESERVATION OF THE FAUNA

We have noted a correlation between animal size and the quality of preservation for the fishes of the Bear Gulch. The well-preserved fish are strongly skewed toward the smaller sizes (up to 150 mm). Well-preserved intermediate-sized fish (200 mm to upwards of 1.5 m) are rare and, although tooth, spine, and scale/denticle evidence demonstrates they did exist, there are no intact fish above 1.5 m. Several factors may account for this correlation. Small microhabitat dwellers would be more susceptible to quick and complete burial while the larger and the migrant fishes may have selectively escaped killing events. In addition, the larger individuals that died in or near the bay are likely to have bloated and floated for an appreciable amount of time. This would permit their body parts to have been distributed over wide areas as decomposition, water transport, and scavenging occurred.

In fact, ample evidence of decomposition, predation, and scavenging does exist among the fossil remains. Yet, given the density/distribution of various fossils, we find it striking that other potential prey items such as worms and other soft-bodied invertebrates are often preserved as flawlessly as the small to intermediate-sized fish. It is even more intriguing to find exquisite preservation of fish heads or other incomplete fish remains that were obviously subject to some initial predation but for which the process was halted or interrupted. (It is virtually inconceivable to us that any organism’s remains, surrounded by diverse and abundant live shrimp, cephalopods, and fish, could lie undisturbed on the bottom of a bay). There are also instances of excellently preserved fish and shrimp extending through several laminae of the Bear Gulch Limestone or through up to 10 mm of rock. Yet, it is established that during the burial and fossilization processes the upper body surface commonly collapses down onto the lower surface for remains found in laminar layers (Elder 1985; Elder & Smith 1988). We can only

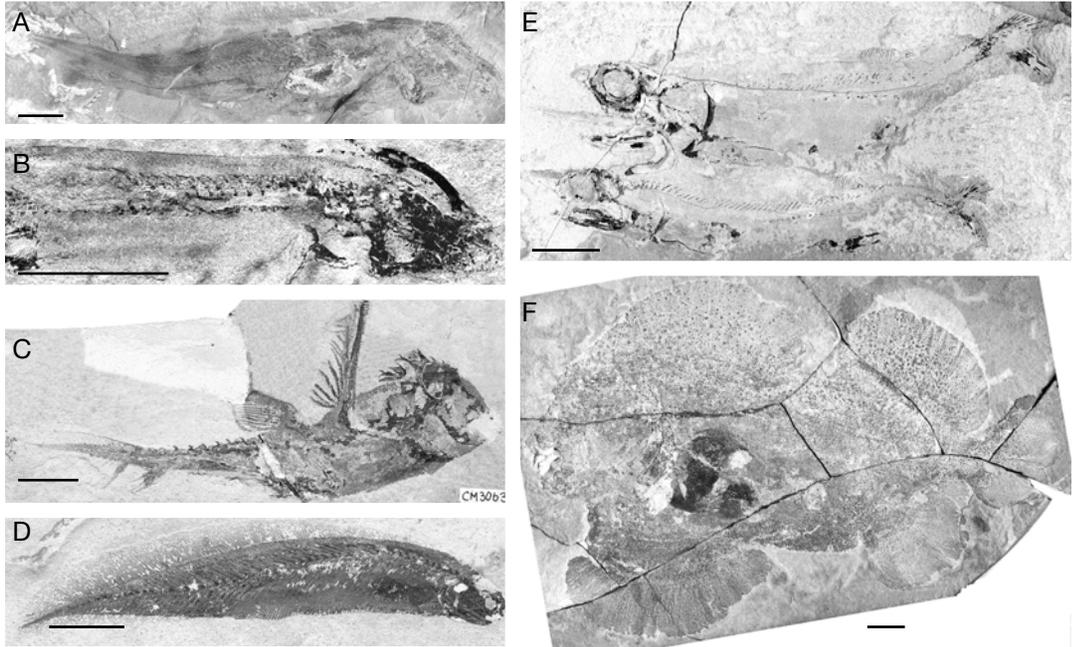


FIG. 8. — Examples of detailed fish preservation; **A**, *Debeerius ellefseni* Grogan & Lund, 2000 (ROM43173, holotype); **B**, *Harpagofututor volsellorhinus* Lund, 1982 (MV 7700); **C**, *Echinochimaera meltoni* Lund, 1977 (CM30630); **D**, *Paratarrasius hibbardi* Lund, 1982 (CM41070); **E**, *Falcatus falcatus* Lund, 1985 (MV 5385, 5386); **F**, *Belantsea montanensis* Lund, 1989 (MV7698, holotype). Scale bars: 2 cm.

envison that some episodic and dynamic burial process might account for these occurrences.

The central basin facies is a focal point in addressing this quandary of preservation. As stated earlier, the quality of preservation in the central basin facies can often be particularly extraordinary, as exemplified by the preservation of features of soft tissues (Grogan 1993; Grogan & Lund 1995, 1997) (Fig. 8). Skin outlines, skin pigmentation patterns and imprints of internal organs are recorded. The blood pigments from highly vascularized tissues such as livers, spleens, and gonads are preserved either as black colored areas or, in the case of livers, are occasionally evidenced as bituminous layers of measurable thickness. Liver pigment preservation seems to vary taxonomically and according to ecomorphology; a coelacanth (*Allenkyperus* Lund & Lund, 1985), select chondrichthyans (code name El Weirdo; *Echinochimaera meltoni* Lund, 1977; *Debeerius ellefseni* Grogan & Lund, 2000) and a paleoniscoid

(*Paratarrasius hibbardi* Lund & Melton, 1982) typically provide the best examples. Splenic tissue is frequently indicated in the chondrenchelyid, *Harpagofututor volsellorhinus* Lund, 1982 and in the petalodont *Netsepoye hawsii* Lund, 1989. Gonadal imprints have been observed in the lamprey, *Hardistiella montanensis* Janvier & Lund, 1983, and permit identification of reproductively mature *Harpagofututor* (Grogan & Lund, 1997) females. A bilobed internal organ and the presumed gut of the enigmatic protochordate *Typhloessus* Melton & Scott, 1973 (Scott 1973; Morris 1985, 1990) also preserve very well. In survey, these organisms are inferred to have different life history patterns (Lund 1990) and reflect organisms ranging from a benthic to sponge reef to migratory habitus.

The preservation of the fishes' venous circulation (rather than the entire vascular or arterial plan) is particularly intriguing, as these capacious, thin-walled structures would normally be most likely

to decompose on a time-scale of hours rather than days after death. The fine preservation of venous elements, as evidenced in the detailed structures of the gills, suggests mortality due to asphyxiation and rapid burial of the fish (Grogan & Lund 1995, 1997). It is also indicated by the observation of distended gills and raised operculums in paraselachian specimens, features that are diagnostic for asphyxiation in recent fish. Similarly, certain actinopterygian taxa and the chondrichthyans *Falcatus falcatus* Lund, 1985 and *Damocles serratus* Lund, 1986 are frequently found curled up, like watch springs. This observation cannot be simply attributed to *postmortem* rigor mortis. Such behavior has been observed for live specimens of the Recent catshark *Scyliorhinus capensis* Smith, 1838 (Compagno *et al.* 1989) and is correlated with the stressful physiological conditions that accompany asphyxiation (Grogan pers. obs.).

Field experience with and common knowledge of recent forms also demonstrates that these symptoms of asphyxiation are not elicited by salinity changes alone. Furthermore, other possible causes of asphyxiation may also be ruled out. For example, we do not find massive kill horizons as might be induced by a significant rise in water temperature. The oxidation of algal debris and organic matter could logically reduce the level of dissolved oxygen and promote an anoxic environment. Yet, the preservation of blood pigments (which requires the oxidation of hemoglobin or other oxygen sensitive molecule) would suggest that the bottom waters were not consistently anoxic. The finding of benthic inhabitants throughout the basin would also negate the idea of a persistently anoxic bottom.

Cumulatively, the biological data suggest that death by asphyxiation and burial were intricately linked. Coincident death and rapid burial is also implicated in the preservation of many invertebrates. The starfish are preserved in relaxed attitudes. Yet, like the worms, it is virtually impossible to kill starfish by simply covering them with sediment (Welch 1984) and burial alone does not solve the preservation quandary. A rise in water temperature would not kill them but

would merely put the starfish to sleep (by invoking reduced metabolic activity). Toxic algal blooms would however kill with no other trace of disturbance but would not ensure burial of the organisms without either predation or post-mortem degradation. Although there are no traces of significant fluvial input, if a sudden freshwater influx were involved it would principally float upon the denser marine waters and so, would have essentially no effect upon benthic organisms. Marked reductions in salinity alone cannot account for the preservational conditions either. Some factor or combination of factors had to both kill and bury the organisms quickly and, in the process hinder or prevent predation and microbial decay.

In summary, the biological data indicate that there was selective, high quality preservation of organisms, that the benthic habitat was not preferentially anoxic, and that there appear to have been repeated events that caused both death by asphyxiation and rapid burial. The evidence of these conditions is best recorded in the fossils of the basin facies, the sediments of which also reflect rhythmic changes (in terms of their nature, color, and thickness). To identify factors which may explain the above, we considered the dynamics of the physical environment (indications of water circulation, climate, sedimentation) and how they relate to the biological environment.

CLIMATOLOGY

GLOBAL AND REGIONAL PALEOGEOGRAPHY

Reconstruction of the paleoclimatic conditions and paleocirculation of the Bear Gulch bay is only feasible through comparison to modern studies of world climate and physical, chemical and biological oceanography. What follows is a model for the Bear Gulch based on these data and on fundamental tenets of physical oceanography.

Like the climate and circulation of today's land and water masses, those of the Paleozoic Bear Gulch bay environment would have been defined by the latitudinal position of the bay, its connection

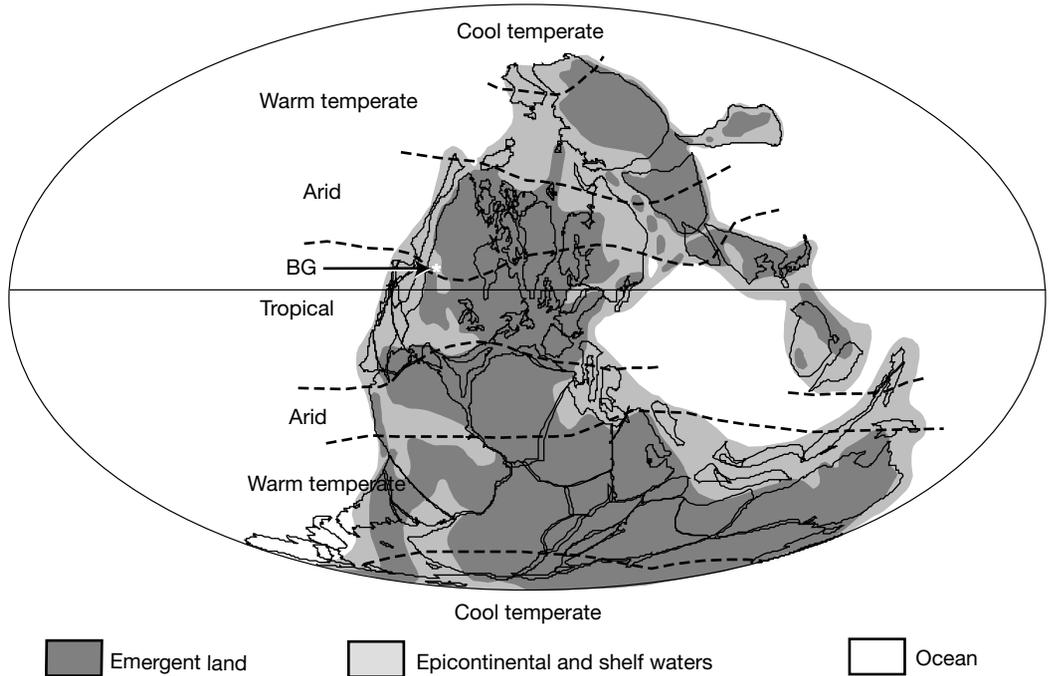


Fig. 9. — Paleogeographic and paleoclimate map of the Late Early Carboniferous (modified from C. R. Scotese, PALEOMAP Project, www.scotese.com). Arrow indicates position of the Bear Gulch deposit (BG).

to the shallow epicontinental sea, the configuration of the continental landmasses, and the influence of a falling Namurian sea level. Witzke (1990) and Scotese & McKerrow (1990) reconstruct the Viséan-Namurian North American continent as rotated approximately 35-40° clockwise relative to its present orientation, with the tectonic plate moving north. Geomagnetic data place Central Montana at about 10-12° north of the equator in upper Mississippian time and on or near the border between an arid climatic belt to the North and a tropical climatic belt to the South (Hidore & Oliver 1993; www.scotese.com; www.ucmp.berkeley.edu/geology) (Fig. 9).

ATMOSPHERIC AND CIRCULATORY CONDITIONS

The latitude at which the Bear Gulch bay existed 320 million years ago is most likely to have been impacted by shifts in the planetary scale Intertropical Convergence Zone (ITCZ) (Figs 9; 10) and characterized by a monsoonal-climatic

regime of rainy and dry seasons (Figs 11; 12). According to Blanchard (1997; webspinners.com/dlblanc/climate/climmods.html), a two Hadley cell atmospheric circulation plan prevailed and the general climate conditions would be classified as a wet cycle, with global rainfall expected to be in excess of 500 cm per year, nearly uniform temperatures across the surface of the earth, and winds ranging from a calm, steady 2-3 miles per hour (3-5 KPH) to storm conditions that are not expected to exceed 5 miles per hour (8 KPH).

Calm, dry/winter season

When the ITCZ was positioned closest to the paleo-equator the 10-12° latitudes would most likely to have been dominated by the dry winds of a winter season (Figs 9; 11A). Because this dry season would have represented an energetically quiet period, the influence of atmospheric or climatic conditions on bay circulation would have

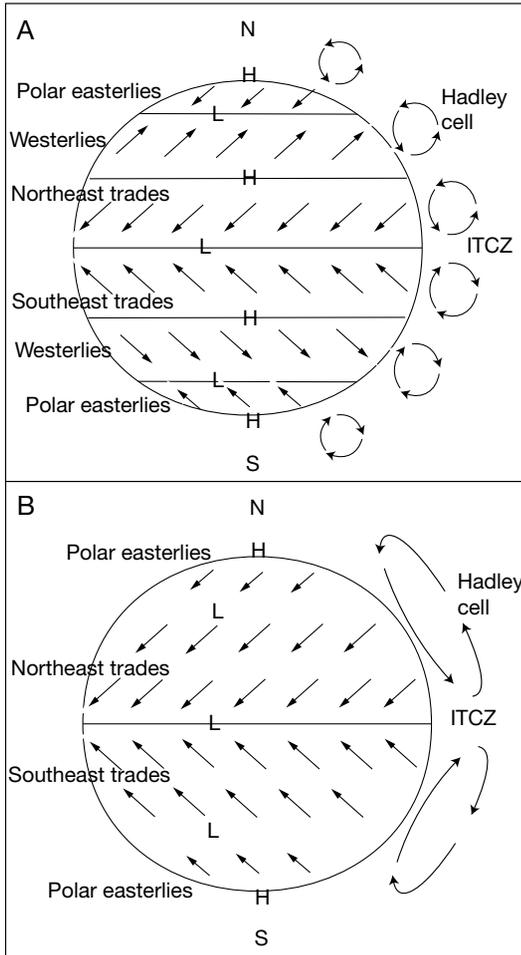


FIG. 10. — Atmospheric circulation patterns; **A**, six cell pattern prevailing today; **B**, two cell pattern predicted (Blanchard 1997) for the Late Paleozoic. The air flow pattern of the tropical Hadley cell follows the same general plan in each scenario. Cool, dry east to northeasterly winds would have been generated as tropical Hadley cell air subsided (at about 30° for the 6 cell model, towards the poles in the 2 cell model). These winds would have undergone adiabatic warming as surface flow continued toward the equator and contributed to desertification of the land under the central and more northern span of the Hadley cell. Closer to the equatorial region, however, increased evaporation and cloud cover would cause the easterlies to become more moist. With the seasonal migration of the ITCZ northward the lands previously subjected to arid conditions would become subject to warmer temperatures and increased rainfall. Arrows indicate direction of winds and atmospheric circulation. Abbreviations: **H**, high pressure; **ITCZ**, intertropical convergence zone; **L**, low pressure; **N**, North; **S**, South.

been limited to evaporative and tidal influences. The absence of significant river or freshwater channel input suggests bay circulation was princi-

pally driven by winds. Light easterly trade winds would have pushed epicontinental (Williston basin) sea-water into the bay mouth and generated anticlockwise flow in cross section as they blew transverse to the long axis of the Bear Gulch bay (Fig. 11A). Surface waters would have built up towards the paleo-western margin and edge of the central bay channel or trough. Geostrophic effects would force the flow of this water downward and across the bottom, to upwell at the paleo-eastern margin of the trough. The entrance of daily tidal and easterly wind-driven epicontinental seawaters would have afforded turnover or refreshment of these waters. Minimal rainfall and evaporative heating would have promoted some horizontal stratification of the water (particularly in the shallows of the western margin) and the extension of a bottom layer of seawater into the higher reaches of the central bay (Fig. 12A). Vertical mixing of water types would have occurred at density-different interfaces and would have been promoted by tidal forces.

Energy pulsed, wet/summer season

Progression from the winter season into spring and summer would have been defined by a northward shift in the ITCZ. As the ITCZ increasingly encroached upon the latitude of the Bear Gulch it would have introduced an increased probability of strong winds and precipitation in spring and into summer.

Winds would have become westerly to southwesterly and basin circulation would switch to a clockwise flow, with surface water downwelling near the eastern margin and bottom water upwelling on the western margin of the central bay trough (Fig. 11A). Under spring to early summer conditions the influx of terrigenous sediments would have been restricted to wind-driven transport and are likely to have accumulated in the shallow western bay margin. Reversal of geostrophic flow may have contributed to sedimentation in the channel and along the western slope. The relatively stronger westerly to southwesterly winds would have effectively increased the impact of geostrophic flow, inducing resuspension of any sediment which had built up along the eastern

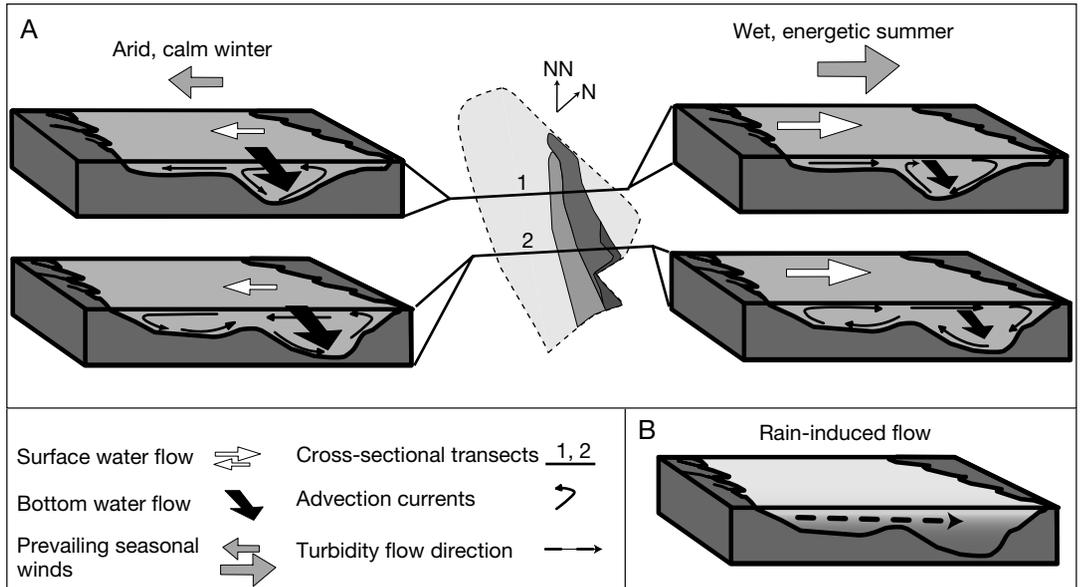


FIG. 11. — Reconstructed Namurian wind and flow conditions at two transects across the Bear Gulch bay; **A**, wind and geostrophic flow conditions at the specified cross-sections (1, 2) during arid, calm “winter” and wet, energetic “summer” seasons respectively. Relative magnitude of wind and flow indicated by arrow size; **B**, monsoonal-rain induced turbidity flow at transect 2. Shading reflects different densities of water masses. Abbreviation: **NN**, Namurian North.

channel margins during the winter and spring seasons.

Refreshment of the bay with epicontinental seawater would have been extremely restricted in this period compared to calm and dry (winter) period. This is because wind-driven waters would have principally entered from the southeast channel rather than the bay mouth proper and because wind direction would have counteracted the impact of daily tidal flow by reducing the forcing influence of the epicontinental sea. Therefore, salinity stratification would have become more oblique to nearly vertically oriented as evaporative loss continued and as the bottom layer of seawater was deterred from extending into the uppermost spans of the bay (Fig. 12B). Compared to the mouth of the bay, the shallow uppermost regions would also be most likely to have become susceptible to hypersaline conditions at all levels of the water column as seasonal temperatures increased. Only the most temperature resilient or burrowing components of the fauna (those normally protected by pore waters)

are expected to have inhabited the uppermost and shallowest extent of the bay during such conditions.

As summer progressed, disturbances of these conditions would have occurred with the onset of monsoonal winds and occasional torrential rainfall. Episodes of heavy rains would likely have generated an increased outflow of surface waters. They would also have provided some moderation of salinity differences in the uppermost section of the water column throughout the bay. In contrast, the shallow waters of the western margins and bay head would have experienced an extreme reduction in salinity at all depths.

Rapid rainfall would have introduced massive amounts of sediment into the bay from the vegetatively depauperate surrounding land as they contributed to mixing of marginal and headwaters. Downstream to these waters the deeper, warm, and hypersaline waters of the channel would persist and permit the sediment rich, rainfall-induced headwaters to flow over this layer and down the bay. This sediment-laden flow

would travel along the pycnocline (Fig. 11B) until its momentum matched that of the surrounding water and initiated its deposition.

The magnitude of seasonal shifts would be driven by the extent of ITCZ migration. So, during the estimated 1000 years that the bay existed it is also likely that conditions intermediate to those predicted in the scenario above also occurred. In the event that the annual flux was more moderate and the center of the ITCZ became localized at or around the latitude of the Bear Gulch the shift in climate would have been less dramatic. Just as in the horse latitudes of today, stable low velocity winds would have continued to flow from east to west during the summer and only occasional changes in atmospheric circulation would cause unstable weather in the form of squalls, windstorms and rainstorms.

JUSTIFICATION OF THE MODEL

Although any reconstruction of the paleoclimate and paleocirculation is potentially flawed by the lack of detailed, first hand evidence for the prevailing air and water conditions, we are confident of this model because it agrees with the preponderance of the geological, biological, and preservational data.

The microturbidites are key to our analysis. The microturbidites reported in most facies could have been generated by the resuspension of unconsolidated shoreward sediments by strong onshore winds, storms, and/or earthquakes before being transported to the area of deposition. Yet, we find these sources cannot adequately explain the deposition of the central basin facies. There are no current indicators in this facies; there is no preferred orientation of any fossils. Furthermore, little to no scouring of underlying microturbidite laminae or their organic drapes is identified in this facies. Thus, the sedimentary evidence agrees with deposition resulting from sediment-charged water being carried over a pycnocline, and having cascaded vertically to the bottom. Such a phenomenon, identified as a cascading or detached turbidity flow (Pierce 1976), is exactly the type of sedimentary pattern we expect during the wet monsoonal period.

Hypersaline bottom waters or a layer of fresh (rainwater runoff) water over denser saline water are known to produce the density-stratified water column necessary for the formation of a turbidity current of very fine particles and particle-organic aggregates (Pierce 1976). Our climatic model for the Bear Gulch environment accounts for hypersalinity and freshwater influx. In the transition to the wet season, all waters, but especially the shallowest, would be susceptible to higher salinities as the winds restricted tidal flow and warmer temperatures promoted increased evaporation. The oblique to nearly vertical stratification of relatively hypersaline waters would permit a rainwater-induced turbidity flow to extend down the bay (Figs 11; 12). Torrential monsoonal rains would produce a hyposaline upper water layer within which resuspended sediment and algal bloom-derived organics would flow, as sheetwash, out across the bay and over more saline layers. Some horizontal density stratification could have occurred during the dry season (because of the arid conditions) but under easterly to northeasterly winds, bay water would be routinely mixed with the epicontinental seawater forced into the bay. This tidal forcing would have ensured more vertical mixing and greater homogeneity throughout the bay waters.

The rhythmicity of the Bear Gulch lithology suggests that microturbidite deposition occurred regularly. The seasonal component of the model accounts for this periodicity and explains the subunit sequences noted for the central basin facies sedimentary unit (Figs 5; 6). The dense basal zone (whose pattern is reminiscent of the Bouma sequence divisions A, B, and D; Kennett 1982) would correspond to turbidity flow deposits during a wet season. The series of laminar beds would correspond to deposition during the arid season (approximating Bouma division E). The predicted pattern of winter and summer circulation is also in accord with all current-aligned and channel features and the wind-blown charcoal along the northeastern edge. Furthermore, inter- and intra-seasonal variation in the amount of wind forcing and rains (as determined by the extent of the ITCZ shift, for

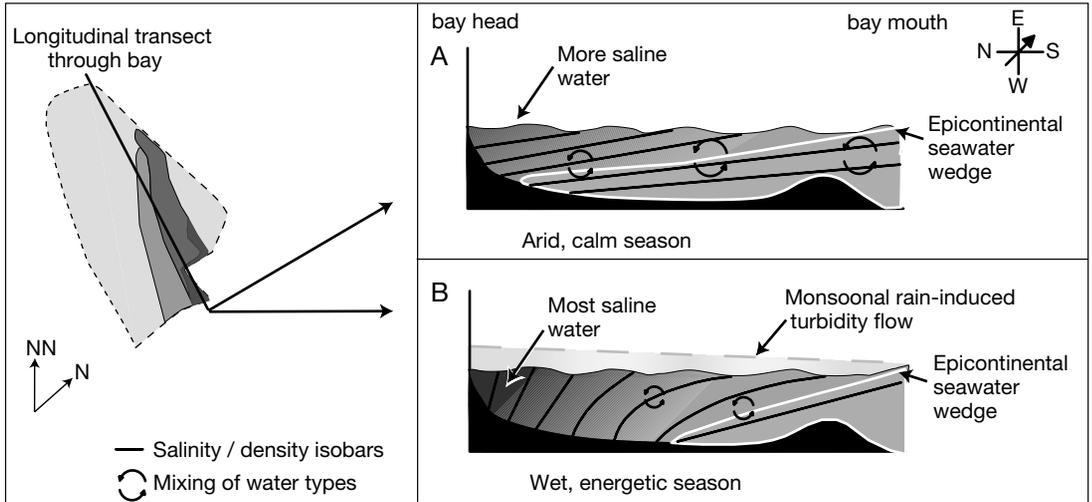


FIG. 12. — Reconstruction of bay waters and salinity regimes along a transect; **A**, general conditions favored during a calm, arid season; **B**, prevailing conditions favored at the early stage of an energetic, wet season and relative position of subsequent rain-induced turbidity flow. Salinity moderation of upper flow waters during turbidity flow not illustrated. Abbreviation: **NN**, Namurian North.

example) could easily account for the statistically inconsistent thicknesses reported (Feldman *et al.* 1994) for several repeating rhythmic subunits. Monsoon-induced resuspension of accumulated marginal sediments that contain high amounts of plant debris, algal mucus and organic compounds is consistent with the alternating (varve-like) organic-rich and organic-poor parts of each sedimentary unit and the quantities of organic sedimentary components needed to produce asphyxia. Bottom water layers would quickly become lethal as resuspended sediments and organics cascaded downward from the upper water column and absorbed the dissolved oxygen of the lower water column (Pierce 1976; Kennett 1982; Feldman *et al.* 1994). Within minutes the resultant combination of higher water temperature and oxygen depletion would generate lethal asphyxiating conditions for any living thing trapped in the lower water column. The descending sediment would immediately bury any trapped and/or killed organism. This scenario thereby accounts for the higher frequency of more detailed fossil preservation in the central basin facies compared to other facies. The conditions leading up to the microturbidite event may

also explain why the fauna of the shallow water is not entrained into the central basin depositional event. The predicted hypersalinity of the shallow marginal waters would preclude the possibility of washing occasional shallow water fauna/flora into the central basin because the biota of this area was probably restricted to burrowing components at best.

The predicted seasonal shifts in wind, rain, and sedimentary influx and their consequences on hydrodynamics sufficiently agree with other biological observations such as the localization of the *Arborispongia* communities in the more hydrodynamically active region (north of the central basin) and filamentous algal community in the less active waters (south of the central basin). As reviewed under our biological observations, the regularity of high turbidity conditions, the high rate of fine sediment deposition, and the seasonal cutoff of (epicontinental sea-derived) replenishing bottom water inflow could very well have prevented the establishment or long term survival of a sessile benthic biota in the central basin sediments. It should also be mentioned that episodic disruption of ecological conditions is strongly implicated in the maintenance of any high diversity ecosystem.

CONCLUSION

Stratigraphic data present the Bear Gulch Limestone as a small, narrow, shallow lens of limestone deposited in the narrow Central Montana Trough and surrounded by littoral and supralittoral sediments. Paleogeographical reconstructions locate the Bear Gulch Limestone at a latitude between 10° and 12° north of the Namurian equator and position the marine bay as having been oriented in a northwest to southeast direction. It is characterized by up to five facies; the *Arborispongia*-productid, filamentous algal, shallow, marginal, and central basin facies. The paleoclimate of this region would most probably have oscillated between semi-arid to arid and tropical conditions as the change of seasonal atmospheric circulation patterns shifted from a dry to monsoonal phase and *vice versa*.

The sedimentologic data present classical indicators of arid to semi-arid climatic conditions. The deposits of gypsum in the adjacent Heath Shale facies and of gypsum and chert nodules in shallow facies corroborate the interpretation of the regional paleoclimate. Gypsum in the shallow facies and along the paleo-eastern margin would reflect high rates of evaporation during the dry times and the terminal stages of filling in of the bay. The rhythmically recurring sedimentary layers, especially those of the central basin facies sedimentary unit, show alternation of dark organic-rich and light-colored laminar organic-poor subunits which, on a very large scale, resemble varve and sapropel deposits. Hydrologic and climatic analyses in concert with all sedimentologic data strongly suggest that microturbidites form the bulk of the dark organic-rich subunits and that these were principally generated during summer monsoonal storms. Torrential seasonal rains would have generated these microturbidites from sheetwash-eroded and resuspended, organic rich marginal sediments and carried them in a hyposaline upper water layer towards the central basin and bay mouth. Repeating events of cascading turbidity deposition during the monsoonal season account for microturbidite layers found atop scour-less

underlayers and the lack of any evidence for shoreward transport of fauna.

The paleontologic data from the Bear Gulch Limestone present a high-diversity marine vertebrate record. The invertebrate record is of low to moderate diversity, with highly localized occurrences and conspicuous absences among the more typical invertebrates of the upper Mississippian. There are virtually no terrestrial macrofossils or indicators of fluvial input, in spite of the narrowness of the Central Montana Trough and the proximity of the shores of the Bear Gulch bay. Had there been significant rainfall throughout the year, the shallow marginal and terrestrial environments would have provided the ideal locations to generate fluvial or terrestrial fossils. Persistent anoxia or hypoxia of the bottom waters or sediments is inconsistent with the ubiquitous benthic and burrowing fishes.

The preservation of the fishes and soft-bodied invertebrates of the Bear Gulch Limestone requires that death and burial were essentially simultaneous. Paleopathologic examination indicates asphyxia as the cause of death for several fish. The zone of best preservation is limited to the central basin, and all lines of evidence point to the deposition of organic-charged, cascading microturbidite flows as the agents of both death and immediate burial.

Seasonal variability in African Sahel-like climatic and wind conditions would have provided the essential atmospheric, hydrologic, sedimentary, and biologic conditions necessary to produce both the repetitive microturbidites and the detailed fossil preservation that characterize the Bear Gulch Limestone.

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REFERENCES

- BABCOCK L. E. & FELDMANN R. M. 1986. — Devonian and Mississippian conulariids of North America. Part B. *Paraconularia*, *Reticulaconularia*. New genus, and organisms rejected from *Conulariida*. *Annals of Carnegie Museum* 55: 411-479.
- BARTHEL K. W., SWINBURNE N. H. M. & MORRIS S. C. 1990. — *Solnhofen. A study in Mesozoic Paleontology*. Cambridge University Press, Cambridge, 236 p.
- BLANCHARD D. L. 1997. — Changing paleoclimates and mass extinctions. The climatic models. <http://webspinners.com/dlblanc/climate/climmods.html>.
- BRIGGS D. E. G. & GALL J. C. 1990. — The continuum in soft bodied biotas from transitional environments: a quantitative comparison of Triassic and Carboniferous Konservat-Lagerstätten. *Paleobiology* 16 (2): 204-218.
- COMPAGNO L. J. V., EBERT D. & SMALE M. 1989. — *Guide to the Sharks and Rays of Southern Africa*. Struik, Cape Town, SA., 163 p.
- ELDER R. 1985. — *Principles of Aquatic Taphonomy with Examples from the Fossil Record*. Unpublished Ph.D. dissertation, The University of Michigan, Ann Arbor, USA, 336 p.
- ELDER R. & SMITH G. 1988. — Fish taphonomy and environmental inference in paleolimnology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 62: 577-592.
- FACTOR D. & FELDMANN R. 1985. — Systematics and paleoecology of malacostracan arthropods in the Bear Gulch Limestone (Namurian) of Central Montana. *Annals of Carnegie Museum* 54: 319-356.
- FELDMAN H., LUND R., MAPLES C. & ARCHER A. 1994. — Origin of the Bear Gulch beds (Namurian, Montana, USA). *Geobios* M.S. 16: 283-291.
- GROGAN E. D. 1993. — *The Structure of the Holocephalan Head and the Relationships of the Chondrichthyes*. Ph.D. Thesis, Virginia Institute of Marine Sciences, College of William and Mary, Gloucester Point, Virginia, USA, 241 p.
- GROGAN E. D. & LUND R. 1995. — Pigment patterns, soft anatomy and relationships of Bear Gulch Chondrichthyes, in LELIÈVRE H., WENZ S., BLIECK A. & CLOUTIER R. (eds), *Premiers vertébrés et vertébrés inférieurs*. *Geobios* 19: 145-146.
- GROGAN E. D. & LUND R. 1997. — Soft tissue pigments of the Upper Mississippian chondrichthyan, *Harpagofututor volsellorhinus* (Chondrichthyes, Holocephali) from the Bear Gulch Limestone, Montana, USA. *Journal of Paleontology* 71: 337-342.
- HIDORE J. J. & OLIVER J. E. 1993. — *Climatology*. MacMillan, New York, 423 p.
- HORNER J. R. 1985. — The stratigraphic position of the Bear Gulch Limestone (Lower Carboniferous) of central Montana. *Compte Rendu, IX^e Congrès international de Stratigraphie et de Géologie du Carbonifère* 5: 427-436.
- HORNER J. R. & LUND R. 1985. — Biotic distribution and diversity in the Bear Gulch Limestone of central Montana. *Compte Rendu, IX^e Congrès international de Stratigraphie et de Géologie du Carbonifère* 5: 437-442.
- KENNETT J. 1982. — *Marine Geology*. Prentice-Hall, Englewood Cliffs, NJ, 813 p.
- LANDMAN N. H. & DAVIS R. A. 1988. — Jaw and crop preserved in an orthoconic nautiloid cephalopod from the Bear Gulch Limestone (Mississippian, Montana). *New Mexico Bureau of Mines and Mineral Resources Memoir* 44: 103-107.
- LUND R. 1990. — Chondrichthyan life history styles as revealed by the 320 million years old Mississippian of Montana. *Environmental Biology of Fishes* 27: 1-19.
- LUND R., FELDMAN H., LUND W. & MAPLES C. 1993. — The depositional environment of the Bear Gulch Limestone, Fergus County Montana. *Montana Geological Society Guidebook 1993, Energy and Mineral Resources of Central Montana*: 87-96.
- LUND R. & POPLIN C. 1999. — Fish diversity of the Bear Gulch Limestone, Namurian, Lower Carboniferous of Montana, USA. *Geobios* 32: 285-295.
- LUTZ-GARIHAN A. B. 1985. — Brachiopods from the Upper Mississippian Bear Gulch Limestone of Montana. *Compte Rendu, IX^e Congrès international de Stratigraphie et de Géologie du Carbonifère* 5: 457-467.

- McROBERTS C. A. & STANLEY G. D. 1989. — A unique bivalve-algae life assemblage from the Bear Gulch Limestone (Upper Mississippian) of central Montana. *Journal of Paleontology* 63: 582-603.
- MENNING M., BELKA Z., KULLMANN J., STOPPEL D. & WEYER D. 2000. — On the number of Carboniferous series and stages. *Newsletter on Carboniferous Stratigraphy* 18: 8-9.
- MORRIS S. C. 1985. — Conodontophorids or conodontophages? A review of the evidence on the “conodontochordates” of the Bear Gulch Limestone (Namurian) of Montana. *Compte Rendu, IX^e Congrès International de Stratigraphie et de Géologie du Carbonifère* 5: 473-480.
- MORRIS S. C. 1990. — *Typhloesus wellsi* (Melton and Scott, 1973), a bizarre metazoan from the Carboniferous of Montana, USA. *Philosophical Transactions of the Royal Society of London Series B*, 327: 595-624.
- NELSON W. J. 1993. — Structural Geology of the Cat Creek Anticline and related features, Central Montana. *Montana Bureau of Mines and Geology Memoir* 64: 1-44.
- PIERCE J. 1976. — Suspended sediment transport at the shelf break and over the outer margin, in STANLEY D. J. & SMITH D. J. P. (eds), *Marine Sediment Transport and Environmental Management*. Wiley, New York: 437-460.
- RILEY N. 2000. — New Project Group proposal: A GSSP close to the Visean/Namurian/ Serpukhovian boundary. *Newsletter on Carboniferous Stratigraphy of the IUGS Subcommittee on Carboniferous Stratigraphy* 18: 7.
- SCHRAM F. R. 1979a. — Limulines of the Mississippian Bear Gulch Limestone of Central Montana, USA. *Transactions of the San Diego Society of Natural History* 19: 67-74.
- SCHRAM F. R. 1979b. — Worms of the Mississippian Bear Gulch Limestone of Central Montana, USA. *Transactions of the San Diego Society of Natural History* 19: 107-120.
- SCHRAM F. R. & HORNER J. R. 1978. — Crustacea of the Mississippian Bear Gulch Limestone of Central Montana. *Journal of Paleontology* 52: 394-406.
- SCOTESE C. R. & MCKERROW W. S. 1990. — Revised world maps and introduction, in MCKERROW W. S. & SCOTESE C. R. (eds), *Palaeozoic palaeogeography and biogeography*. *Geological Society Memoirs* 12: 1-21.
- SCOTT H. C. 1973. — New Conodontochordata from the Bear Gulch Limestone (Namurian, Montana). *Publications of the Museum of Michigan State University, Paleontology Series* 1: 81-100.
- STAROPOLI J. 1993. — *On the Relationship between Morphology, Form, Function, Ecology and Time: A Case Study from the Paleozoic of Montana*. Westinghouse Science National Finals Project, Waldorf School, Garden City, N.Y., USA, 19 p.
- WELCH J. R. 1984. — The asteroid, *Lepidasterella montanensis* n. sp., from the Upper Mississippian Bear Gulch Limestone of Montana. *Journal of Paleontology* 58: 843-851.
- WILLIAMS L. A. 1981. — *The Sedimentational History of the Bear Gulch Limestone (Middle Carboniferous, Central Montana)*. Ph.D. dissertation, Princeton University, Princeton, New Jersey, USA, 242 p.
- WILLIAMS L. A. 1983. — Deposition of the Bear Gulch Limestone: A Carboniferous Plattenkalk from Central Montana. *Sedimentology* 30: 843-860.
- WITZKE B. J. 1990. — Palaeoclimatic constraints for Palaeozoic Palaeolatitudes of Laurentia and Euramerica, in MCKERROW W. S. & SCOTESE C. R. (eds), *Palaeozoic palaeogeography and biogeography*. *Geological Society Memoirs* 12: 57-73.
- ZIDEK J. 1980. — *Acanthodes lundi*, new species (Acanthodii) and associated coprolites from uppermost Mississippian Heath Formation of Central Montana. *Annals of Carnegie Museum* 49: 49-78.

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