Description of the 'square objects' of the Bear Gulch Limestone, Montana, USA

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Abstract:
The 'square objects' are a group of unidentified soft bodied invertebrate fossils that have yet to be assigned to any taxon. These fossils occur in a 300 million year old limestone lens within the Heath Formation known as the Bear Gulch Limestone. The objectives of this study were to characterize the morphometrics of the square objects and to identify any distinguishing structural and/or geochemical features that might suggest a taxonomic affinity for at least some of these objects. Morphometric data collected on the fossils included length along the long axis, width, degree of circularity, and roughness, Photographic techniques, including polarized lighting stacking and Reflectance Transformation Imaging (RTI), were employed to enhance the visualization of distinct morphological features. Based on the collected morphometric data, fossils were separated into six distinct categories; the majority of the 158 fossils examined were characterized as "gumdrop" shaped. The photographic imaging provided insights into the three-dimensional nature of some of the fossils and elucidated some detailed anatomical structures that were not visible under simple light microcopy. Geochemical techniques (Raman spectroscopy, micro XRF, environmental SEM) were also employed in efforts to identify any unique geochemical signatures within the square objects. The results of these analyses indicate that certain elements appear to be more concentrated within certain square objects but are not definitive. Based on the morphological and geochemical evidence, several "square object" fossils have been tentatively identified as having affinities to the cnidarians, tunicates, and sponges but more definitive work still remains to be done.

Introduction:
The Bear Gulch Limestone is a lens of the Heath Formation (Upper Mississippian, Chesterian age) that outcrops in Montana and North Dakota (Cox 1986); it is most well-known for its well-preserved shark fossils (Lund and Poplin 1999). The limestone lens ranges from 15 to 30 m thick and extends up to 15 km laterally (Feldman et al. 1994). The beds are a plattenkalk deposit comprised of a fine-grained, non-bioturbated carbonate mudstone believed to be deposited within a stratified water column within a marine embayment (Williams 1983; Feldman et al. 1994). The whole Bear Gulch unit is fairly homogeneous with laminations being its most distinct feature. The laminations are thought to have been produced by rapid deposition from a cloud of suspended sediment (Feldman et al. 1994, Lund and Poplin 1999).

At the time of deposition, the embayment was located at 10°-12°N latitude, on the boundary between tropical and arid environments (Grogan and Lund 2002). The bay was connected to an epicontinental seaway along its northeast side (Lund and Poplin 1999; Grogan and Lund 2002).

The climate of the bay was monsoonal with a dry winter season and a wet, monsoonal summer (Grogan and Lund 2002). During the dry winter, winds were light and blew in an easterly direction, creating a counter-clockwise rotation of water throughout the water column and depositing sediments on the shallow shelf of the west coast. In the summer, winds increased and switched directions, blowing in a west-to-southwest direction. This reversed the movement of water in the bay, producing a clockwise flow. Sediment that had been deposited on the shelf during the winter was resuspended during the summer and redeposited in other parts of the bay. The increased runoff during the wet season also brought an influx of sediment into the bay, producing large accumulations of rapidly-deposited sediments (Grogan and Lund 2002). The bay's ecosystem is believed to have been both highly productive and highly complex and is thought to have persisted for ~1000 years (Grogan and Lund 2002). The monsoonal climate, the productivity of the water column, and the physical oceanography of the embayment combined to produce periodic stratification in the bay, resulting in hypoxic and anoxic conditions.

The high water column productivity and the rapid deposition of sediments during the summer months led to the fast burial and preservation of a great number of a wide-variety of specimens within the bay. Within some of these fossils, soft tissue details such as internal organs, skin details, and pigmentation are preserved; a significant number of soft-bodied organisms, marine algae, as well as ichnofossils, are also preserved in these deposits (Grogan and Lund 2002). Interestingly, almost all the fossils in the Bear Gulch deposit, no matter the taxon, are found as two-dimensional images on bedding plane surfaces and do not extend into the sediments. Soft-bodied animals from the Bear Gulch are preserved as dark or multi-colored organic films while some fossils contain small impressions suggesting that they are casts and molds of the original organism (Feldman et al. 1994).

One of the more numerous fossil types collected from the Bear Gulch are unidentified ones known simply as "square objects" These fossils, named because of the shape of the first ones that were found, are generally square or rectangular in shape. Many of these were initially believed to be tubular in shape but no definitive assignment was ever able to be given to these organisms. Square objects range in color from pale to deep brown and black with a mottled texture (Rosbach and Cuomo, personal observations). One study of square objects indicated that they appear to be composed on an amorphous carbon film (Thomas 2004). Despite these studies the Bear Gulch square objects remain an enigma to this day. The objectives of the present study were to collect morphometric data on a wide-variety of square objects from the Bear Gulch in an effort to characterize the variance within this group, to use photographic techniques in order to elucidate structural details that might assist with taxonomic assignment of the square objects and to collect geochemical data using a wide-variety of analytical techniques in order to ascertain whether or not any of the square objects possessed a unique geochemical signature that could be used in taxonomic identification by comparison with geochemical signatures of extant marine taxa.

Methods and Materials:

A total of 158 Bear Gulch square object fossils, on loan to the Yale Peabody Museum of Natural History's Invertebrate Paleontology Division from the Carnegie Museum and the Royal Ontario Museum, as well as from the personal collections of Dr. Carmela Cuomo, were examined for this study

Shape and Size:

All fossils were subjected to an initial visual inspection, followed by examination under light microscopy. From these inspections, each individual specimen was assigned to a shape category (gumdrop, circle, oval, rectangle, triangle or other). Individual fossils were then measured using a digital caliper; the measurements taken depended on the shape category assigned. Those in the "gumdrop" class had height and bottom width measurements taken. Some fossils within this group had small portions

Figure 1: Photos showing easurements taken for the circle and gumdrop shape categories.

of the bottom covered or broken off. In this case, the width measurement was taken as close to the bottom as possible in the portion of the fossil that was completely visible. For fossils classed as circles or ovals, the widest width across was taken. For all other groups, the maximum length and width measurements were taken, regardless of where in the fossil these occurred. Figure 1 illustrates how measurements were taken for two shape categories, the gumdrops and circles.

Stacked Photography:

Each fossil was photographed with a technique called stacking in which a series of photos are taken a set distance apart so that each photo is taken at a different elevation with the fossil in focus. For this study, each photo was taken 250 µm apart. The number of photos taken depended on the height of the fossil (difference between the highest and lowest point on the fossil). Those with a larger difference required more photographs. All photos taken for one fossil were then combined into a single image using the Horizon™ program. The resulting combined image displays every part of the fossil in focus and allows for morphological structures to be clearly seen.

Alcohol and Polarized Light Photography:

Another series of stacked photos were taken using a polarized lens and a thin layer of ethyl alcohol over the fossil, which brings out any chitin that may be in the fossils. Photos were taken 500 µm apart to prevent the alcohol from evaporating before the photos were complete. The stacks were then combined using the same Horizon™ program..

Figure 2: RTI in Digital Lab at Yale University West Campus

Reflectance Transformation Imaging (RTI)

RTI is a photographic technique that utilizes a 4.5' diameter dome fitted with 45 halogen lights distributed on 4 levels and fixed at specific angles (Figure 2). Images produced using RTI can be manipulated and viewed under the direction of light at different angles, which allows for different features to be seen. Photos are viewed using the program or as nearly 3D images in the program (shown in Figure 3). A total of 6 specimens were photographed with RTI. Manipulation of these images in RTI Viewer™ and MeshLab™ revealed structural details that were otherwise invisible to the eye.

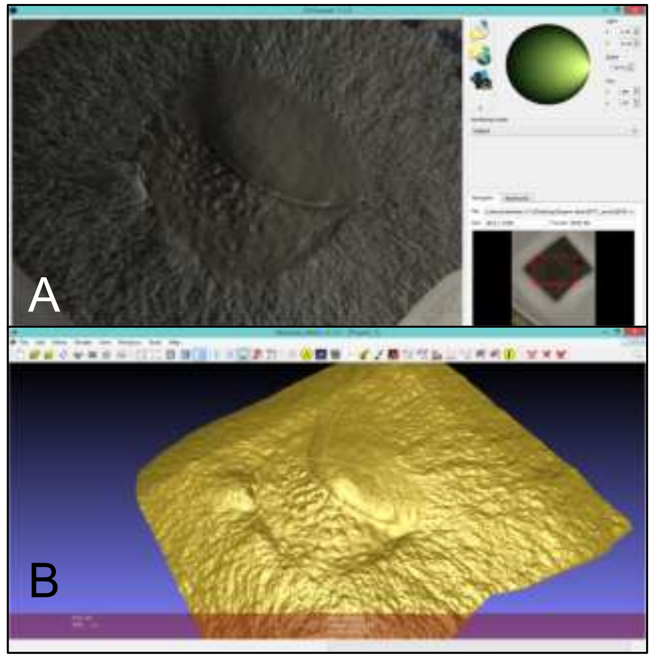

Figure 3: The fossil 'bob' in the programs RTIviewer™ (A) and MeshLab™ (B).

Results:

Shape and Size:

A total of 158 individual "square objects" were assigned to 6 different shape categories (gumdrop, circle, rectangle, oval, triangle and other). Fossils assigned to the "other" group were missing too much of the original fossil to determine the shape. The largest groups were gumdrops (82 individuals) and circles (16 individuals); all other groups had $\leq$ 5 specimens. A total of 10 specimens were assigned to the 'other' category but the unique shape of each specimen in this group prevented comparisons from being made with other "square objects". The distribution of sizes for gumdrops and circles are shown in Figure 4.

Photography:

The stacked photographs of the specimens provided a clear, focused image of each fossil that was used to look for more details. The polarized photographs showed no evidence of chitin in the fossils, but did emphasize other features within some specimens. Examples of each are shown in Figure 5.

The various renderings and lighting angles from RTIviewer and MeshLab files provided vital morphological information about very small details in the fossils that would not have been visible otherwise.

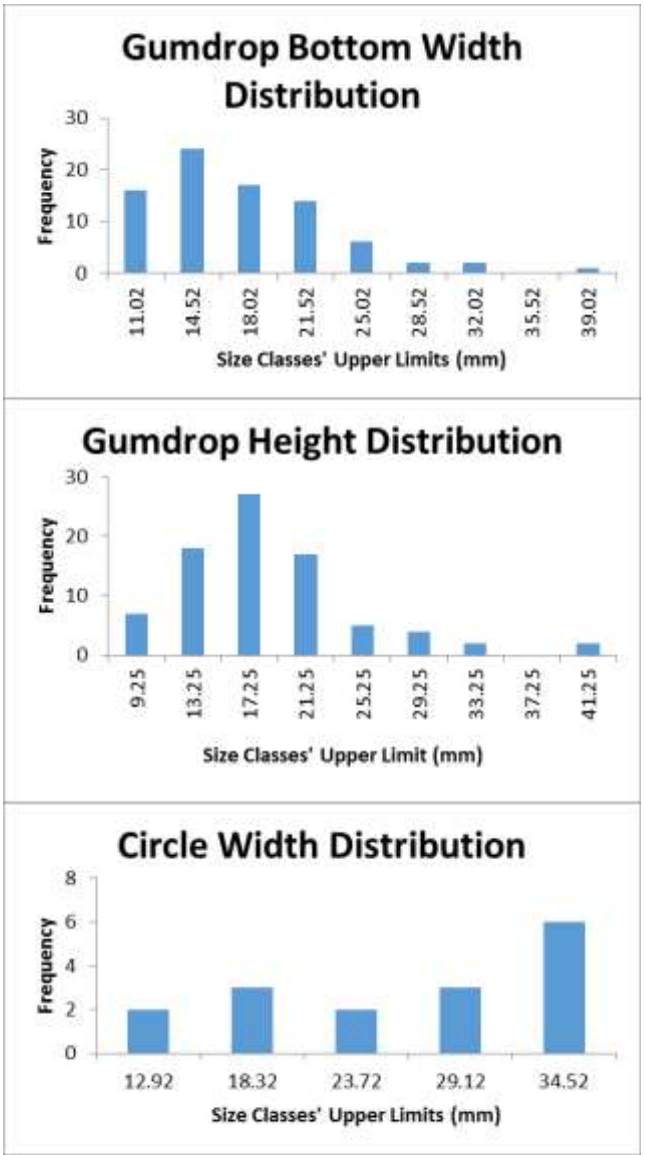

Figure 4: Size frequency distributions for two shape categories with the greatest number of individuals. The standard error for all measurements is ±0.01 mm.

Discussion:

The data collected in this study has brought to light two very important facts about the “square objects”. The first being that not all of the “square objects” are square; in fact, very few of them are actually square in shape. The majority of them possess a gumdrop shape, which is slightly flatter on the bottom with an arch shape on top (see Figure 1). The rest are a variety of shapes, none of which are actually a true square. The second fact is that “square objects” are the fossilized remains of animals belonging to more than one taxonomic group. Many “square objects” displayed unique characteristics (e.g. spicules, bumps, textures) that were not found in any other fossil. Thus, the fossils that have all been called “square objects” are actually a mixed grouping of several different fossil organisms that are difficult to distinguish from each other at first glance.

There was one exception – the fossils preserved on the two large slabs all exhibited similar features, including gumdrop shape, bumps, and a mottled red-brown texture. These fossils also resembled one individual fossil, referred to as “Bob” (shown in Figures 1, 3 5C and 5D) although Bob was preserved with more dimensionality that the fossils on the slabs. The morphological features of “Bob” as seem under light microscopy, stacked photography, and RTI combined with its geochemical signatures, have led to the assignation of “Bob” to the Cnidaria.

In particular, “Bob” appears to show features that resemble modern Rhizostome jellyfish and the fossils on the slabs appear to represent a mass stranding of these jellyfish. The overall shape of “Bob” and the fossils on the slabs are believed to represent the “bell” of the jellyfish; the bumps preserved very clearly on “Bob” , along with the appearance of several thick protrusions emerging from the bell, are thought to represent the tentacles characteristic of rhizostome jellyfish. “

Conclusions:

The enigmatic “square objects” of the Bear Gulch limestone represent a case of exceptional preservation of unknown soft-bodied forms in the fossil record. This study has demonstrated the utility of combining standard light microscopic techniques with modern photographic and geochemical techniques in order to derive data from such fossils that can then be utilized to assign them to taxonomic groupings. In particular, the morphological and geochemical information gathered in this study has narrowed down the assignment of possible taxonomic groups for the “square objects” to the following:. cnidarians, ctenophores, sponges, and tunicates. Research is ongoing on the Bear Gulch “square objects” as well as on similarly shaped organism from other exceptionally preserved localities.

Continuing Research:

Presently, Raman and other techniques are

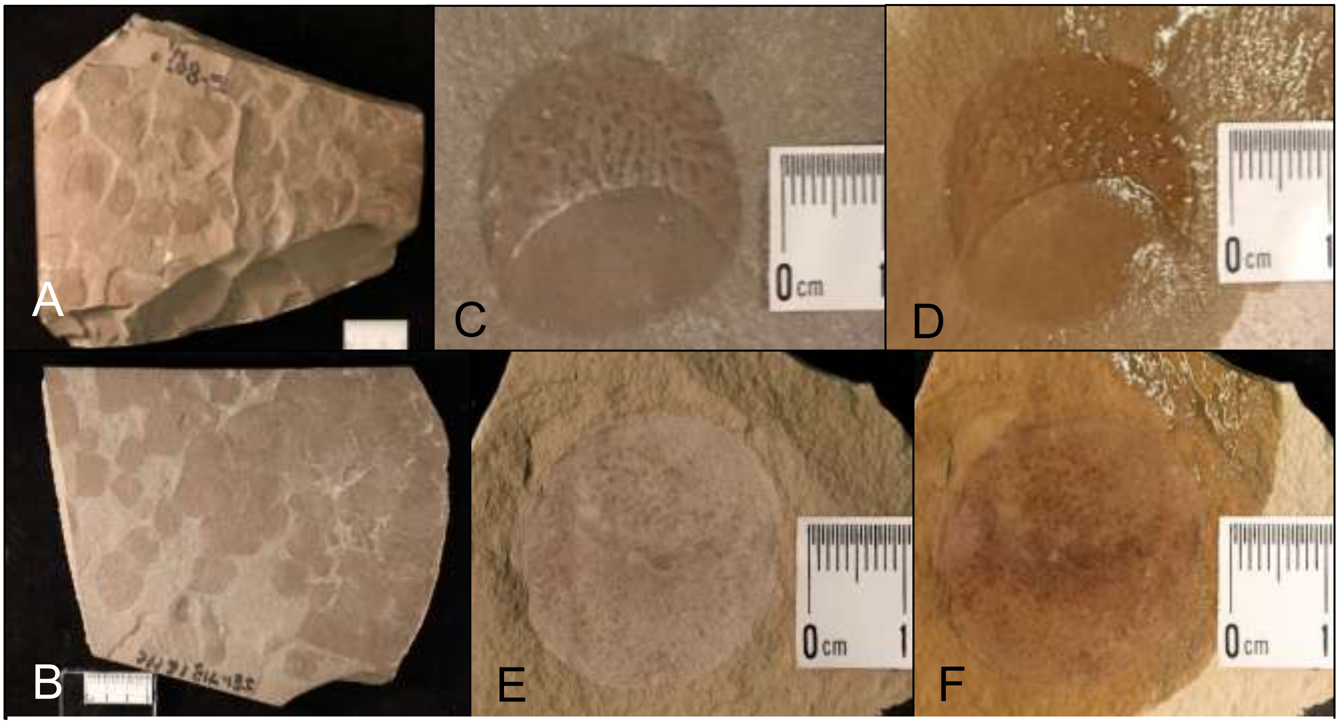

Figure 5: (A & B) Stacked photo of large slabs, (C) Dry, stacked image of fossil known as 'bob', (D) Stacked image taken with alcohol and polarized lens of 'bob', (E) Dry, stacked image of 'tina', and (F) Stacked image of 'tina' with alcohol and polarized lens.

being employed to further elucidate the chemical composition of each fossil relative to modern analogues. Experimental taphonomic studies are also being carried out to better understand the preservation potential of tunicates, ctenophores, and cnidarians. It is anticipated that such studies will shed light on these and other exceptionally-preserved soft-bodied fauna.

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Biography:

Stephanie Rosbach, a senior from Hallsville, Missouri is currently working towards a BS in marine biology and. environmental science. She works in Dr. Carmela Cuomo's lab on other paleontology-focused projects. In her spare time, she enjoys practicing ukulele and attending theatrical performances. After graduation, she is planning to pursue a Ph.D. in invertebrate paleontology