Taphonomy of Sediments: Bioturbation in the Triassic Moenkopi Formation in Southwestern Utah

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Taphonomy of Sediments: Bioturbation in the Triassic Moenkopi Formation in Southwestern Utah

by

James Vernon Bird Jr.

A Thesis submitted in partial satisfaction of the requirements for the degree
Master of Science in Geology

March 2016
Each person whose signature appears below certifies that this thesis in his/her opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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DEDICATION

To California Preparatory College for giving me the flexibility at work to allow me to investigate, learn and spend time in the outdoors I enjoy.
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ABSTRACT OF THE THESIS

Taphonomy of Sediments: Bioturbation in the Triassic Moenkopi Formation in Southwestern Utah

by

James Vernon Bird Jr.

Master of Science, Graduate Program in Geology
Loma Linda University, March 2016
Leonard Brand, PhD, Chairperson

Measurement of bioturbation reflects physical and biological processes operating over time and can be used to reveal information about paleo-environments. The purpose of this study was to determine the intensity of bioturbation in Triassic Moenkopi Formation at Hurricane Mesa in Southwestern Utah. This formation is interpreted as having been deposited mostly in large ancient river channels, tidal flats, delta and shallow marine environments. Five stratigraphic sections measured in the Virgin Limestone Member provided the basis for this study. Detailed descriptions and quantification of bioturbation were recorded in each of the sections. Similar treatment was given to additional study sites in the rest of the formation, above the Virgin Limestone. Treatments on selected samples were implemented to better reveal evidence of bioturbation. In these treatments samples were coated with water or oil, etched with HCL and viewed under blacklight. Integrating the results of the treatments with x-ray diffraction and petrographic analysis suggest that there was minimal bioturbation. These findings are consistent with more rapid deposition than previously reported by other researchers.
CHAPTER ONE
INTRODUCTION

A “subject that I have perhaps treated in foolish detail.”

- Charles Darwin, 1881 – on what is now referred to as bioturbation

Bioturbation studies ought to play a significant role in the study of sedimentary rocks, deposition rates and preservation of sedimentary structures. Bioturbation is a type of ecosystem engineering that involves the modification of geochemical gradients, sedimentary features and the redistribution of food and resources. Darwin, in his last scientific book *On the Formation of Vegetable Mounds through the Action of Worms with Observations on their Habits* (Darwin, 1881) covered the activity of rooting plants and burrowing animals such as worms. Today we know that bioturbation is not a topic of “small importance” as Darwin at first believed but one that plays a role in the fields of ecology, geomorphology, hydrology and even archeology (Feller et al., 2003). The study of burrowing organisms is now understood to affect nearly the entire surface of the earth (Meysman et al., 2006). In terrestrial as well as aquatic environments bioturbation by animals results from similar activities. A study of bioturbation along with other indicators such as stratigraphy, sedimentary structures and fossils can yield information useful in interpreting paleoenvironmental conditions and rates of deposition. It should be noted that it is recognized that sedimentation is the result of unsteady geomorphic processes (Sadler, 1981) and it is assumed that the stratigraphic record is incomplete. These assumptions lead researchers to conclude that some beds were completely removed by erosion while others remained. Although continuous deposition and erosion are assumed,
the rock record often does not show evidence of erosion (Peters, 2007). Peters suggests that lack of bioturbation is not solely the result of erosion, or “no one being home”, rather lack of bioturbation is often the result of a combination of these geomorphic and sedimentary processes.

Bioturbation is defined as the disturbance of sedimentary deposits by living organisms. It is the process of particle translocation vertically and/or laterally within near-surface unconsolidated sedimentary deposits by animals or plants (Balek, 2002; Bateman et al., 2007; Whitford & Kay, 1999). In both terrestrial and aquatic environments there are many potential sources of disturbance such as worms, gophers, moles, bivalves, gastropods and crustaceans. These organisms bioturbate sediments in the process of creating burrows, mounds and tunnels. This nearly ceaseless movement of sediment modifies substrate as tunnels collapse and burrows are back filled. Though the activity of bioturbators is continuous it is mostly limited to the uppermost layers. Hence, bioturbation is most intensive within a meter or so of the surface. It appears that the primary control on bioturbation depends on how long sediments remain in the upper 1-2 m and the depth of sediment deposited in any single event (Bateman et al., 2007).

Bioturbation in modern sediments, particularly by animals including infaunal organisms has been documented to be very effective at reworking sediments while building new pedogenic structures and destroying others. Garkaklis et al. (2004) found that the small, less than 1 kg, marsupial Bettongia penicillata of Australia can dig up to 100, 15 cm deep holes per night and can displace over 4 tons of sediment annually. Intensely burrowed modern sediments are usually interpreted to indicate low sedimentation rates (Howard, 1975; Nara, 2002).
Mermillod-Blondin (2011) discusses five functional groups of bioturbators in soft-bottom sediments; 1) biodiffusors, organisms whose activities result in random sediment mixing on the surface; 2) upward conveyors and 3) downward conveyors, characterized by organisms whose feeding activities (ingestions and egestion) move sediment vertically; 4) regenerators, digging organisms that leave open burrows that fill with newer sediments when abandoned; and 5) gallery-diffusors which are organisms that build extensive galleries of burrows that are irrigated by biotic activities. However in barren units with unaltered sediments it may be assumed that colonizers either were not present or could not adjust to the changes in sea floor as might be expected from modern environments where new burrows are made during quiet periods (Nara, 2002). It is not clear whether the five functional groups identified by Blondin were present, or were absent or rare during the entire lower to middle Triassic at Hurricane Mesa. If the record of those five functional groups was not preserved, perhaps sedimentation rates or environmental conditions played a more important role than is currently recognized.

**Objectives**

The overall goal of this research is to quantify bioturbation in the Triassic Moenkopi formation at Hurricane Mesa, Utah. Quantification of the bioturbation found in the sedimentary record provides insight to understand the paleoenvironmental impact on burrowing organisms. This is accomplished through the identification of bioturbation through study of exposed sedimentary surfaces of sediment samples. The application of different surface treatments such as water, oil, blacklight and acid etch on samples may help reveal obscured bioturbation features.
References


CHAPTER TWO

GEOLOGY AND BIOTURBATION OF THE MOENKOPI FORMATION

Introduction

Sedimentary taphonomy is the study of factors that influence how sedimentary features are or are not preserved. Preserved sedimentary structures such as cross bedding, graded beds, ripple marks, or burrowing by organisms are commonly found throughout the geologic column. These features were part of the sediments when they were first deposited prior to lithification. Bioturbation produces biogenic sedimentary structures that involve the mixing, reworking and displacement of sediments by organisms (Stow, 2012). Sediment layers are bioturbated when plant roots penetrate into the ground and when organisms such as worms, bivalves and gastropods burrow to carry on their normal daily functions. Prominent examples of bioturbation are invertebrate organisms such as Callianassa shrimp or bivalves that live in the sediments (Bromley, 1990). In this process the original bedding and sedimentary structures may be destroyed.

This paper reports a study of bioturbation in the Moenkopi Formation in Southwestern Utah. The Moenkopi Formation is a widespread formation found on the Colorado Plateau of the western United States. The formation is found in six western states of the United States including Arizona, Colorado, California, Nevada, New Mexico and Utah (McKee, 1954). It is underlain by Permian age rocks making the Moenkopi Formation the basal Triassic formation. It is overlain unconformably by the Late Triassic Chinle Formation (Cadigan, 1971).
Geologic Setting

L.F. Ward in his study of the *Geology of the Little Colorado Valley* (1901) seems to have been the first to name and describe the Moenkopi Formation. It was originally called “Moenkopie” for a section of reddish-brown siltstone and sandstone he identified near the junction of the Moenkopi Wash and Little Colorado River in north-central Arizona (Blakey, 1974).

Later the term was incorrectly applied to sediments in Utah and it wasn’t until 1918 that W.B. Emery used the term to describe the sediment now known as the Moenkopi Formation. McKee’s (1954) study focusing on the northern Arizona portion of the Moenkopi Formation was the first comprehensive study of the formation. Work on the area was continued by Richard Blakey (1974) who presented detailed facies analysis and proposed depositional environments of the Moenkopi Formation in southeastern Utah. Reeside and Bassler (1922) investigated the Moenkopi Formation in southwestern Utah and identified six units. In ascending order they are: Timpoweap Member (formerly Rock Canyon Conglomeratic Member), Lower Red Beds, Virgin Limestone Member, Middle Red Beds, Shnabkaib Shale Member and the Upper Red Beds (Stewart et al., 1972).

While there now are many recognized members of the Moenkopi Formation, none extend throughout the entire depositional area (Fig. 1). In the area around Virgin, UT at Hurricane Mesa, five members of the formation are observed. In ascending order these are: the Lower Red Member, Virgin Limestone Member, Middle Red Member, Shnabkaib Member and Upper Red Member. In the west near St. George, Utah, Moenkopi deposits are thicker and gradually thin out towards the east as indicated in Figure 1 (Stewart et al., 1972).
Near Virgin, Utah at Hurricane Mesa a roadcut exposes almost all of the Moenkopi Formation (Figs. 2 & 3) which may be the best exposure of Moenkopi available. It has been suggested that during much of the Triassic the area was covered by a shallow epeiric sea which submersed what is now western Utah and parts of Nevada (McKee, 1954). The western portion of the Moenkopi Formation found near Hurricane Mesa contains ripple-laminated siltstone that is interpreted as having been deposited in part on tidal flats or in a shallow sea (Stewart et al., 1972). The Moenkopi preserves deposits that seem to include ancient tidal and shallow marine shelf deposits, evidence of the Early Triassic seaway. As such, some portions of the formation may be comparable to the shallow marine shelf off the coast of Florida or the bank margins of the Bahama Banks. Other depositional environments associated with the Moenkopi include large ancient river channels and deltas. The multitude of depositional environments transition from continental deposits in the east to more marine deposits in the west (Wilson & Stewart, 1967; Stewart et al, 1972). A shallow aqueous environment is suggested by the occurrence of mud cracks, ripple marks and other sedimentary structures. There are also salt crystal casts in Moenkopi mudstones which are interpreted as the result of evaporation of sea water on tidal flats, further indicating a shallow marine environment in some parts of the Moenkopi (Bannister, 1998).

This study included the Virgin Limestone Member and those members above it. The Lower Red Member was not studied because of a lack of good exposure in this area. The Virgin Limestone Member of the Moenkopi Formation is a carbonate-siliciclastic deposit that varies in thickness from 50 to 300 m (Pruss & Bottjer, 2004). The Virgin Limestone Member at Hurricane Mesa near St. George, Utah, is made up of layers of
light to dark claystone, shale, siltstone and bioturbated sandstone which is believed to have been deposited during a marine incursion. It is overlain by the Middle Red Member, which is made up of layers of reddish brown claystone with abundant secondary gypsum veins and siltstone. The Middle Red Member transitions into the Shnabkaib Member and is capped by the Upper Red Member which marks the surface contact with the Shinarump Conglomerate of the Chinle Formation (Fig. 2). The member that came to be known as the Virgin Limestone Member was first described in detail by David White who proposed the name while serving as Chief Geologist of the U.S. Geological Survey in 1921 (White, 1921).

The Moenkopi is bound both above and below by unconformities. It is separated from the Permian Kaibab Limestone by a basal unconformity. The Kaibab limestone is believed to have been deposited by warm advancing shallow sea waters. The marine deposition of the Kaibab is evidenced by its limestone composition in addition to shark teeth, mollusks, brachiopods, corals and ichnofossils (McKee, 1938; McKinney, 1983; Fillmore, 2000).

The upper contact is marked by an unconformity followed by the upper Triassic Shinarump Conglomerate. The Shinarump Conglomerate is a bed that typically ranges from 14 to 29 meters thick with a maximum thickness in some areas of 100 meters. It stretches over nearly 260,000 square kilometers (Dubiel, 1994; Stokes, 1950). The Shinarump is believed to have been deposited by numerous braided stream systems whose constant movement across a relatively flat surface resulted in a thick veneer-like conglomeritic sandstone.
The work of organisms on sediment produces changes that accumulate over time. The continuous reworking and processing of sediments leads to a modified substrate since the process of bioturbation is destructive to sedimentary features. Burrows may be categorized by function or structure. Burrows are produced by organisms for the functions of protection, concealment, respiration, suspension feeding, deposit feeding, detritus feeding, gardening, predation, reproduction and to escape trauma (Bromley, 1990). Whatever the type of burrowing, the reworking of the sediment leads to an increased likelihood that the sediment is processed and altered after deposition resulting in more or less destruction of original sedimentary structures.

Recent research on bioturbation indicates that the mixture of marine sediments by organisms such as marine worms, bivalves, arthropods and echinoderms can occur within a short period of time (Froede, 2009). Over time the total reworking of the sediment in which burrowing organisms live is the norm along shallow marine shelves. In the case of the Grand Bahama Banks, the Callianassa Shrimp has been found to vertically mix sand to a depth of more than a meter (Bathhurst, 1975). In 1957, Ginsburg found that laminated sediment in an aquarium was completely obliterated by bioturbation within one month (Bathurst, 1975). A total reworking of modern sediment, such that bedding is obliterated has been observed by Imbrie and Buchanan (1965).

Bromley (1990, p. 201) states that “a totally bioturbated rock clearly provides evidence that the rate of biogenic reworking exceeded that of sedimentation.” Thus, sediments that are not totally bioturbated provide evidence that the rate of sedimentation exceeded that of biogenic reworking. Yet, many paleo-sediments are persistently bedded
(Sarkar & Chaudhuri, 1992) indicating that sedimentation rate may have exceeded rate of bioturbation, and/or the burrowing environment was stressful.

Sarkar and Chaudhuri (1992) suggest that slowly accreting, low stress environments with periodic breaks in deposition were most conducive to development of dwelling burrows. They found that burrowing organisms could not withstand high-stress environments that may be characterized by storms or when the rate of sedimentation exceeded the ability of the burrower to keep pace with vertical aggradation of sediments. Bathhurst (1975) cautions that any interpretation of ancient environments must be tempered since paleo-sediments are often not bioturbated to the same degree as modern sediments. However this must be evaluated carefully in an attempt to understand the degree of bioturbation and the reason for it.

Measurement of bioturbation intensity is an important key to reconstructing paleoenvironments. The intensity of bioturbation in one particular area reflects both physical and biological processes and can be used to meaningfully discuss accumulation rate, availability of oxygen and composition of the benthic community (Marenco & Bottjer, 2008). Bioturbated as well as unbioturbated sediments reveal important information about their paleoenvironment (Peters, 2007).

The time for deposition of the Moenkopi is believed to have been 10-15 million years. Such long periods of time generally are expected to result in bioturbation. Exceptions can occur when rapid sedimentation threatens the life of or kills the bioturbators. Also bioturbation can be incomplete as a result of lack of oxygenated water or high salinity or temperature (James & Dalrymple, 2010; Peters, 2007). Incomplete bioturbation implies that some stress factor prevented organisms or plants from
reworking sediments and destroying original bedding, or the sediments were deposited too rapidly for much bioturbation to occur (Bathurst, 1975; Sarkar & Chaudhuri, 1992).
**Fig. 1.** Formal and informal members of the Moenkopi Formation and related strata in the Colorado Plateau region (modified from Stewart et al., 1972).

**Fig. 2.** Members of the Moenkopi Formation and the Shinarump Conglomerate member of the Chinle Formation – From top to bottom; TRcs: Shinarump Conglomerate Member of the Chinle Formation TRmu: Upper Red Member (shoreline grading into fluvial [river]); TRms: Shnabkaib Member [shoreline/sabkha]; TRmm: Middle Red Member: (shoreline); TRmv: Virgin Limestone [marine]; TRml: Lower Red Member (shoreline).
CHAPTER THREE

METHODS

All of the field work for this project was completed during the months of June, 2012 and September, 2013. Five sections were investigated and measured in the Virgin Limestone Member along with nine additional sample sites next to the roadcut on Mesa Road at Hurricane Mesa, above the Virgin River Limestone Member and throughout the rest of the formation (Fig. 3).
Fig. 3. Map of the research area depicting sample sites at Hurricane Mesa roadcut. B, 1-5 designate the measured sections. R, 1-9 indicate sampling locations along the road cut above the Virgin Limestone Member.
Mapping and Choice of Study Sites

A preliminary study found that the Virgin Limestone Member had obvious bioturbation, but no evidence of bioturbation was found in the upper members. Because of this five sections were measured in the Virgin Limestone Member (Fig. 3). Each bed of the Virgin Limestone Member was measured in five sections. These five sections were correlated and compared and samples were collected for further study.

Above the Virgin Limestone Member nine additional exposures were studied along the road cut throughout the Middle Red, Shnabkaib and Upper Red Member. The sample sites were chosen at topographic elevation increases of approximately 50 meters, where possible (Fig. 3). At each 50m vertical interval the exact study site was chosen on the basis of quality of outcrop exposure and lack of cover, including slumping. All sections are georeferenced using the WGS84 datum used for GPS locations (See Fig. 3).

Two site number prefixes were used during this field study:

1) B – prefix indicates samples taken from the Virgin Limestone Member (Fig. 4).
2) R – prefix for measurements and samples taken along the roadcut above the Virgin Limestone Member.
Fig. 4. Sites were labeled with a sequence of letters and numbers. The letter (B) indicates that the section was in the Virgin Limestone Member and the number corresponds to the measured section. Beds were labeled using letters A-I which indicate beds from the base through the top of a section. For example in section B5B corresponds to the second bed from the base in the fifth section measured in the Virgin Limestone member.
Sampling and Analysis

At each outcrop site field descriptions of lithologies, including grain size and sedimentary structures were taken along with intensity of bioturbation, GPS locations and collection of samples. At the five measured sections, the lower, middle and upper portions of each portion of each bed of the Virgin Limestone Member was examined over a lateral area of approximately five meters. In total, one hundred samples were collected from representative lithologies; seventy-one samples were collected from the five measured sections in the Virgin Limestone Member and twenty-nine throughout the roadcut which included samples from the Middle-Red, Shnabkaib and Upper Red Members. Each of the one hundred collected samples were treated by several process to determine if burrows were present that could not be detected in untreated samples. These treatments included slabbing, wetting treatment, viewing under blacklight, etching with 10% hydrochloric acid and wetting with mineral oil.

Sediment samples were also examined by x-ray diffraction to determine mineral composition. Petrographic and textural analyses of thin sections were done on fifteen selected samples. Features including grain size, grain maturity and minerals present were recorded. Thin sections were also examined under the dissection microscope for bioturbation not visible at the outcrop. Two thin sections were selected and analyzed with 150 point count using the Petrog Analysis program to texturally and compositionally classify the samples (Fig. 12). They were chosen because they were silicilastic rocks representative of the siltstones and sandstones with grain size coarser than clay or mud.
Intensity of Bioturbation

Since the qualitative nature of bioturbation descriptions allows for marked variability, it is important that an investigator choose a bioturbation intensity scale that allows for objective evaluation. In this study vertical ichnofabric index/bioturbation intensity was evaluated using the scale developed by Droser and Bottjer (1986) modified by Brand where vertical exposures are on a scale of 1-4 based on the intensity of bioturbation and the degree of disruption in the primary bedding (Fig. 5).
Fig. 5. Key to ichnofabric index (bioturbation intensity) used for study (modified from Droser and Bottjer, 1986) to determine intensity of bioturbation observed in Moenkopi Formation sediments at Hurricane Mesa. An intensity of 1 indicates that there was little to no bioturbation with laminations and sedimentary structures easily identifiable; 2, bioturbation is easily visible however laminations and sedimentary structures are largely intact; 3, bioturbation intensity has mostly obliterated traces of laminations and original sedimentary structures; 4, all traces of original laminations and sedimentary structures have been obliterated. A bed with a bioturbation intensity of 4 could have a boundary within it that is not detectable.
The score of 1 includes no bioturbation to little bioturbation because in field observations it does not seem realistic to claim that there was actually no bioturbation. If more bedding plane surface was visible there could be more bioturbation, but we can observe that there has been little or no disturbance of sediment laminations. If the bedding was completely bioturbated it was scored as 4 (Figure 6A-D). This bioturbation index was based on the Droser and Bottjer bioturbation intensity index as opposed to Taylor and Goldring’s (1993) ichnofabric index method because the Droser and Bottjer index utilizes illustrations which allow for more efficient field analysis.
Fig. 6. Field observation of the intensity of bioturbation on the different layers of the Moenkopi Formation at Hurricane Mesa. A. Bioturbation intensity of 1. B and C (water used to reveal bioturbation). Bioturbation intensity of 2. D. Bioturbation intensity of 3.
Sample Treatments for Enhancing Bioturbation

The following techniques were used to determine if they would expose burrows not visible in untreated and un-polished samples. Slabs were treated with water, black light, HCL and oil. Thin section analysis was also used to look for bioturbation at the microscopic level.

If the condition of the sample permitted, it was cut. Friable samples considered valuable for analysis were first embedded in plaster so that they could be slabbed. Treatment with water included cleaning the surfaces of each cut sample so that identification of intensity of bioturbation using other treatments would be more readily identifiable. After treatment with water, prepared surfaces were observed under black light. Then samples were immersed in 10% HCL for twenty seconds in a glass pan to etch their surfaces. For the final treatment, mineral oil was applied to cut surfaces before bioturbation was scored. Pictures were taken for each treatment (Fig. 7).

Bioturbation intensity averages found in tables 1 & 2 were derived by adding the bioturbation intensity of individual samples from each outcrop and dividing the total bioturbation intensity by the number of samples that were treated from the entire outcrop. For example the average of bioturbation intensity observed in samples from outcrop B1 was 1.2 while the average observed after treatment with water was 1.35 (Table 1). Table 1 gives the average bioturbation intensity for each of the 5 measured sections. Table 2 gives a comparison of the intensity of bioturbation identified by each of the treatments of five selected samples.
Fig. 7A. B1D-1. Treated with water. B. B1D-1. Viewed under black light. C. B1D-1. Etched with 10% HCL for 20 seconds. D. B1D-1. Treated with oil.
X-Ray Diffraction Analysis

Samples were prepared for x-ray diffraction analysis by powdering in a marble mortar and pestle. After the samples were powdered (~10µm), identification of mineralogy of clay constituents was undertaken using a Siemens D-500 x-ray diffractometer (XRD). A total of thirty-one representative samples were analyzed from the five measured sections of the Virgin Limestone Member and nine roadcut sites from the roadcut at Hurricane Mesa.

Petrographic Analysis

A total of fifteen representative samples were selected and made into thin sections. All thin sections were made according to the same protocol, but thickness varied, depending on how well objects could be seen. The thin sections were analyzed using the petrographic microscope in the Earth and Biological Sciences Department of Loma Linda University. Petrographic analysis was completed using the 2013 Petrog Software to conduct point-count analysis, derive classifications along with producing textural and compositional classification plots (Figs. 14 & 15). The classification diagrams used to classify the thin sections was from Folk (1954).
CHAPTER FOUR

RESULTS

STRATIGRAPHY

The five measured sections of the Moenkopi Formation Virgin Limestone member at Hurricane Mesa are portrayed in Figure 8. All information is based on field, laboratory and petrographic examination of observed rocks. The five sections (Fig. 14) of the Virgin Limestone Member measured at Hurricane Mesa averaged ~20 m in thickness. This member is thought to have been deposited in a mixed carbonate siliciclastic paleoenvironment. The characteristic color of sediment found in the member at Hurricane Mesa was tannish/yellow for the sandstone marker beds (A,G & I) and brownish-purple for the claystone with some rarer grey and green claystone layers. In some sections, the outcrop was covered or poorly exposed possibly hiding some beds that were identified in other sections.
Fig. 8 Stratigraphic Sections in the Virgin Limestone Member, Moenkopi Formation, at Hurricane Mesa.
Working from left to right, the stratigraphic columns will be described from bottom to top and will include lithological description, sedimentary structures and evidence of bioturbation. The beds show a general pattern of alternation of sandstone and claystone/siltstone. The A bed ranges in thickness from 3.3 to 5.8 meters across the five sections and is mainly represented by siltstone as well as fine to very fine sandstone and calcareous sandstone with local clay lenses. The primary sedimentary structures observed were herringbone cross stratification, hummocky cross stratification and planar parallel laminations (Fig. 9a & b). Bioturbation was observed in various places throughout this bed. Above this bed there are sandstone lenses that pinch out, followed by the D bed that consists of a brownish-purple friable claystone layer that ranged in thickness from 1.8 to 7.5 meters with no observed sedimentary structures and no observed bioturbation. The next major bed was a very fine sandstone (G bed) and calcareous sandstone that displayed normal grading into siltstone and ranged in thickness from 1 to 2.2 m (Fig.9b). Evidence of bioturbation in observed mostly in the top 5 to 10 centimeters of this bed. The H bed overlies the G bed and is composed of brownish-purple claystone ranging in thickness from 3.85 to 5.24 meters with no observable evidence of bioturbation. The final I bed across the five sections is 1.3 to 1.7 meters of fine to very fine sandstone that transitions into calcareous siltstone with a bioturbation intensity varying between 1 and 2.
Fig. 9.  A. B5A – fine to very fine herringbone cross-stratified sandstone; this feature indicates shallow water current ripples possibly from tidal effects. B. B4D-B4G. From the bottom to the top, B4D (brownish purple claystone); B1E (very fine sandstone); B1F (medium gray claystone with lenses of silt) corresponding to deeper water; B1G (bioturbated sandstone to fossiliferous sandstone). C. B3A – Close-up of B3A (siltstone with hummocky cross-stratification) with evidence of possible mega ripples typically indicative of large storms.
Fig. 9. D.B2D and B2G - 6.16-7.2 meter thick layers of brownish-purple claystone. These are overlain by B2F (siltstone), not shown here.
**Bioturbation from Virgin Limestone Outcrops**

Bioturbation in layers of the Virgin Limestone Member occurred in three beds which were composed of fine to very fine sandstone or siltstone (Figure 8). Each of these three beds were identified in all measured sections. These three beds (A, G & I) were used as marker beds with the A unit in each section marking the basal bed of the Virgin Limestone Member and I bed marking the uppermost portion of each measured section. Besides the A, G, and I, other beds were also identified in each of the measured sections that showed bioturbation. For example, the C bed was identified in all sections except for B4 while the E layer was found in B5, B4 and B1 but not B3 or B2. No bioturbation was observed in beds with a primarily clay lithology.

The treatment that best displayed the intensity of bioturbation was HCl acid etch. Table 1 shows that while the observed intensity of bioturbation was low for all treatments, treatment with mineral oil and HCl best displayed bioturbation. It is likely that etching treatment was most revealing because the HCl was able to remove carbonates that precipitated as a secondary process exposing bioturbation. Oil was also found to be helpful in identifying bioturbation, black light and water had similar results and as expected an untreated sample was least effective in revealing bioturbation.
Table 1. Comparison of the different treatments to reveal bioturbation in Moenkopi samples from Hurricane Mesa. Numbers were derived by taking the average bioturbation intensity of each sample and dividing by the total number of samples that were treated from that layer.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Textural Classification</th>
<th>Untreated</th>
<th>Water</th>
<th>Oil</th>
<th>Etch</th>
<th>Black Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Claystone - Very Fine Sandstone</td>
<td>1.20</td>
<td>1.35</td>
<td>1.66</td>
<td>2.00</td>
<td>1.37</td>
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<tr>
<td>B2</td>
<td>Claystone - Fine Sandstone</td>
<td>1.20</td>
<td>1.14</td>
<td>1.00</td>
<td>2.00</td>
<td>1.36</td>
</tr>
<tr>
<td>B3</td>
<td>Claystone – Very Fine Sandstone</td>
<td>1.22</td>
<td>1.22</td>
<td>1.67</td>
<td>1.80</td>
<td>1.11</td>
</tr>
<tr>
<td>B4</td>
<td>Claystone Very Fine Sandstone</td>
<td>1.29</td>
<td>1.46</td>
<td>1.43</td>
<td>1.83</td>
<td>1.31</td>
</tr>
<tr>
<td>B5</td>
<td>Claystone – Fine Sandstone</td>
<td>1.13</td>
<td>1.25</td>
<td>1.67</td>
<td>1.67</td>
<td>1.18</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td>1.21</td>
<td>1.28</td>
<td>1.49</td>
<td>1.86</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 2. B1 - Twenty-two samples from section B1 were treated to evaluate if the treatments enhanced the visibility of bioturbation. The observed intensity of bioturbation for all B1 samples was 1.41. This matches the observed bioturbation in other sections as well. Overall bioturbation was relatively consistent, regardless of the treatment method used.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Textural Classification</th>
<th>Untreated Samples</th>
<th>Water</th>
<th>Oil</th>
<th>Etch</th>
<th>Black Light</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>B1D-1</td>
<td>Fine Siltstone</td>
<td>2</td>
<td>2</td>
<td>3</td>
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<td>2.4</td>
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<tr>
<td>B1I-2</td>
<td>Fine Siltstone</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>B2G-1</td>
<td>Medium Siltstone</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>B3G-1</td>
<td>Coarse Siltstone</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>B4G-1</td>
<td>Very Fine Sandstone</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>B5G-2</td>
<td>Fine Siltstone</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td>1.33</td>
<td>1.50</td>
<td>1.83</td>
<td>2.40</td>
<td>1.33</td>
<td></td>
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</table>
There is a strong correlation between grain size and intensity of bioturbation found using the different treatment methods. For example claystone showed the lowest values when compared with siltstones and sandstones.

Figure 10. The ternary diagram shows the majority of samples had a larger grain size, ranging from silt to sand, and a mix thereof. Clay was found to be in a minority of samples. Furthermore, bioturbation intensity only reached the maximum of 3 in 8% of samples, an intensity of 2 was observed in 13% of samples, while the remaining 79% of samples showed relatively little bioturbation.
Middle Red Member

The Middle Red member of the Moenkopi at Hurricane Mesa fills the interval between the lower Virgin Limestone Member and the upper Shnabkaib Member. It is characterized by its red color and generally thin, fine-grained, stratified, mudstones and continuous undisturbed, laminated beds (BI-1) with veins of secondary gypsum in the lower portion of the Upper Red Member which corresponds with R1 and R2 of this study. Crosscutting veins of gypsum were present throughout the lower and middle portions of the Middle Red Member through the R5 site (Fig. 10).
Fig. 10. Outcrop view of the R1 section made up of mudstone with gypsum veins. Acid treatment showed no evidence of carbonates or limestone.
The crosscutting veins of gypsum are generally about 0.5 cm thick and a white to off-white color. While some gypsum occurred as nodules along bedding planes the gypsum veins observed generally were not perpendicular to the bedding plane but instead were crosscutting at a forty-five degree angle indicating that they are diagenetic. Gypsum veins found in the Middle Red Member show cross-cutting relationships. The researchers found no primary gypsum.

**Shnabkaib Member**

The Shnabkaib Member of the Moenkopi located above the Middle Red Member was a lighter white to greenish grey color (Fig. 11a) made up of thinly laminated siltstone beds with pockets of clay and mudstones crosscut with gypsiferous sediments throughout and reddish-brown sediments higher in the member (Appendix A, Fig. 20b). This member corresponds to the R3, R4 and R5 sites of this study. Some possible teepee structures were identified (Fig. 11b). In this member it was difficult to determine the bioturbation though bedding seemed to be largely intact. The beds, when observable, were finely laminated with abundant secondary gypsum that was similar to gypsum found at R1. At R4 a one meter section seven meters across was investigated and no evidence of burrowing was found (BI-1). The gypsum found at R3 and R4 appears to have been emplaced after deposition. Located above the lighter colored sediments, reddish-brown mudstone interlayered with siltstone and fine grained sandstone was found (Fig. 11c). The siltstone and sandstone beds were crossbedded and no bioturbation was observed at R5 (BI-1).
Fig. 11. A. Lighter colored sediments of the Shnabkaib compared to the Middle Red Member. B. Possible teepee structures. Scale is 10cm. C. Interlayered beds of mudstone, siltstone and sandstone.
**Upper Red Member**

This member corresponded to the R6-R8 beds of this study and mostly consisted of interlayered mudstone, very fine to fine grained sandstone and siltstone (Fig. 12a). Upon closer examination, some places initially believed to be bioturbated were found to be mudcrack related structures. Very clear examples of crossbedding were found at the R6 stop (B1-1) (Fig. 12b). Greenish colored sediments collected at R7 were claystones with silty clay located below an erosion resistant laminated siltstone (Fig. 12c). Some of the finely grained orangish sediments found at R8 may be due to sulphur staining. In general there was an increase in silt with elevation at R8, with evidence of what appears to be soft sediment deformation (Fig. 12d).
Fig. 12. A. R-6. Characteristic reddish-brown sandstone and mudstone of the lower beds of the Upper Red Member. B. R-6. Interlayered mudstone, siltstone and sandstone. Scale = 10cm. C. R-7. Laminated claystone bed interlayered with lenses of silty clay. Scale = 10 cm.
Fig. 12. D. Possible soft sediment deformation in the lower claystone portion of the R-8 section.
X-Ray Diffraction Analysis

Once thin sections were made, each sample was X-rayed. Minerals were identified using one x-ray diffractometer trace presented as natural with water and air dried as opposed to solvation with ethylene glycol or heating (Brewster, 1980). The associated diffraction peaks have been interpreted according to Carroll (1970). The samples analyzed using the XRD were samples B1C-1, B5E-1, R2-3 and R3-2. The dominant minerals identified in B1C (sandstone) were quartz, anorthite and dolomite, in B5E-1 quartz, illite and clinohlore (Fig. 13). For the roadcut samples above the Virgin Limestone member in the Middle Red Member the major minerals identified were quartz, dolomite, phengite and secondary gypsum found in fractures. R3-2 was primarily composed of dolomite (89.3%).
Fig. 13 – Selected diffractograms from samples collected from bed and roadcut sites. B1C-1 the main minerals present in this sample are quartz, anorthite and dolomite. B5E-1 mostly made up of quartz, illite, clinochlore. R2-3 represented by gypsum, quartz and dolomite. R3-2 mainly dolomite with a low percentage of quartz.
Table 3. Samples from various sections were collected analyzed for bioturbation, in order to determine if mineralogy may have had some control in presence and degree of bioturbation. Samples B1C-1 and B5E-2 showed signs of bioturbation, however R2-3 and R3-2 did not show any signs of bioturbation. The only difference between the two transects are presence of clay minerals. All samples were categorized as an intensity of 1 because they either exhibited no bioturbation or minor amounts of bioturbation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Textural Classification</th>
<th>Dominant Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1C-1</td>
<td>Claystone - Very Fine Sandstone</td>
<td>Quartz 46% Anorthite 25.2% Dolomite 19.5%</td>
</tr>
<tr>
<td>B5E-2</td>
<td>Claystone-Fine Sandstone</td>
<td>Quartz 29.8% Illite 29.5% Halite</td>
</tr>
<tr>
<td>R2-3</td>
<td>Claystone – Very Fine Sandstone</td>
<td>Gypsum 28.8% Quartz 17.8% Dolomite 16.8%</td>
</tr>
<tr>
<td>R3-2</td>
<td>Wackestone</td>
<td>Dolomite 89.3% Quartz 10.7%</td>
</tr>
</tbody>
</table>
Petrographic Analysis

The samples collected at Hurricane Mesa were analyzed using thin section petrography in the labs at the Loma Linda University Department of Earth and Biological Sciences. A total of fifteen thin sections were analyzed from the five measured stratigraphic sections and nine roadcut transects. The results were plotted in ternary diagrams and summarized (Figs. 14 & 15). B5A-1 and B5I-1 were selected for analysis because they are siliciclastic rocks that are representative of Moenkopi siltstones and sandstones.

Petrographic analysis of B5A-1 indicates that it is nearly a quartzite made up of authigenic quartz grains, organics and porosity. Unlike the other A layers identified, B5A did not have dolomite in the matrix. Dolomite is often found in supersaturated saline environments. In contrast B5I-1 was composed of almost thirty-five percent detrital grains, forty percent matrix and twenty-four percent organics. This suggests these grains are remnants of living organisms.
Textural & Compositional Classification

Fig. 14. A. B5A-1. Thin Section – Point Count and compositional classification. B. B5I-1 Thin Section – Point Count and compositional classification.
Figure 15. B5A-1. classification according to Folk (1974). Folk classification shows that the majority of feldspathic minerals have been dissolved away, showing that the preserved sediment was re-worked over a long period of time.
The low intensity of bioturbation observed at Hurricane Mesa outcrops was confirmed by petrographic analysis. In some cases, bioturbation, biogenic and sedimentary structures that could not be identified in hand samples were identified in thin section (Figs. 17f, 18b). Thin section analysis confirmed field observations of no confirmed bioturbation, however evidence of soft sediment deformation, laminations, microfossils and possible bioturbation were observed. Laminations, microfossils and potential bioturbation were observed almost exclusively in very fine siltstone to fine sand. No evidence of bioturbation was observed in claystone.

In general petrographic analysis confirmed that there was more bioturbation in the beds of the Virgin Limestone Member as compared with the Middle Red, Shnabkaib and Upper Red Members (Figs. 16 & 17).
Fig. 16. A. B1A-1AP1. Folding due to soft sediment deformation. B. B1A-1AP2. Laminations with no identifiable bioturbation. C. B1D-1P2. Glauconite and fossil fragments.
Fig. 16. **D.** B1D-1P3. Organics surrounding calcite carbonate crystals where shell originally was. **E.** B4A-1P2. Representative photo of mostly continuous sandstone laminations observed. **F.** B4A-1P4. Illustration of possible bioturbation.
Fig. 17. A. R3-2P1. Laminations of silt (lighter) and clay (darker) with no identifiable bioturbation. B. R6-1P1. Representative picture of well laminated claystone, oxidized sediment with no bioturbation. C. R8-4P1. Micritic claystone with a fossil (possible gastropod
CHAPTER FIVE

DISCUSSION

The Moenkopi Formation is thought to represent depositional environments that include tidal and shallow marine environments that persisted for some period of time. Environments such as those found in even brackish or in estuarine modern environments can be expected to have a high level of bioturbation. The Virgin Limestone Member which crops out in Utah, Nevada and California was deposited during the Early Triassic and is believed to have been part of a transgressive marine tongue from the Panthalassa seaway to the west (Pruss & Bottjer, 2004; Blakey, 1974). The Virgin Limestone Member commonly has bioturbation, but at a very low intensity. In this study no evidence of bioturbation was found in the Moenkopi Formation above the Virgin Limestone Member. The obvious question is why is there so little bioturbation? Several factors have been suggested as possible explanations for little or no bioturbation in paleoenvironments in which more bioturbation can be expected.

This study does not deal with the particular ichnotaxa, or seek to classify and describe the type of burrowing observed. Rather, we are examining the occurrence and intensity of bioturbation in order to understand better the conditions that precluded bioturbation throughout the Virgin Limestone member.

There often is a significant difference observed between modern sedimentation and the results of ancient sedimentation. Several reasons have been posited for lack of bioturbation including rapid sedimentation that precludes organisms from establishing themselves in an environment, low levels of dissolved oxygen, hypersalinity in some cases, and low density of organisms.
One possible explanation for the low intensity of bioturbation observed is that the Moenkopi was deposited more rapidly than currently suggested by other researchers. Bateman et al. (2007) found that bioturbation is most intensive within the upper meter of the surface. They believe that the primary control on bioturbation is the length of time sediment remains within the upper 1-2 m. Time control on sediment remaining in the upper 1-2 meters of sediment can occur from relatively rapid sedimentation, or from relatively rapid environmental changes that lead to increased rates of deposition, or storm events. The evidence in this case may infer both. Observed clay lithologies have well-preserved fine laminations, suggesting little to no disturbance across the basin where we studied, which suggests relatively rapid rates of sedimentation that precluded bioturbation, which were interrupted by short-term storm events that transported fossiliferous silts and sands into the basin.

Another, supplemental, explanation for the lack of bioturbation observed in Moenkopi sediments is that there may have been a low dissolved oxygen concentration. Low oxygen levels, resulting in a hypoxic environment would have likely resulted in the exclusion of metazoans. In modern environments rapid deposition typically results in an oxygen-depleted environment that leads to the premature demise of the transported infaunal dwellers. However in our study evidence for storm processes are in the coarser sediments, where at least some bioturbation was present. Sediment with evidence of storm currents are not likely to be oxygen depleted.

Evidence for episodic sedimentation in the Moenkopi is supported by sedimentation patterns throughout the measured sections. Sedimentation patterns in the Virgin Limestone show repeated episodes of clay deposition being interrupted by coarser
beds of silt and fine sand. Often, these contain both sedimentary structures and fossils, which are characteristic of storm deposits. Storm events are inferred from the herring-bone cross stratification, coarse sediment, and unoriented conglomerations of fossils that are characteristic of the fossiliferous silts and sands.

One frequently observed sedimentary feature in the coarser sediments of the Moenkopi was hummocky cross-stratification. This feature usually forms during large storms below fair-weather wave base and above storm-weather wave base. Hummocky cross-stratification, present in the coarser units is used as an indicator of shallow marine environments on the shore face or at times on land when large storms deposit water onto tidal flats (Bannister 1998). Even if there was such a large storm and a bed was deposited, modern studies suggest that all evidence of the storm should be erased in a short time by bioturbation. In 1961 after Hurricane Carla hit the Texas coast depositing a bed of sediment it was bioturbated to the point that it was indistinguishable from lower sediment within twenty years (Dott, 1983). Such intense bioturbation was not found in the Moenkopi sediments.

While the Virgin Limestone member has fossils and burrows, they are limited to the non-clay lithologies. Clay lithologies show no observable bioturbation, even in thin section, are not calcareous, and the laminations in all thin sections observed are well-preserved. These criteria often are associated with deeper water below wave base. Interruptions in the clay lithology are thought to be storm events that have the energy to transport coarser grains into the basin. The coarser units also suggest that the clay depositional environments differed significantly from the origin of the coarser sediment, as abundant fossils are found in some units, while no fossils are found in the clay units.
It has been suggested that another possible reason for the low level of bioturbation in some Triassic sediments may be that the abundance of organisms was greatly reduced at the Permian mass extinction (Ausich & Bottjer, 1982, 2002). Pruss and Bottjer (2004), speculate that the low levels of deep bioturbation found in some Early Triassic environments is evidence that there was a return to Cambrian style substrates that may have been triggered by environmental stress of some sort. This explanation is made based on a comparison between end-Permian substrates with a pronounced mixed ground as compared with Early Triassic marine substrates which evidence a return to the low levels of vertical bioturbation that are typical of Cambrian substrates (Ausich & Bottjer, 2002). The density of organisms following the Permian extinction may have been low enough that evidence of bioturbation was not recorded or no bioturbation occurred.

The gypsum found in the Middle Red Member has been interpreted as representing a restricted sabkha like environment. The marine water along with a restricted environment and the increasing temperatures that are thought to have characterized the Triassic are believed to have resulted in ideal conditions for the precipitation of gypsum. Numerous researchers working in different parts of the Moenkopi have interpreted the presence of gypsum as evidence of an arid environment (Lambert, 1980; Bannister, 1998). However, this research was unable to corroborate those findings at our research area. At Hurricane Mesa, no evidence of primary gypsum was found; gypsum was only found in fractures. Furthermore, the alternation between sand, silt and clay indicate that it is unlikely that the paleo-environment at Hurricane Mesa was always a tidal flat.
Both the bedding and roadcut exposures of the Moenkopi Formation investigated along Mesa Road at Hurricane Mesa display little evidence of bioturbation. However research on depositional environments such as the Bahama Banks that are thought to correspond in some ways to the depositional environment found in southwestern Utah during the Triassic when the Moenkopi was deposited should be more bioturbated and display more biogenic features. At the time the Virgin Limestone Member of the Moenkopi Formation was deposited during the early to middle Spathian a major transgression deposited carbonate facies in what appears to be coastal and marine conditions. Much of Utah was located near the equator, which seems likely to have resulted in an environment more suitable to burrowing organisms (Mickelson et al., 2006). However, the transgressive sequence observed by other researchers, may suggest that basinward deposition was significantly different from landward deposition, which included significant biological contributions.

The low levels of bioturbation in the Moenkopi Formation in Southwestern Utah remain somewhat puzzling. Portions of the formation may have had low oxygen levels, inhibiting bioturbators, but this does not seem likely in the higher energy conditions during parts of the Virgin Limestone deposition. Second, both episodic and secular sedimentation rates suggest relatively rapid sedimentation in the basin that helped preclude colonization in the study area. There may have been other factors reducing the presence of bioturbators, but the nature of these factors remains uncertain.
Conclusions

The Moenkopi Formation at Hurricane Mesa in Utah exhibits remarkably little bioturbation. The minimal amount of bioturbation observed is unusual when compared with modern shallow marine environments such as the Bahama Banks. While many factors may have played a role in the lack of bioturbation observed, it is unlikely that all of those factors remained constant and continued to impact bioturbation during nearly the entire deposition of the Moenkopi. Rather, it seems likely that sedimentation rate exceeded bioturbation rate, or bioturbators were rare during this interval.
REFERENCES


Lambert, R. E. (1980). Shnabkaib Member of the Moenkopi Formation: Depositional Environment and Stratigraphy near Virgin, Washington County, Utah. (M.S.), Bringham Young University, Salt Lake City.


APPENDIX A

STRATIGRAPHIC

Detailed Description of Stratigraphic Sections

Section B5

The base of this section is 4.5m of fine to very fine calcareous sandstone (B5A) with parallel laminations (2mm) and herringbone cross-stratification (Figure 9) with a bioturbated layer 2.3m above the base. The entire 4.5m bed had a bioturbation intensity of 1. It is overlain by a 1.5m bed of grey claystone with a bioturbation intensity of 1 (B5B) and a 48cm bed of fine to very fine calcareous sandstone (B5C) displaying ripples scaled at a bioturbation intensity of 1 followed by a bed of 4.9m of brownish-purple claystone (B5D) (intensity 1). The next bed corresponds to very fine sandstone (B5E) and a bioturbation intensity of 1 with a thickness of 18cm which is overlain by a 1.43m grey claystone (B5F) with no observable bioturbation (intensity 1). Continuing upwards is 2.2m of alternating siltstone and very fine calcareous sandstone (B5G) with no observable bioturbation (Fig. 18). B5G exhibits both parallel and hummocky cross-stratification and is overlain by 5.3m of brownish-purple claystone (B5H) displaying a bioturbation intensity of 1. The top of this section is capped by 1.3m of bioturbated (average intensity 1.5) very fine sandstone (B5I).

Section B4

The base of this section is 5.8m of very fine light grey sandstone alternating with siltstone and lenses of clay before grading back into sandstone with lots of silt (B4A). B4A had parallel laminations lower and a bioturbated layer that was approximately two
eters above the base. Above the bioturbated layer, evidence of a change in water velocity is evidenced by an immediate transition from the bioturbated layer to a hummocky cross stratified layer before a sharp contact with planar laminations truncating the hummocky cross stratified lower portion. The upper portion is marked by a 4-5cm layer that is burrowed at an intensity of 3 before transitioning into planar laminations (2-4mm). The average intensity of bioturbation for all four samples collected at B4A is 1.5.

The B4A sandstone and siltstone is overlain by a 7.5m bed of brownish-purple claystone (B4D) with no observable bioturbation (Fig. 10). The next bed corresponds to very fine sandstone (B4E) with a thickness of 14cm with evidence of bioturbation (intensity 1) lower in the layer and displaying ripples. Above the layer exhibiting ripples is a 1.75m bed of grey claystone (B4F) with no observable bioturbation. Continuing upwards there is a 2.20m bed of very fine sandstone (B4G) which displays reverse grading from very fine to fine sand at the top of this layer (Fig. 19). Throughout this 2.2m bed very few vertical burrows were identified except for the uppermost 3-4cm. The top 3-4cm of B4G is marked by what appears to be the casts of numerous bivalves with evidence of tool marks and heavy bioturbation in some places (intensity 3) when moving laterally to the right towards the B3 Section. The average intensity of bioturbation of the samples collected from B4G was 2. B4G is overlain by 3.85m of grayish claystone (B4H) with no observable bioturbation. The top of this section is capped by 1.4m of bioturbated (intensity 2) very fine sandstone (B4I).

**Section B3**

The base of this section is 3.5m of siltstone with lenses of clay and mud between
siltstone layers (B3A). Possible storm deposit is evidenced by planar laminations abruptly transitioning into hummocky cross bedding on left of outcrop with rare (only 2 burrows) evidence of bioturbation (intensity 1) within a 50m lateral section (Fig. 11). It is overlain by 1.8m of brownish-purple claystone (B3B) with no observable bioturbation followed by 12cm of sandstone (B3C) displaying ripples but no bioturbation (intensity 1). The next bed is 6.1m of brownish-purple claystone (B3D) with no observable bioturbation followed by 1.5m of siltstone (B3G) with scattered horizontal burrows (intensity 1) that cover between 1-5% of the surface. B3G is overlain by 5m of brownish-purple claystone (B3H) with no observable bioturbation. The section is capped by a 1.2m layer of fine to very fine fossiliferous bioturbated sandstone which transitions into calcareous siltstone (B3I) with a bioturbation intensity of 1.5.

Section B1

The base of this section is 3.5m of finely laminated (1/2-1mm) very fine sandstone transitioning into very fine calcareous sandstone (B1A) with less than 1% clasts with very rare burrows along a 10-15m lateral section which transitioned from no laminations to laminated. B1A exhibits both planar laminations and hummocky cross stratification above the planar laminations. The average intensity of bioturbation for B1A was 1. It is overlain by a 1.4m bed of brownish-purple claystone (B1B) where a bivalve but no bioturbation (intensity 1) was found followed by a 30cm bed of fossiliferous (intensity 1) siltstone displaying ripples and a 5.83m bed of brownish-purple claystone (B1D) exhibiting no bioturbation (intensity 1). The next bed corresponds to a siltstone (B1E) with a thickness of 25cm (intensity 2) which is overlain by a 1.65m bed of grayish
claystone (B1F) with no observable bioturbation. Above BIF is observed a 1m bed of very fine bioturbated (intensity 2) sandstone (B1G). Continuing upwards, the next bed is 4.5m of brownish-purple claystone (B1H) with no observable bioturbation. The section is capped by 1.65m bed of very fine sandstone in which the last 25-35cm layer of very fine bioturbated sandstone (B1I) displays extensive horizontal but not vertical bioturbation at the top (intensity of 1.5).

**Section B2**

The base of this section is 3.3 meters of calcareous sandstone (B2A) with minimal bioturbation (intensity 1) that displays reverse grading from very fine to fine sand (Fig. 20). While more bioturbation was found in this bed than others, there was not enough to obscure sedimentary structures or destroy evidence of laminations, bioturbation in this bed included both horizontal as well as vertical burrowing. Lower in the bed a 2-3cm layer of planar laminations are observed with some vertical burrowing which is abruptly truncated by hummocky cross-stratification. It is overlain by a 1.5m bed of unbioturbated (intensity 1) of brownish-purple claystone (B2B) followed by a 10cm bed of very fine sandstone that displays ripples but no bioturbation. In section B2, the D bed observed in B1, B3, B4 and B5 was broken into three lithologies. Those beds were labeled B2D-1, B2D-2 and the brownish purple claystone that corresponds to the brownish purple claystone found in each of the other sections (Fig. 12). This claystone bed had no observable bioturbation (intensity 1). B2G corresponds to the B4G bivalve bed and is made up of 1.3m of very fine calcareous sandstone with mudclasts with possible but unconfirmed bioturbation. B2G is overlain by 5.24m of brownish-purple
claystone (B2H) with no observable bioturbation. The top of this section is capped by 1.7m of comparatively bioturbated (intensity 1) very fine sandstone (B2I) that displays both horizontal as well as vertical bioturbation.
Fig. 18. A. B1B-1 Brownish-purple claystone that is characteristic of the measured sections of the Virgin Limestone member at Hurricane Mesa (bioturbation intensity 1). B. B5D (brownish purple claystone transitioning into brownish grey shale); B5E (siltstone); B5F (brownish grey shale); B5G (sandstone with mudclasts grading into very fine sandstone and siltstone). C. B4A Generalized features of this 5.8m bed represented by mostly very sandstone grading into siltstone with lenses of clay before grading back into sandstone with lots of silt.
Fig. 19. In this picture B1A-B1G layers are observed. From the bottom to the top, B1A (very fine sandstone); B1B (siltstone); B1C (brownish purple claystone); B1D (siltstone with clay interclasts transitioning to fossiliferous siltstone with clay interclasts); B1E (brownish purple claystone); B1F (very fine calcareous sandstone transitioning into bioturbated sandstone).
**Figure 20** – A. B2A, 3.3m calcareous laminated bioturbated siltstone displaying reverse grading into sandstone  B. Gypsum veins crosscutting mudstone. C. Gypsum veins in mudstone. Round greenish colored balls in middle third of outcrop was due to staining.
Figure 20 – D. A, G & I marker beds with the C bed that was identified in all measured sections except for B4.
APPENDIX B

PETROGRAPHIC PICTURES

Thin Section Preparation

Standard glass slides were ground until the surface was parallel to the grinding wheel. The slides were then polished until the grooves and chips were gone, using 400 grit powder on a glass block. 600 and 800 grit were used successively to polish the slide until there were no visible marks on the surface when viewed with a 10x hand lens. Rock chips were cut by first impregnating the sample with a heat-cured 2 part, epoxy and resin. After curing at least one day, the samples were cut into 3/4" slabs, and then cutting chips with dimensions at least 1 mm from the edge of the glass slide. The rock chips went through the same polishing process as the glass. After the chips were dried in an oven overnight, they were then glued to the slides using UV-cured adhesive. After at least one hour, the chips were cut to approximately 150 microns thick. The chips were then ground on a wheel until they were 30-50 microns thick. The chips were then polished using 600 and 800 grit on a glass block until the blemishes were no longer visible.

Resulting thin sections are shown in Figure 21.
**Fig. 21.** A. B3A-1P2. Picture of bioturbation found in dolomitic clay. B. B3A-1P4. Possibly dissolved fossil (organic) or cast filled with organic matter. C. B4F-1P3. Picture of a more bioturbated area found.
Fig. 21. H. R9-1QP2. High in organic matter, no evidence of bioturbation.
APPENDIX C

BIOTURBATION AND SEDIMENTARY STRUCTURES

PHOTOS OF CUT AND POLISHED SECTIONS, AND OF SOME OTHER SAMPLES SHOW DETAILS OF SEDIMENTARY STRUCTURES AND SOME BIOTURBATION (FIG. 22 AND 23).
**Fig. 22.** A. R5 – Cross-section showing ripple cross-bedded sandstone with no evidence of bioturbation (BI-1). All foresets are well-preserved. B. B1-I Planar view of a bioturbated silty-sandstone. The sample shows horizontal burrows while cross-section showed no vertical bioturbation. C. BI-2 Cross-section of a mottled planar bioturbated sandstone (BI-3).
Fig. 22. D. Cross-section of a bioturbated sandstone. Burrows are mostly horizontal with a few vertical burrows. Some original bedding is preserved in the lower portion of the sample (BI-3). E. B2C. Rippled sandstone (BI-1) F. B2C. Rippled sandstone (BI-1).
Fig. 23.  A. R2-1 – Gypsum veins.  B. Sandstone with evidence of planar burrowing.  C. R-9 – Planar-laminated siltstone (BI-1).
Fig. 23. D. Cross-section of an bioturbated sandstone. Burrows are mostly horizontal with a few vertical burrows. Some original bedding is preserved in the lower portion of the sample (BI-3). E. B4G – An allochthonous fossiliferous sandstone unit of bivalves believed to have been transported because none were found life-like positions. F. Clear evidence of planar bioturbation was observed on this mottled sandstone.