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HOW DOES AN UNDERWATER DEBRIS FLOW END?: FLOW TRANSFORMATION EVIDENCES OBSERVED WITHIN THE LOWER REDWALL LIMESTONE OF ARIZONA AND NEVADA

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KEYWORDS: Debris flows, subaqueous, hyperconcentrated, concentrated, turbidity, flow transformation, Whitmore Nautiloid Bed, Redwall Limestone

ABSTRACT

Sediment transportation and deposition mechanisms responsible for the placement of the Phanerozoic stratigraphy (i.e., Cambrian through Cretaceous Periods) in about a year pose a significant quandary for Creationists. How might incredible volumes of sediment move on continent-wide scales in time frames of days? Marine sedimentologists are now arguing that underwater debris flows are the primary way sediment moves in the modern deep ocean (Parsons et. al., 2007). Creationists are arguing that underwater debris flows were a primary agent in the Genesis Flood, producing some substantial deposits such as bedded limestones (Austin, 2003, 2005). These debris flows are now generally believed to be laminar, subcritical, pressurized and liquefied slurries that move with extremely low friction, essentially as hydroplaning wings (Kranenburg, 1978; Mohrig et. al., 1998; Mulder and Alexander, 2001).

When studying an underwater debris flow, does it end by becoming frictional, fluidized and freezing rapidly as is observed in many terrestrial debris flows? Or, does an underwater debris flow end by becoming turbulent, ingesting fluid and transforming into a tractive current? If a debris flow freezes rapidly, there will be no indication of flow transformation and there will be no transitions to study resulting in a lateral disconformity. If the flow does not frictionally freeze, the deposit should be laterally contiguous and have potential flow transformations to study.

Lateral study of the stratigraphy, bed forms and textures of the Whitmore Nautiloid Bed (Austin, 2003, 2005; Stansbury, 2003, 2010) through Arizona and Nevada offer an exceptional opportunity to answer these primary questions.

INTRODUCTION

The conventional depositional interpretation of the Mississippian System, Redwall Limestone, Grand Canyon, Arizona (Figure 1) is that of two separate marine transgressions and regressions (McKee and Gutschick, 1969).

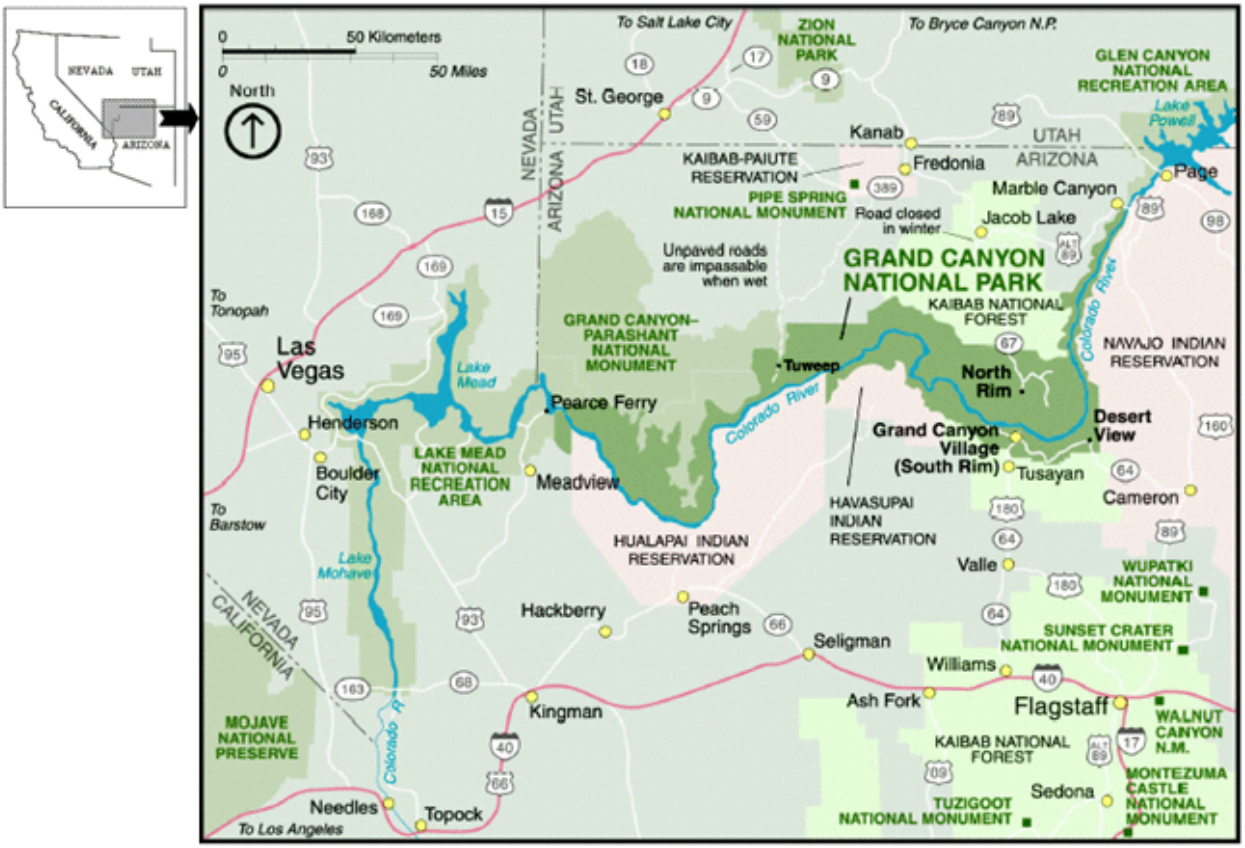

Figure 1. Orientation map of Grand Canyon, Arizona. Grand Canyon map courtesy of U.S. National Park Service.

The Redwall Limestone is composed of four members in ascending order: the Whitmore Wash, Thunder Springs, Mooney Falls and Horseshoe Mesa Members (McKee, 1963) as shown in Figure 2. The depositional environment is interpreted to be a "shallow, epeiric sea that produced a submerged continental shelf across northern Arizona" spanning a time period of some 20-25 million radiometric years (Beus and Morales, 1990, p. 128).

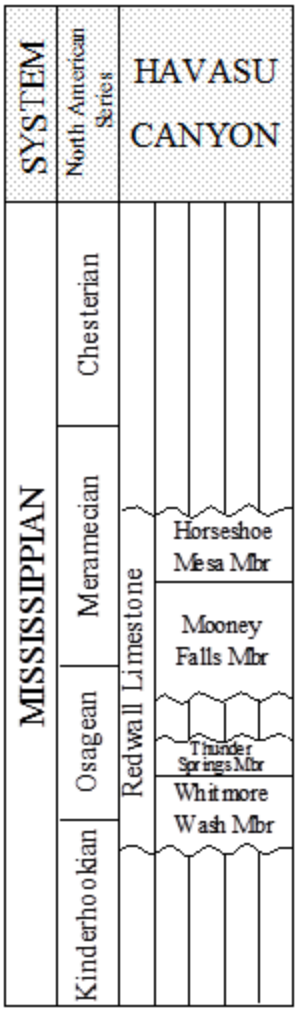

Figure 2. Sample stratigraphic section for Redwall Limestone at Havasu Canyon (Beus, 1989, p. 296)

Current research has challenged the depositional interpretation of lower Redwall Limestone, Arizona and Nevada. Specifically, the lowest member of Redwall Limestone has indications of rapid deposition (Austin, 2003). It is possible that the deposition of a major portion of Redwall Limestone did not take millions of radiometric years but was accomplished in hours as a result of a submarine debris flow. If the deposition were a result of a submarine debris flow, either evidence of the flow ending by frictional freezing with a resulting westerly disconformity, or indications of flow transformation from proximal to distal flow ends should be recorded in the strata. Are either such stratigraphic records identifiable in the lower Redwall Limestone as the flow progressed from Colorado to Nevada?

The density flow (Arrow, Figure 3) is hypothesized to have traversed northern Arizona, from southwestern Colorado into Nevada, and has a currently identified extent of 290 km (Austin, 2003, p. 55). Previous studies have been performed on WNB in the region of this study area (Austin 2003, 2005; and Stansbury, 2003, 2010). The objective of this study is to increase the knowledge of WNB throughout the study area by correlating stratigraphy, documenting and

interpreting bedforms at each location and performing a textural analysis to gain an increased understanding of the nature of the deposits. This information will add to the body of knowledge regarding, specifically, the nature of the Whitmore Nautiloid Bed deposit and generally, how an underwater debris flow ends and what the resulting characteristics of the deposit looks like.

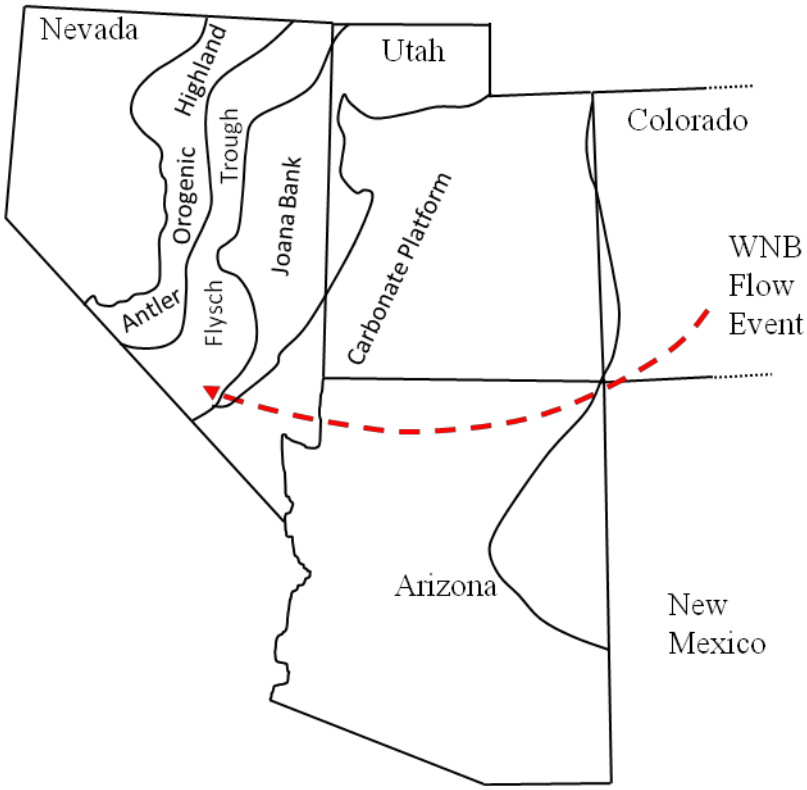

Figure 3. Plan view of lower Redwall Limestone showing the direction of the hypothesized flow event. The flow, denoted by the arrow, is hypothesized to have began in SW Colorado and traversed the carbonate platform of Arizona and dropped rapidly down the Joana Bank into the Flysch Trough of central Nevada prior to encountering the Antler Orogenic Highland. Graphic modeled from Poole & Sandberg, 1992.

When studying the deposit left behind by the Whitmore Nautiloid Bed flow event, frictional freezing, flow transitions, long-runout, depositional shape and duration are of interest. What are realistic duration values for such a flow? As a modern analogue, the 1929 Grand Banks earthquake triggered a submarine slide that transformed into a debris flow and then a turbidity current traveling a distance of at least 1000 km in 12 hours (Locat and Lee, 2002; Piper and Aksu, 1987; Piper et. al., 1999). Thus, a density flow interpretation of the Whitmore Nautiloid Bed, Whitmore Wash Member in the lower Redwall Limestone could indicate an event time, and subsequent deposition, of hours instead of millions of radiometric years.

HYPOTHESIS

Submarine debris flows are believed to end primarily by the process of flow transformation. They are hypothesized to end by becoming turbulent, ingesting fluid and transforming into a

tractive current. If submarine debris flows end by exploding into turbulence as they become diluted with water, a wide variety of tractive current structures should form very quickly from sediment-overloaded suspensions.

TEST OF THE HYPOTHESIS

Whitmore Nautiloid Bed is a widespread limestone stratum in the lower Redwall Limestone best understood to be a shallow marine debris flow deposit (Austin 2003, 2005). The western end of Whitmore Nautiloid Bed in Mojave County, Arizona, and Clark County, Nevada, is the distal (down current) end of the debris flow. If flow transformation occurred, the bed should thicken and a wide assortment of tractive current bedforms should appear. These tractive current structures should become more abundant in the distal direction (westward). Because turbulent flow displaces laminar flow, vertical sorting of the grains within the limestone beds should increase and matrix supported texture should give way westward to clast supported texture. Thus, if the hypothesis of flow transformation is correct, a pronounced change in bed thickness, bed structure and bed texture should occur distally.

STRATIGRAPHY

At the Arizona-Nevada border, formation names change for the stratigraphic sections under study. In Arizona, the Redwall Limestone is composed of four members, the Whitmore Wash, Thunder Springs, Mooney Falls and Horseshoe Mesa Members (McKee, 1963). In Nevada, the same stratigraphically correlated section is named the Monte Cristo Group and is composed of four formations: the Dawn Limestone, Anchor Limestone, Bullion Limestone and Yellowpine Limestone Formations (Stevens *et al.*, 1993). The Redwall Members and the Monte Cristo Formations correlate as follows from the bottom up: Whitmore Wash Member – Dawn Limestone Formation, Thunder Springs Member – Anchor Limestone Formation, Mooney Falls Member – Bullion Limestone Formation and Horseshoe Mesa Member – Yellowpine Limestone Formation (Langenheim and Schulmeister, 1987).

Whitmore Nautiloid Bed provides a time-stratigraphic correlation from the Whitmore Wash Member, Redwall Limestone in Arizona, through the Dawn Limestone and into the Anchor Limestone of Nevada (Figure 4). A discussion of the stratigraphy and correlation may be found in Austin (2003). Of note is the missing Whitmore-equivalent stratum within the Leadville Limestone, San Juan Mountains, Colorado (Armstrong and Holcomb, 1989; Armstrong and Mamet, 1976; Poole and Sandberg, 1991). Is it possible that this missing section is the source sediment for the Whitmore Nautiloid Bed density flow?

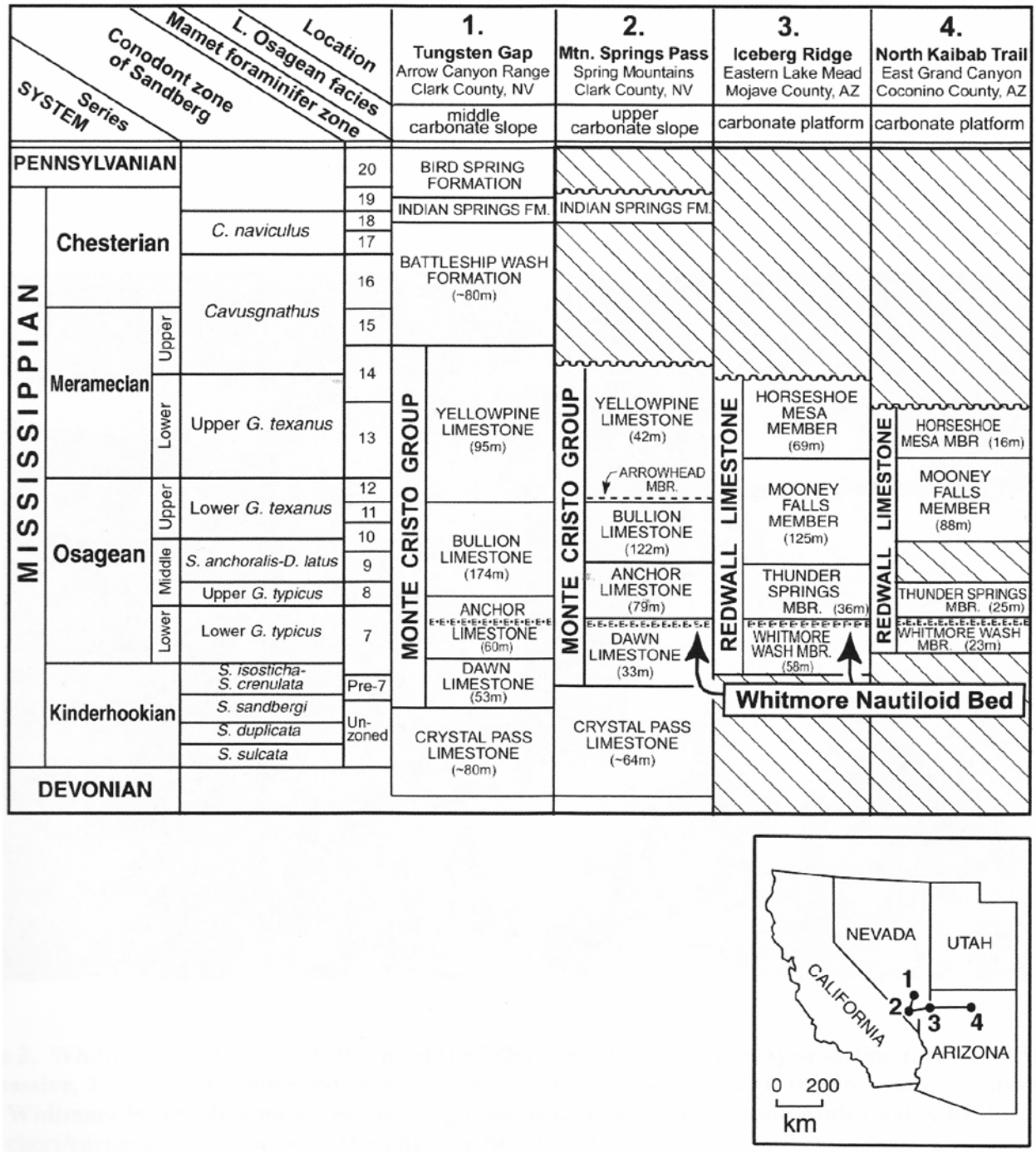

Figure 4. Regional stratigraphic correlation chart of Mississippian rocks of northern Arizona with southern Nevada. Two thin but persistent lithostratigraphic units are the Arrowhead Member and Whitmore Nautiloid Bed. Nevada strata nomenclature follows revisions of Stevens *et al.* (1993). Conodont zones are for western U.S. by Poole and Sandberg (1991) and foraminifer zones are by Mamet and Skipp (1970). Diagram courtesy of Austin, 2003, Figure 2, p. 67.

DEPOSITIONAL ENVIRONMENT

Near the end of lower Osagean, when the Dawn Limestone and Whitmore Wash Member were being deposited, the sea level was shallow and the continental shelf was relatively flat (Figure 5). This environmental description encompasses the study area from northern Arizona into southern Nevada.

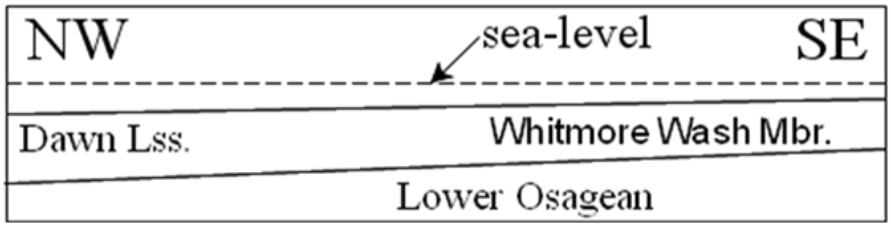

Figure 5. Cartoon of depositional environment of lower Mississippian corresponding to the lower Whitmore Wash Member and Dawn Limestone. Modeled from development of the Mississippian carbonate platform on data from eastern California and southern Nevada (Stevens *et al.*, 1995).

"Probably the most important event in development of the Mississippian carbonate shelf, indicated by all the sedimentologic and paleontologic data, was a rapid deepening of the entire platform at the beginning of deposition of the Anchor Limestone in Nevada … close to the early-middle Osagean break" (Stevens *et al.*, 1995, p. 184). Additionally, Pierce (1969) discusses the facies change from relatively thin deposits on the shelf to relatively thick deposits in the northwest of the study area as the shelf transitioned to a miogeosyncline. Figure 6 may be used to visualize the tectonic change after the rapid deepening of the platform in the western part of the study area and is interpreted to be the depositional environment of the Anchor Limestone in southern Nevada.

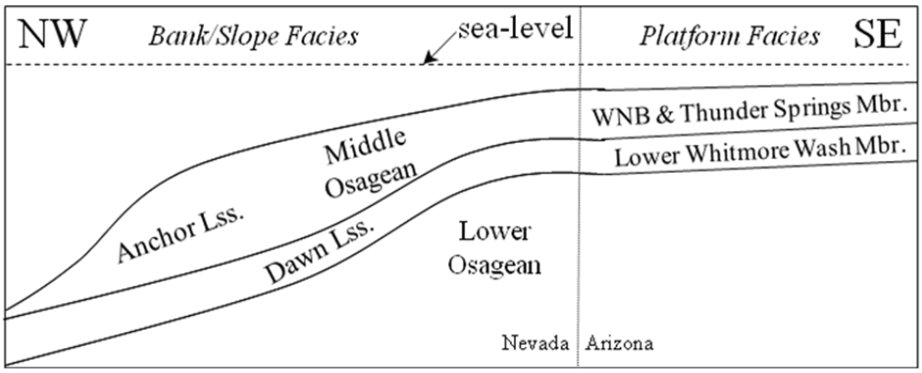

Figure 6. Cartoon of the depositional environment for the Whitmore Nautiloid Bed, Thunder Springs Member and the Anchor Limestone. Modeled from development of the Mississippian carbonate platform on data from eastern California and southern Nevada (Stevens *et al.*, 1995).

The cartoons of Figures 5 and 6 are meant to depict the developmental history of the Mississippian carbonate platform in rough cross-section from southern Nevada to eastern California, pertaining to the Monte Cristo Group. Beginning as a continental shelf facies as in Figure 5 and deepening to a continental slope facies during lower-middle Osagean as in Figure 6. Northwestern Arizona remained a carbonate platform, unaffected by the deepening to the west, similar to Figure 5. The platform facies "probably dipped almost imperceptibly to the northwest" during the Devonian System (Stevens *et al.*, 1995, p. 184). Could such a substantial tectonic change have a direct effect on the stability of platform sediments and have also initiated the WNB event? "Thus, although the similarities show that these carbonate sequences were deposited on the same platform, the nature of the shelf on which the Mississippian carbonate platform developed varied considerably laterally" (Stevens *et al.*, 1995, p. 184).

STRATIGRAPHIC SECTION LOCATIONS

The central problem of this study is the determination of how an underwater debris flow ends, specifically Whitmore Nautiloid Bed. The first step in analyzing the problem is to look at a stratigraphic correlation of Whitmore Nautiloid Bed. It is not the objective of this study to provide a full stratigraphic section of the Monte Cristo Group/Redwall Limestone Formation at each location. The objective is to provide a correlation of WNB at each of these locations.

Figure 7, Stratigraphic section locations, identifies the locations of the four stratigraphic sections chosen for this study. The four sections starting at the easterly most section moving westward are 1 – Squaw Canyon (N36.89333^{o}, W113.80370^{o}); 2 – Virgin River Gorge (N36.92321^{o}, W113.85254^{o}); 3 – Mormon Mountains (N36.85204^{o}, W114.30294^{o}), and 4 – Meadow Valley Mountains (N36.77419^{o}, W114.78178^{o}). A fifth location, Las Vegas Range North indicates a previous area of study by Stansbury (2003). An arrow is added to the map to show the relative direction of the WNB flow event through northern Arizona and into southern Nevada. Additionally, the stars in Nevada represent the estimated restored locations of the sections as identified by Austin (2005).

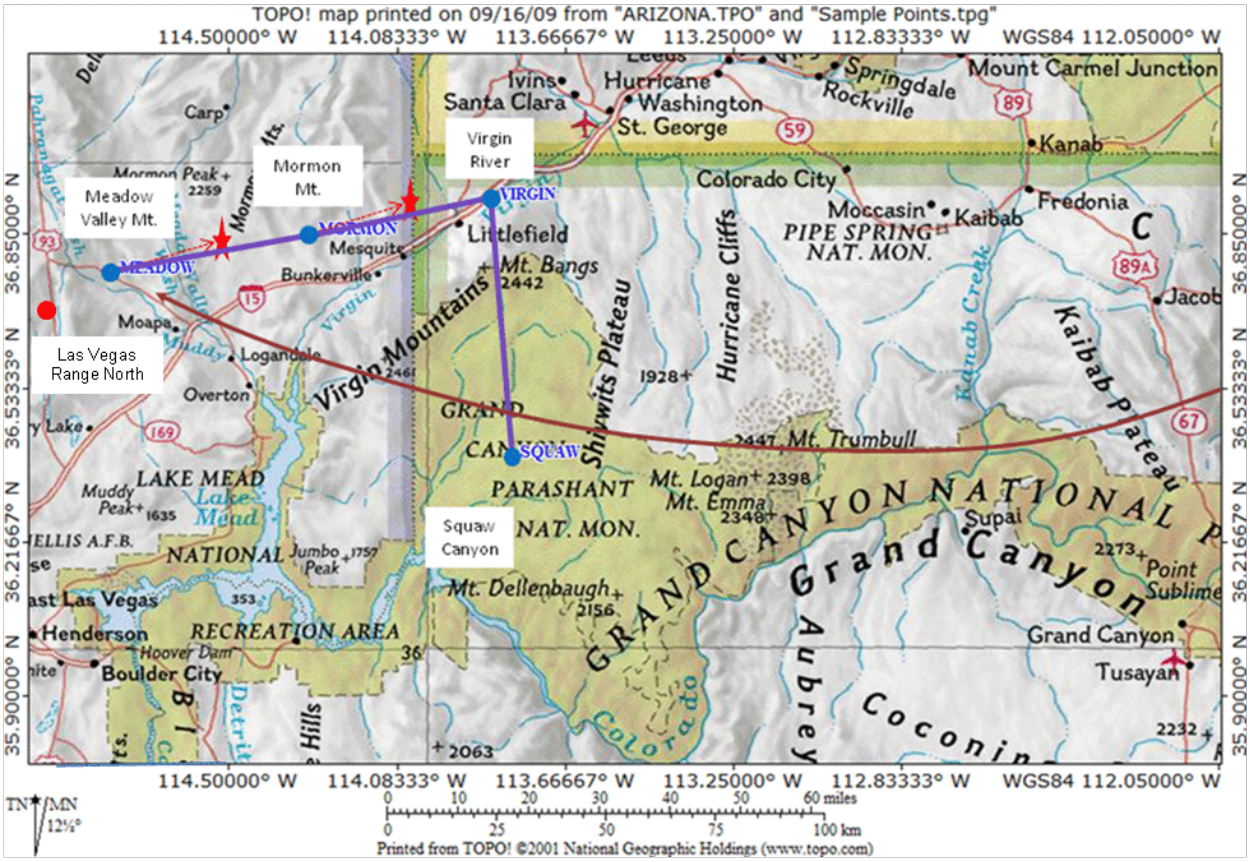

Figure 7. Stratigraphic section locations. Map of northern Arizona and southern Nevada showing the four stratigraphic sections of Squaw Canyon, Virgin River Gorge, Mormon Mountains, Meadow Valley Mountains and Las Vegas Range North. The two stars in Nevada show the estimated restored locations of the Nevada sections based on Austin (2005) while the arrow depicts the general direction of WNB flow.

Whitmore Nautiloid Bed is identified at each location by first finding the easily located rhythmic chert/carbonate Mississippian Thunder Springs Member of the Redwall Limestone Formation in Arizona and its correlation in Nevada, the Anchor Limestone Formation of the Monte Cristo Group.

In Arizona, once the Thunder Springs Member is identified, WNB is found at the base of the Thunder Springs Member as the uppermost bed in the Whitmore Wash Member of the Redwall Limestone. Figure 8, Virgin River Gorge – WNB to Thunder Springs Member transition shows the transition, as is typical in Arizona, from WNB as a light-gray deposit to the overlying rhythmic chert/carbonate of the Thunder Springs Member.

Figure 8. Virgin River Gorge – WNB to Thunder Springs Member transition. The lower light-gray, weathered packstone bed is WNB with a sharp, upper transition to the rhythmic chert/carbonate sequence of the Thunder Springs.

As the flow traversed westward, WNB is found in the middle to upper Anchor Limestone of the Monte Cristo Group in Nevada. The light-gray deposit of WNB is bounded by the dark-gray deposit of the rhythmic Anchor Limestone at Meadow Valley Mountains and Las Vegas Range North. As a further example, the contact is easily identifiable as in Figure 9, showing the contacts of WNB at the roadcut of the Virgin River Gorge location.

Figure 9. Contacts of WNB at Virgin River Gorge. The roadcut provides a fresh exposure of WNB and the guard rail in the lower portion of the picture provides scale.

It should be noted that flow experiments in tanks (Harbitz *et. al.*, 2003) have indicated that the flow front does not remain intact as a straight line. Flow fronts are likely to be complicated with variations in distance and structure due to topographical anomalies, sediment densities, fluid intake, head decapitation, and flow re-concentration.

STRATIGRAPHIC CORRELATION

As part of the analysis of how an underwater debris flow ends, it is important to ensure a stratigraphic correlation between the different measured sections of Whitmore Nautiloid Bed. Also of interest, is whether or not there is a thickness change in the bed as the flow progressed westerly.

Referring back to Figure 3, Plan view of lower Redwall Limestone, WNB in Arizona is on the platform facies and the paleogeography transitions to the slope facies of the Joana Bank in southeastern Nevada, as depicted in the cartoon of Figure 6. As has been noted, Whitmore Nautiloid Bed is the uppermost bed of the Whitmore Wash Member, Redwall Limestone in Arizona. At Mormon Mountains in Nevada, WNB is also the uppermost bed of the Dawn Limestone, Monte Cristo Group. The Dawn Limestone of Nevada correlates with the Whitmore Wash Member of Arizona. In Arizona, the Thunder Springs Member, Redwall Limestone immediately overlies WNB as does the Anchor Limestone of the Monte Cristo Group at the

Mormon Mountains location in Nevada. The Thunder Springs Member and the Anchor Formation are highly recognizable and identifiable due to the rhythmic chert sequences. This makes finding and identifying WNB a simple task as WNB in these locations marks the beginning of the rhythmites. The light gray of WNB is highly contrasted with the medium to dark gray of the surrounding formations. The formations surrounding WNB are usually a finer texture, which aides in identifying the coarser texture of WNB at each of these locations.

Farther west at Meadow Valley Mountains, the location of WNB in the section does not mark the top of the Dawn Limestone. Instead, WNB is just above the midpoint of the Anchor Formation. Here, chert rhythmites are found below and above WNB.

The stratigraphic cross section is presented as Figure 10. Whitmore Nautiloid Bed is 2.0 m thick at Squaw Canyon and increases in thickness through Virgin River Gorge and Mormon Mountains from 3.8 m to 8.4 m respectively. At the Meadow Valley Mountains section, the thickness of WNB decreases from 8.4 m at Mormon Mountains to 6.0 m.

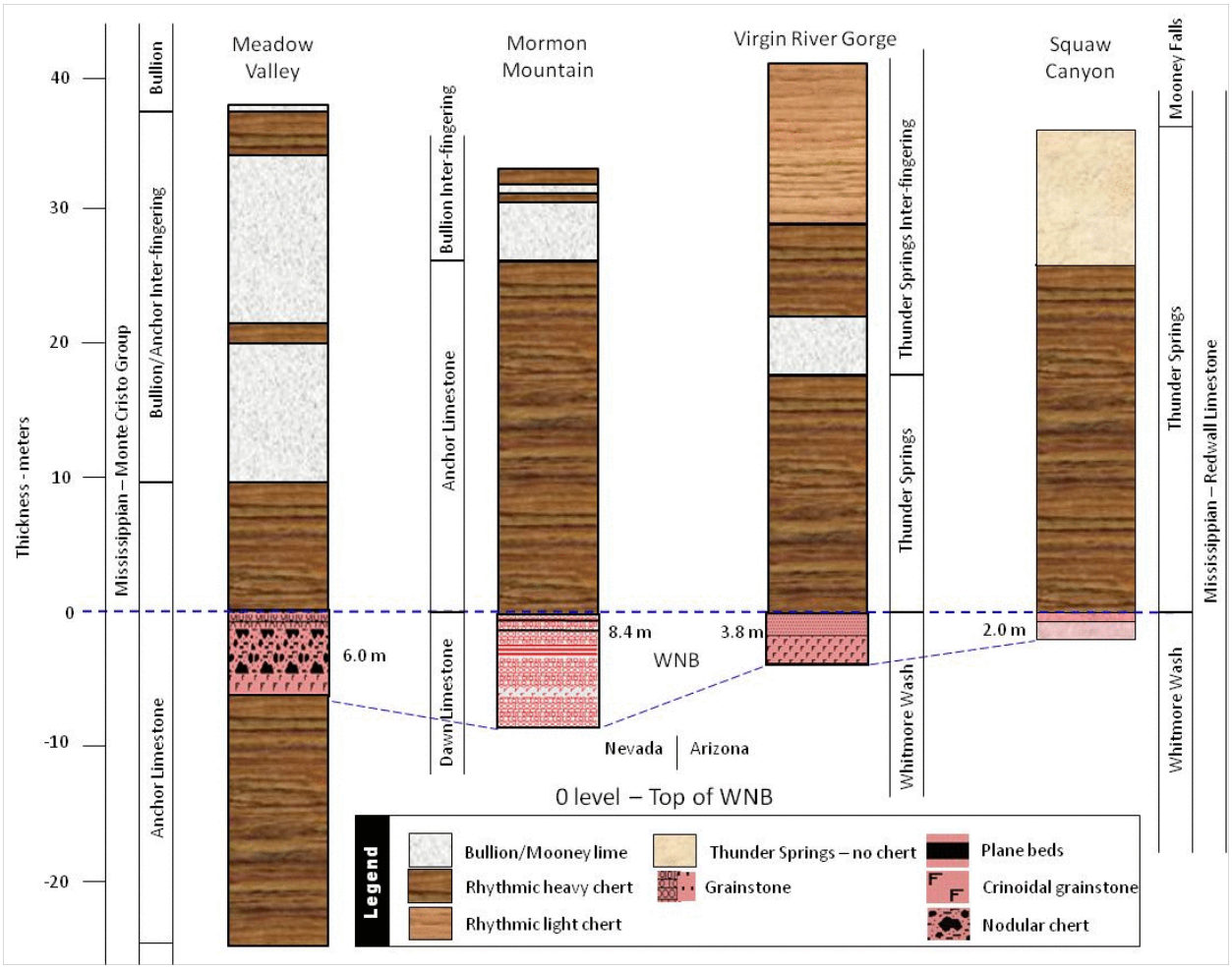

Figure 10. Whitmore Nautiloid Bed stratigraphic cross section. Squaw Canyon is the easternmost of the measured sections. Substantial changes in bedform and structure occur at each location. Graphic generated courtesy of TerraStation II, 2009.

Farther east of Squaw Canyon and into Grand Canyon, Arizona, WNB is a uniform 2.0 m thick (Austin, 2003). As the platform transitions to a deepening platform towards the Joana Bank at Virgin River Gorge and Mormon Mountains, the thickness of WNB increases. There is a drop in WNB thickness at Meadow Valley Mountains from Mormon Mountains and the stratigraphic position of WNB changes to the upper-middle of the Anchor Limestone. West of Meadow Valley Mountains in the Las Vegas Range, WNB is a preserved cross bedded dune of 7.5 m with an estimated complete dune height of 15 m (Stansbury, 2003), also lying above the mid-point of the Anchor Formation.

The questions of the stratigraphic correlation were: Is the bed stratigraphically correlated and does the bed change thickness as it progresses from east to west? Based on the results of the stratigraphic cross section study, the bed correlated between locations and does increase in thickness as the bed is traced westerly with a thinning at Meadow Valley Mountains.

BEDFORM ANALYSIS

Deposits of Whitmore Nautiloid Bed are analyzed from east to west. The determination of how an underwater debris flow ends will be made from the substantial exposures of the WNB in northern Arizona and southern Nevada. The objective of the bedform analysis is to determine if vertical particle sorting is evident in the deposits of WNB. If a flow transitions from hyperconcentrated to concentrated and/or turbulent flow, sediment concentration should reduce and allow for vertical particle sorting. This would result in the appearance of normal grading, coarsening-upward and fining-upward textures and tractive current structures such as plane bed laminations or cross-bedding.

Whitmore Nautiloid Bed at Squaw Canyon is 2.0 m thick separated into a lower, weather resistant section of 1.3 m and an upper, heavily weathered section of 0.7 m. At Virgin River Gorge, WNB is a 3.5 m thick including water escape pipes in the upper 0.5 m. Indistinct parallel stratification exists throughout the lower portion of the bed and is noted more by color than by texture.

Moving west to the Mormon Mountains location, WNB shows a marked difference in form and structure. At Mormon Mountains, WNB displays vertical particle sorting characteristics and is light gray with a high fossil content, primarily crinoids and brachiopods. A zone of high concentration fossil material, brachiopods and crinoids, is about 2.5 m up from the base and another section at 4.3 m from the base shows tractive fossil segregation.

Meadow Valley Mountains presents yet other differences in form and structure. WNB is 6.0 m thick and consists of multiple, vertical sorting changes throughout the bed. These include inverse graded, massive and sorted beds.

At Las Vegas Range, further west, Stansbury (2003) notes that WNB is a preserved, large, subaqueous dune 7.5 m thick. Cross-bed stratification is readily apparent at this location.

SQUAW CANYON BEDFORM ANALYSIS

Squaw Canyon (Figure 7) is the easternmost location of the study area and is in western Arizona. Upon entering Squaw Canyon, WNB is immediately identifiable below the Thunder Springs Member. Continuing into the canyon easterly, much of the canyon bottom is WNB. Here, in the western part of the canyon, complete upper sections of WNB and Thunder Springs are exposed but the base of WNB is buried. WNB is seen on the lowest sides of the canyon and also forms resistant benches on the canyon floor.

Travelling eastward into the canyon, eight such benches or ledges are passed. These benches are kept at the canyon bottom by a series of normal faults.

In three locations, nautiloid fossils were found on the water polished surface of the ledges. One such example, Nautiloid 1, was found 0.25 m below the top of WNB, and is located at N36.39460° W113.80695°. There is a high density of water escape pipes, approximately 4 x 10 cm^2, and acid fizz is high. Fossil content is average, meaning it is easy to find fossils and they are not sparse or dense. Two stylolites, just above the nautiloid fossil, and two bedding planes separating massive sections of WNB were noted. The first bedding plane is just below the nautiloid fossil and the second is one meter below the first. No bottom of WNB is visible in this ledge.

Nearly 2.0 km into the canyon is where the measured section at N36.39333° W113.80370° was selected. WNB was approximately 20 m above the canyon floor on the northern side of the canyon. Here both WNB and Thunder Springs were fully exposed and accessible. Figure 11 shows the prominent weather resistant base of WNB including a clean, non-eroded contact between the lower Whitmore Wash Member and WNB. The measured section is east, just around the back of the outcrop of Figure 11.

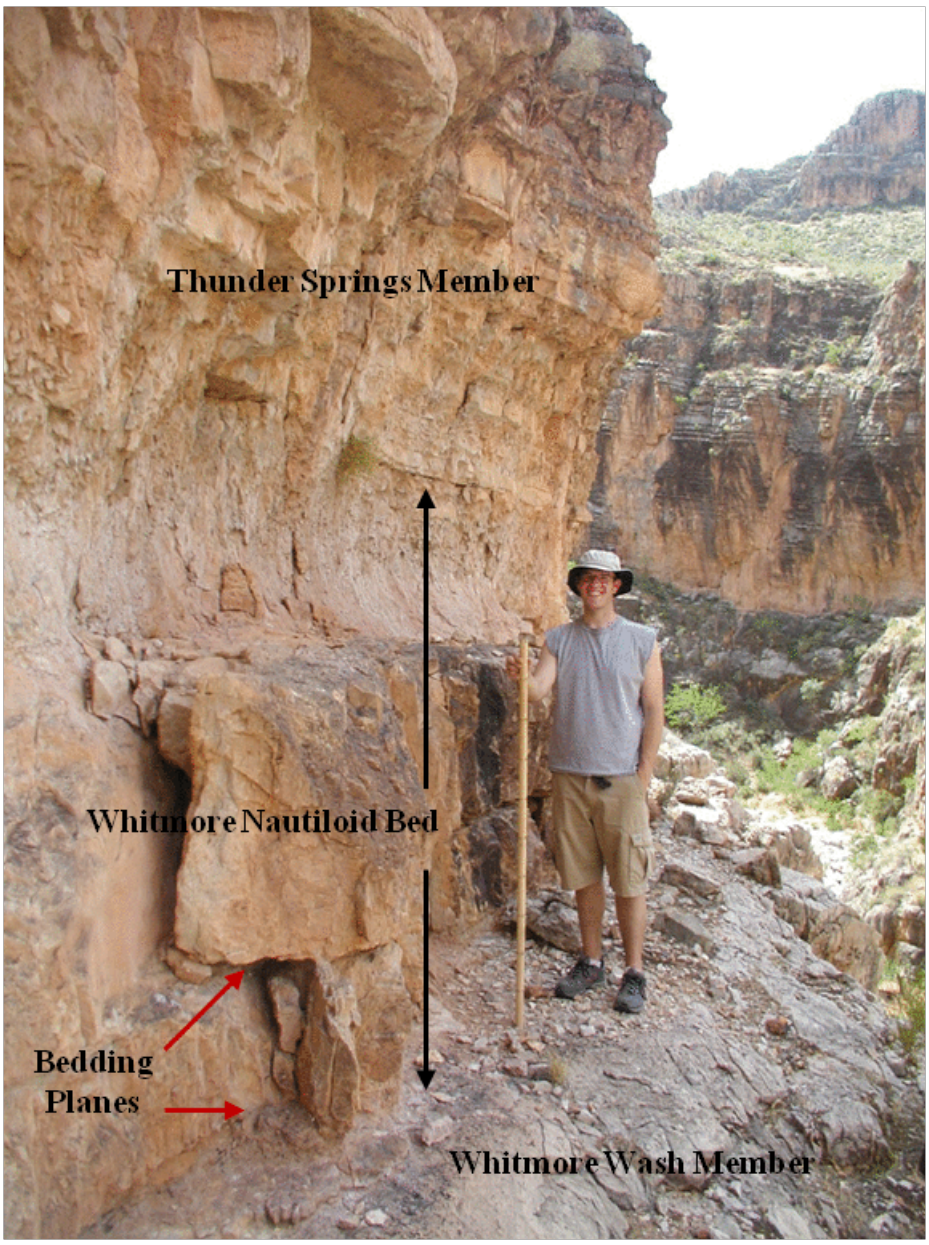

Figure 11. Whitmore Nautiloid Bed at Squaw Canyon. The lower, weather resistant WNB and bedding planes are identified and the upper, heavily eroded WNB is immediately overlain by Thunder Springs.

Three massive units are noted by the bedding planes in the left of Figure 11. The first bedding plane is very near the bottom and the second is just below half-way up the weather resistant section. The upper 0.7 m of WNB, above the staff in Figure 11, is fractured and heavily eroded, re-crystallized and/or replaced solution structures are laterally continuous throughout this exposure. The first chert bed of the Thunder Springs Member lies directly over the eroded upper WNB in Figure 11. No fossils were noted in this section and WNB produced a minor acid fizz.

Figure 12, Squaw Canyon WNB graphic, depicts the three massive units at the base composing the weather resistant section of WNB at the measured section and the re-crystallized upper section which is more easily eroded. From bottom to top, there are minimal structure changes and no vertical sorting of grains is apparent. There is a sharp lower contact with the Whitmore Wash Member and a sharp upper contact with the overlying Thunder Springs Member. No erosional features are noted at either contact.

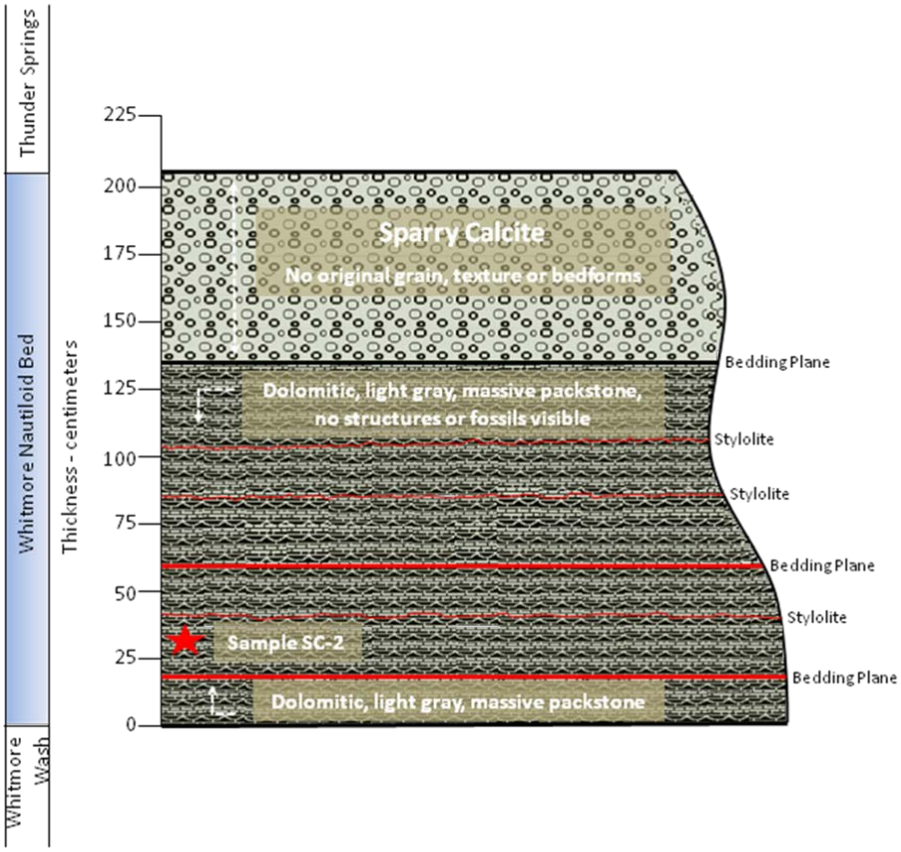

Figure 12. Squaw Canyon WNB graphic. Two main sections of WNB exist, a lower weather resistant section and an upper weathered section.

VIRGIN RIVER GORGE BEDFORM ANALYSIS

The outcrop at Virgin River Gorge has two exposures in the gorge, one being a roadcut with relatively fresh exposure on the south side of the road and river and a second exposure on the north side of the river which is water polished (Figure 13). The discussion of the bedforms is based on the water polished section north of the river at N36.92321^{o} W113.85254^{o}. The roadcut exposure displays knife-like boundaries between the lower Whitmore Wash Member and WNB and also the upper boundary between WNB and the Thunder Springs Member. Similar to Squaw Canyon, no basal erosion is noticed.

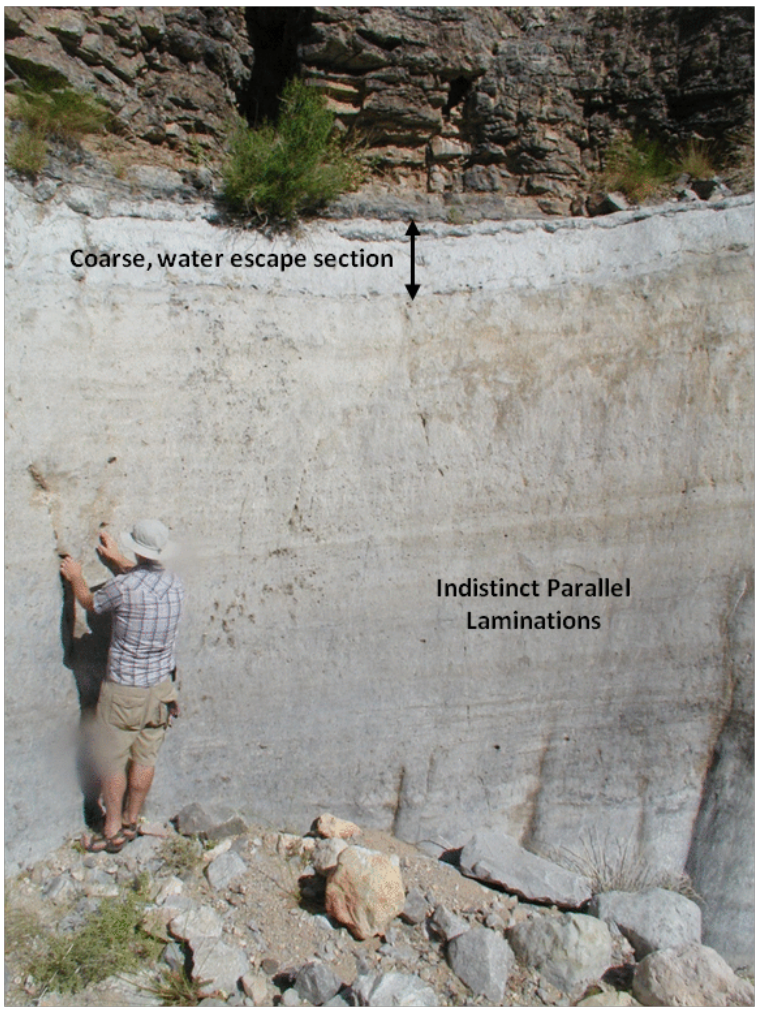

Figure 13. Water polished WNB north of the Virgin River at Virgin River Gorge. This is a bowl structure just above the water level. Note the upper 0.5 m of very light gray, coarse grained sediment and the colored laminations throughout the lower bed.

The uppermost 0.5 m appears as a lighter gray than the lower section (Figure 13) and has a coarser texture with water escape pipes at a concentration of approximately 4 per 20 cm^2. Faint plane bed laminations, noted by color and not grain size variations, are visible in the lower section of WNB. Fossil content is high, consisting mainly of crinoids and rugose coral with a colonial coral rafted parallel to the laminations 2.8 m from the top of the bed.

WNB on the north of Virgin River is a water polished erosional bowl where the base is buried in the stream exposure while well exposed at the roadcut just south of the bowl. Measurements of Figure 14, Virgin River Gorge WNB graphic, are estimated from actual measurements in the bowl due to the varying angles and dip of the bowl. The measured thickness of WNB is 3.8 m as measured at the roadcut (Ahlstrom, 2007). It is estimated that only a small lower section of WNB is buried by debris north of the river in the bowl. The only bedding plane in the deposit is identified 0.5 m from the top of WNB separating the upper, coarser textured light gray deposit from the lower section. Four stylolites were noted in the lower section of the Bed but no other

bedding planes were recognized. Vertical variation in bedforms and particle sorting is minimal at this location. There is no normal or inverse grading or plane beds noted by varying particle sizes other than perhaps some sort of micro particle change noted by the color laminations.

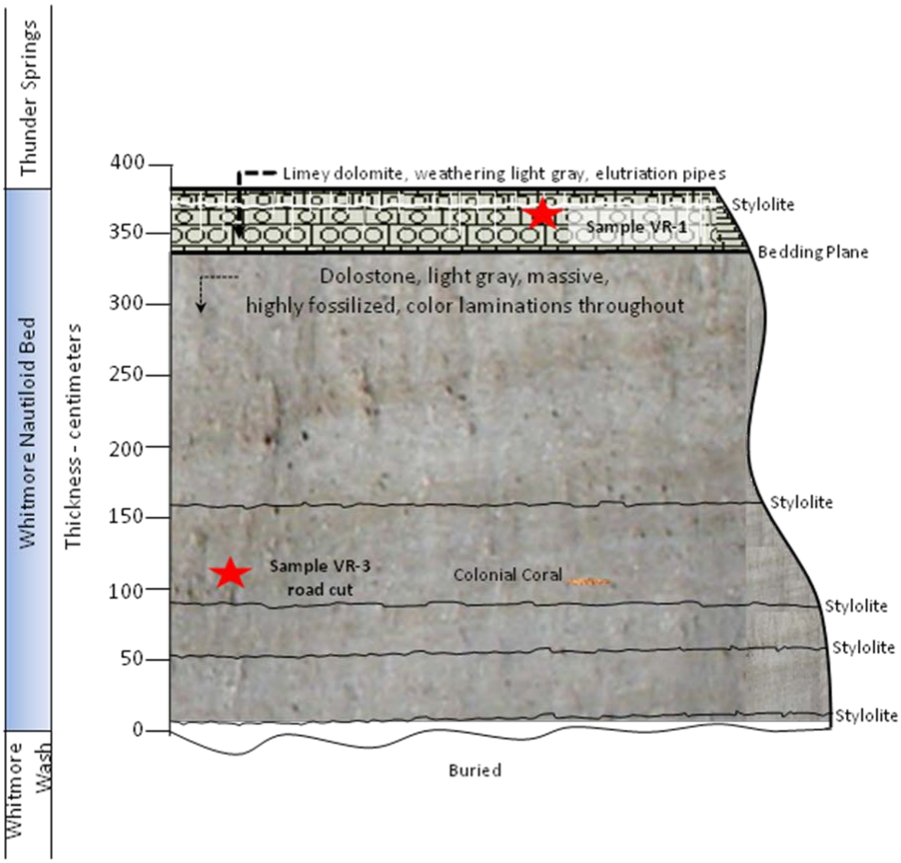

Figure 14. Virgin River Gorge WNB graphic. At Virgin River Gorge, WNB is massive with fossils and indistinct parallel stratification in the lower section. The upper 0.5 m is light gray and coarser than the lower section and includes water escape pipes.

MORMON MOUNTAINS BEDFORM ANALYSIS

At the Mormon Mountains location, WNB weathers light gray and is again easily identified in outcrop. Here in Nevada, the Dawn Limestone Formation of the Monte Cristo Group lies directly below WNB. The dark gray of the Dawn Formation, which highly reacts with acid, contains some chert nodules but not the familiar rhythmic chert beds of the Anchor Formation.

Moving up strata, the base of WNB is identified via a color change to light gray and also a textural change from the finer grained Dawn Limestone to the coarser grained WNB. There is no noticeable or substantial erosion between the top of the Dawn and the bottom of WNB. Whitmore Nautiloid Bed is 8.4 m thick here at Mormon Mountains, which is nearly four times thicker than the 2.0 m at Squaw Canyon and just over twice as thick as the 3.8 m at Virgin River Gorge.

The bed remains massive while moving up strata until a noticeable increase in both fossil content and fossil size begins (Figure 15). The transition to the increased fossil zone does not happen at a sharp plane, but subtly occurs. This type of change, where larger clasts are increasing up strata is termed "coarsening-upward." The clasts in this case happen to be fossils.

Figure 15. Massive fossiliferous packstone of Whitmore Nautiloid Bed at Mormon Mountains. This section of WNB is interpreted as the upper part of the coarsening-upward section of the debris flow roughly 2.5 m from the base.

Continuing up slope, a subtle thinning upward of the clasts (*i.e.*, fossils) occurs. Again, there is no abrupt transition from the heavily fossilized section to the more sparsely fossilized upper section. From where the heavy fossils begin thinning to the next overlying bedform, is about 2.25 m of again massive and sparsely fossilized WNB (Figure 16). For the next 1.0 m, four plane beds are noted due to vertical particle (*i.e.*, fossil) sorting. These plane beds are identified and measured at 5.8 m, 6.0 m, 6.1 m and 6.2 m from the base of WNB.

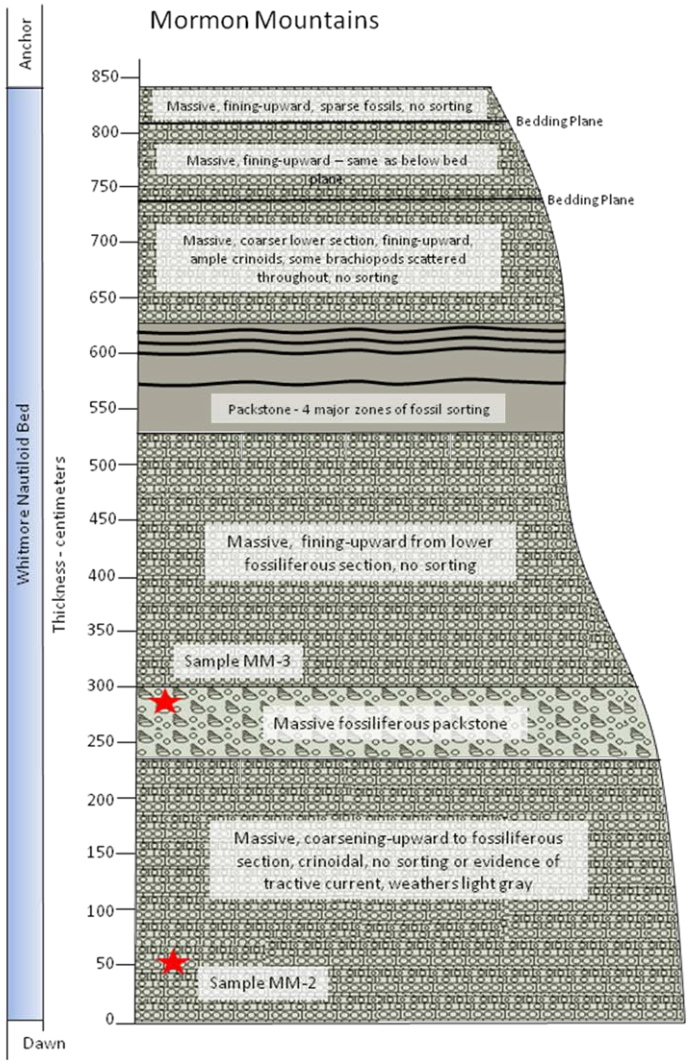

Figure 16. Mormon Mountains WNB graphic. Fossil coarsening-upward culminating in the massive fossiliferous packstone at 2.5 m is followed by thinning-upward leading to fossil sorting and bedding planes in the upper section of WNB.

The upper section of WNB contains three distinct bedding planes (Figure 16). In between each bedding plane, WNB is massive with the lowest of the three sections containing many small fossils with some larger fossils scattered about. The second and third sections are also massive but fossils of any size are sparse.

Figure 17 clearly shows the upper contact of WNB with the overlying Anchor Formation. At the base of the cactus in the photograph, the coarse, light gray of WNB is easily contrasted with the transition to the first chert bed of the Anchor. This also demonstrates the relative ease with which nearly all WNB contacts are identified.

Figure 17. Upper WNB contact with the Anchor Limestone at Mormon Mountains.

The results of the measurements and observations for the Mormon Mountains location are presented in the bedform graphic of Figure 16. Substantial vertical variation in particle sorting is first noted at this location as opposed to the Squaw Canyon and Virgin River Gorge locations. This is particularly evident in the coarsening upwards, fining upwards and plane bed sections of the Bed.

The base of Figure 16 is the boundary between the Dawn Formation and the WNB. WNB is technically the upper bed of the Dawn Formation and is not part of the Anchor Formation at this location.

MEADOW VALLEY MOUNTAINS BEDFORM ANALYSIS

The Meadow Valley Mountains section is the most westerly end of the four measured sections. Unlike the other three study locations, WNB is bounded by the Anchor Formation below and above. At this location, WNB is 6.0 m thick, showing a reduction in thickness from the Mormon Mountains location and also showing varying bedform characteristics. The base of WNB in the Anchor Formation is a sharp contact delineated by a 10 cm thick chert bed.

Two locations were studied at Meadow Valley Mountains as denoted by location markers Medow1 and Medow2 on Figure 18 – refer to Figure 7 for macro-location. The first location is a hillside slope with substantial amounts of debris. Although WNB is different in color and

texture to the surrounding Anchor Formation, boundaries are difficult to identify due to the slope debris. This is the location where the measured section was made. Medow2 is an outcrop of WNB at the top of a hill to the north of Medow1. The covered location of Medow1 made it difficult to perform a detailed bedform analysis. Therefore, the outcrop at Medow2, providing an excellent view of WNB, was used for the detailed study. However, the top 1.5 m of WNB is missing at Medow2. It appears that the upper section of WNB, from 4.0 m to 4.5 m, is weather resistant and serves to cap the outcrop at Medow2.

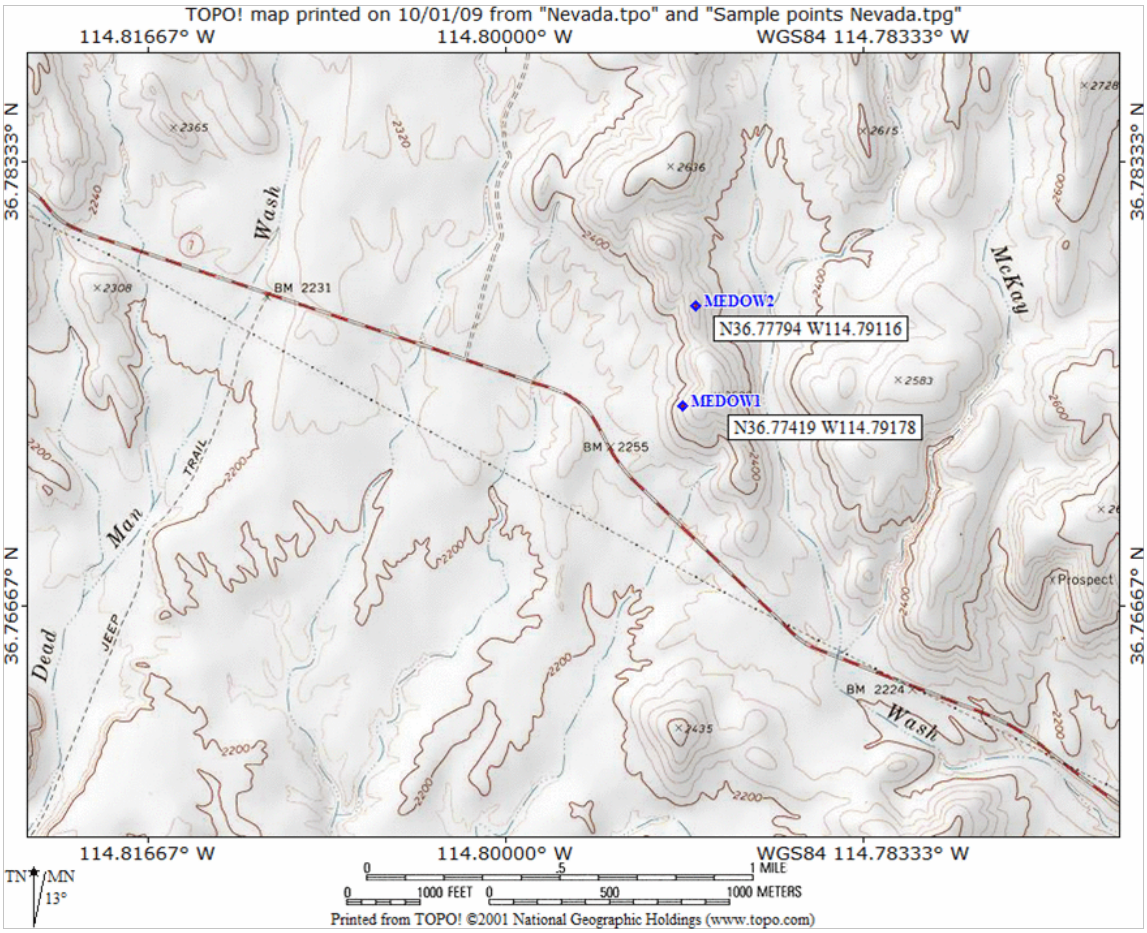

Figure 18. Meadow Valley Mountains sections north of Moapa, Nevada on Highway 168. Here the Monte Cristo Group is exposed on the west side of the hill just east of Dead Man Wash. Medow1 and Medow2 sections are shown on this map, TOPO! 2001.

The base of WNB is a sharp contact with the lower Anchor and is easily identified by the 5-10 cm thick chert bed delineating the Anchor from WNB. Approximately 10 cm up from the chert bed is a stylolite. At the base of WNB, grain texture is fine below the stylolite and coarsens upward through the 0.4 m inverse graded section (Figures 19 and 20). Although inverse graded, the grading is not as distinct as is the case with the upper inverse graded bed. No indications of water escape pipes have been found in either of the inverse graded beds. Overlying inverse graded bed #1 is another chert bed, as can be seen just at the top of the photograph in Figure 20.

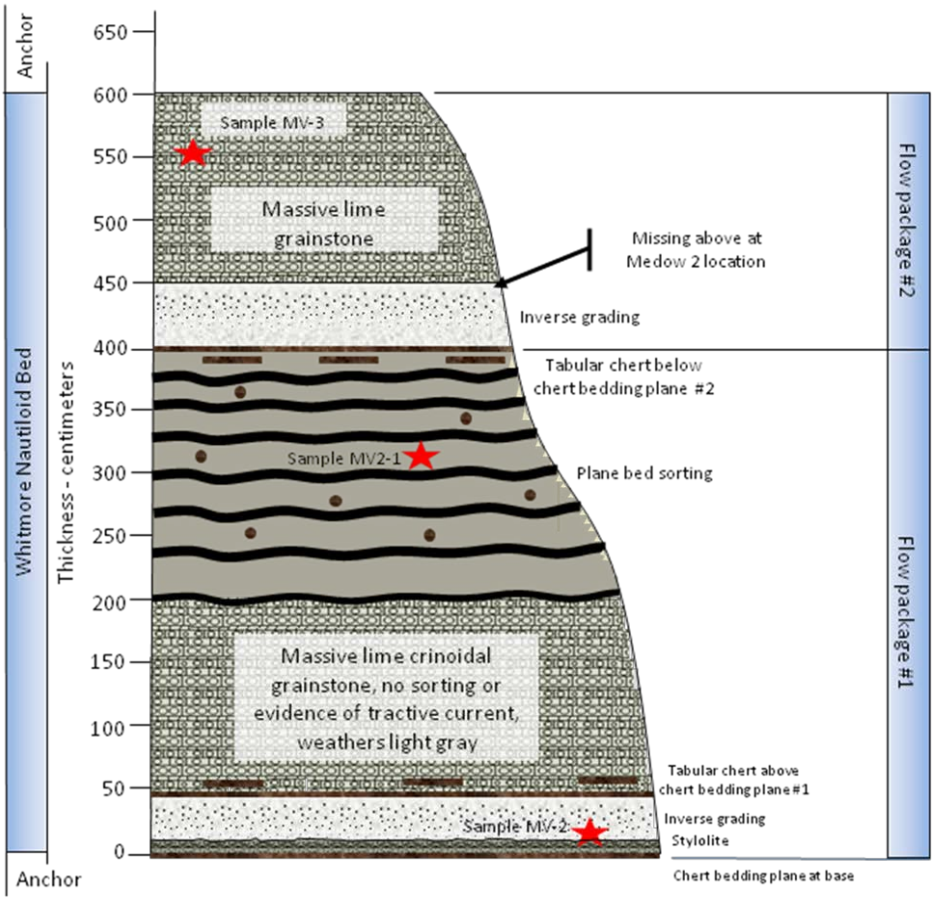

Figure 19. Meadow Valley Mountains WNB graphic. Two locations, Medow1 and Medow2 were used to construct this diagram with Medow2 providing excellent detail in the outcrop.

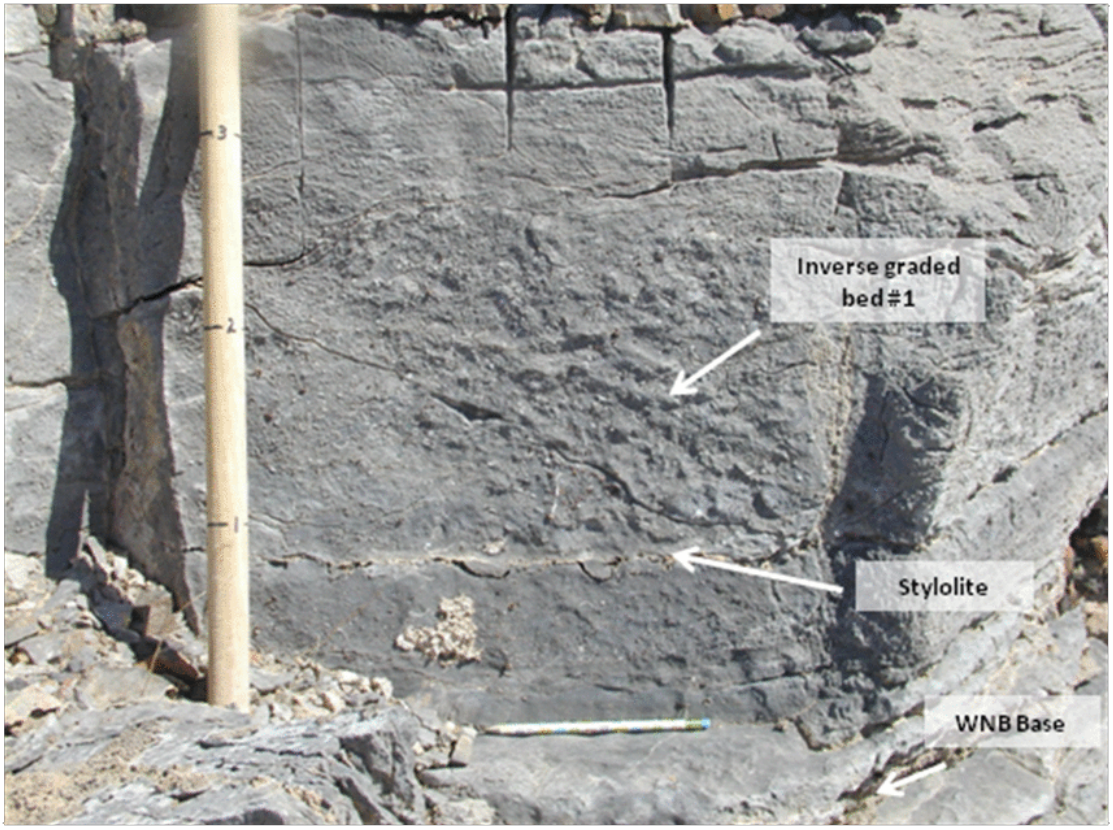

Figure 20. WNB Inverse Graded Bed #1 at location Medow2. Note the fine texture below the stylolite at the pencil and the coarsening-upward until the chert bed above is reached.

On top of the chert bed at 0.4 m is a massive bed changing into sorted plane beds at 2.0 m from the base of WNB (Figure 19). The sorted plane bed section is identified by coarse grained beds alternating with fine grained packstone where the coarse grained beds are 4-5 cm thick and the packstone beds are thicker at 10-20 cm. Some chert nodules are interspersed within the plane bed section. Chertification is heavy from the chert nodules all the way down to chertified crinoidal detritus.

Just above the plane bed section at 4.0 m is another laterally continuous chert bed underlying the second inversely graded bed. Figure 21 is a picture of the 0.5 m thick, inversely graded bed #2, beginning at 4.0 m from the base of WNB. The grading of inversely graded bed #2 at 4.0 – 4.5 m is more distinct and clear than the grading of the lower inversely graded bed #1. This bed is the cap of the outcrop at the Medow2 location.

Figure 21. WNB inversely graded bed #2 at Meadow Valley Mountains. This 0.5 m thick inversely graded bed forms the outcrop cap.

Since the upper part of WNB is missing at Medow2, at this level in WNB, the description moves back to the Medow1 location. At Medow1, 4.2 m from the base, WNB is noted to change back to primarily a coarse deposit with few chert nodules. This corresponds to inversely graded bed #2 at the Medow2 location. From here to the top of WNB at 6.0 m, WNB is noted to be a massive packstone. No additional structures were noted until WNB ends and Anchor again appears as a dark gray grainstone with distinct chert layers.

Scour and fill structures were identified in the Dawn Formation below the Anchor Formation, about 19 m below WNB. However, the lower boundary of WNB is identified as a 5-10 cm thick chert bed marking the change from Anchor to WNB without noticeable erosion. A similar chert boundary exists at the 4.0 m level below the second inverse graded bed. Vertical particle sorting

is apparent here due primarily to the plane bed sorting in the middle of WNB and both the inverse graded beds.

WNB at the Meadow Valley Mountains location is interpreted to be comprised of a primary concentrated density flow overlain by a second concentrated density flow. The overlying, second concentrated density flow formed from re-concentrating the heavy sediment laden surge-like turbidity flow overlying the concentrated density flow at Mormon Mountains. The flow deposit exhibits hyperconcentrated bed characteristics that likely result in a thinner deposit.

The objective of the bedform analysis was to determine if vertical particle sorting became more prevalent in the westerly deposits. As has been documented, the Mormon Mountains and the Meadow Valley Mountains locations show increased vertical particle sorting over the Squaw Canyon and Virgin River Gorge locations.

LAS VEGAS RANGE NORTH BEDFORM ANALYSIS

Previously studied by Stansbury (2003), the Las Vegas Range North section is here included. This analysis extends the westerly description of WNB bedform analysis and is located southwest of the Meadow Valley Mountains section (Figure 7).

At the outcrop at Las Vegas Range North, WNB is identified near the top of hill. Figure 22 shows the base of the dune about 2 m above the person's head where the chert beds can be seen to pinch together along a horizontal surface. To the right of the photograph, plane-bed configurations are apparent. This is interpreted to be the inter-dune deposit and is consistent with the high velocity 3-D dune analysis of Boguchwal and Southard (1990). No other dune structure can be identified in the down dip direction as the structure goes underground approximately 100 m westward. To the left in Figure 22, the chert beds can be seen to angle upwards in the formation at approximately 6-8°. This section is interpreted to be the lee (downstream) slope of the dune, the angle of slope being consistent with subaqueous dunes (Prothero and Schwab, 1996, p. 46). Flow direction is interpreted to be nearly straight west with bearing of 280°.

Figure 22. Oblique side view of dune bed form at Las Vegas Range North. The WNB outcrop at the point of the hill shows the base of the event bed about 2 m above the head of the person where the chert beds pinch together. The top of WNB is not visible in the photograph. Notice the upward sloping angle of the chert beds towards the left of the outcrop. This is interpreted as the lee (downslope) side of the dune.

The top of the preserved dune is approximately 2 m higher than the exposure in Figure 22. The top and bottom of the event bed is easily identified at this location. The Anchor Limestone is a dark-gray wackestone in this section as compared to the light gray weathering, coarse crinoid grainstone of the event bed. The upper contact of WNB with the Anchor is a very straight bedding plane. In contrast, the lower contact has minor variations and is not as clean a contact as that of the upper contact. This is most likely the result of interaction between the flow and base, caused by minor erosion. This is consistent with the flow's loss of hydroplaning capability as the flow inflates and becomes diluted in the concentrated regime.

The measured section of the outcrop is 9 m as compared to 8.4 m at Mormon Mountains and 6.0 m at Meadow Valley Mountains. The preserved dune formation comprises 7.5 m of the WNB in this section. Because no sigmoidal dune curvature was identified, and based on preserved dune geometries of $^1/_2$ to $^1/_3$ of the original dune being preserved, it is conservatively estimated that the original dune height was 15 m. As the exposure of the dune is observed around the nose of the outcrop, variation in thickness and a slightly concave upward base is seen. This could be interpreted as the result of scouring. However, the large extent of the flow would seem inconsistent with localized channel scours. More likely, this is an indication of the 3-D structure of the dune whereby the outcrop is presenting a change in thickness associated with a scour pit and curved lee face. Utilizing the dune classification scheme of Ashley (1990), this bedform is interpreted as a very large, subaqueous 3-dimensional dune.

WNB is described as a cross-bedded, pebble-granule-sand grainstone, dark gray weathering to light gray, with a mean grain diameter of 1.5 mm, containing abundant crinoid debris with some sparry replacement between calcite grains. Pebbles are over 4 mm with a maximum near 15 mm,

supporting the coarse crinoid grainstone description. The event bed is extremely reactive with acid. The chert beds within WNB are almost identical in color and texture to the limestone when un-weathered, but weather to a reddish brown or dark brown/black color. The chert is not reactive with acid.

Evidence of bed load layers, consistent with traction deposition, may be interpreted from the indistinct parallel lamination of larger particles (Figure 23). Further stratification of WNB may be inferred from the chert beds, where layers of accumulated fines may have been replaced by the chert. No large clasts, nautiloids or corals were identified in the event bed. The largest clasts were crinoids ranging from 10 to 15 mm in diameter. Because no larger clasts are present, it may be assumed that the flow concentration must have been less than that of a hyperconcentrated density flow that would have had the competency to carry them. Additionally, the crinoid debris and traction layers would not be consistent with suspension deposition. Therefore, WNB in this section is interpreted to be the depositional product of a tractive current at the base of a non-hydroplaning concentrated density flow.

Figure 23. Indistinct parallel laminations of larger grains within WNB. The light gray laminations, composed of large grains are indicative of traction deposition.

TEXTURAL ANALYSIS

At each of the four study locations, excluding the Las Vegas Range North section, samples were taken within Whitmore Nautiloid Bed. The samples were sent for thin sectioning and microphotography to Calgary Rock and Materials Services (Alberta, Canada), whose help is gratefully acknowledged.

Hyperconcentrated flows are expected to be matrix supported and concentrated density flows are expected to be clast supported. As WNB progressed westerly, it is hypothesized that the flow would transform from hyperconcentrated to concentrated to turbulent. If this hypothesis is correct, the textural analysis should show matrix support in the east and increasing clast support westerly.

The objective of the textural analysis is to classify each sample via petrographic name and determine matrix or clast support. Petrographic classification will assist in confirming the flow type based on the classification scheme of Mulder and Alexander (2001). Samples will be assigned a name based on the Dunham Classification for carbonate rocks (Figure 24). Scholle and Ulmer-Scholle's (2006) reference book was instrumental in the analysis of the following microphotographs.

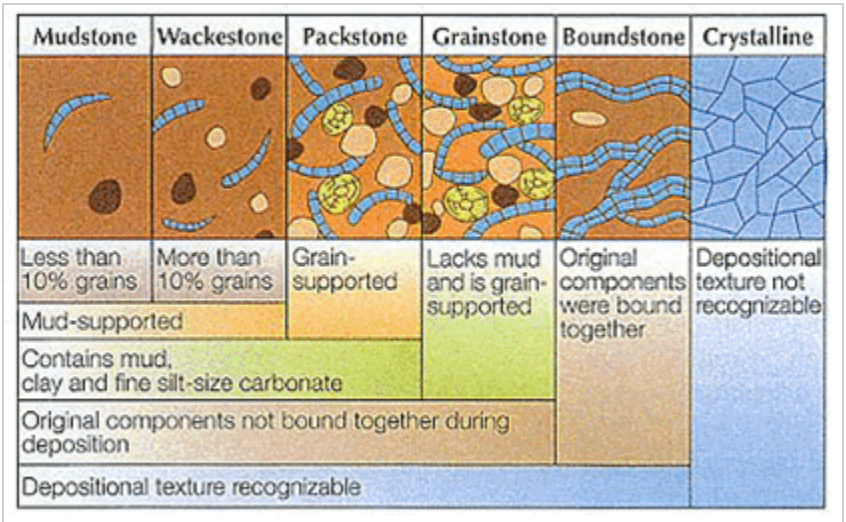

Figure 24. Dunham classification for carbonate rocks. Graphic citation from Schlumberger http://www.glossary.oilfield.slb.com/DisplayImage.cfm?ID=24. Dunham, 1962.

SQUAW CANYON TEXTURAL ANALYSIS SAMPLE SC-2

Sample SC-2 was taken from the bottom of WNB; approximately 29 cm from the base (see Figure 12). At Squaw Canyon, WNB is persistent and two meters thick. The lower 1.3 m is described as massive, weathering to light gray with two horizontal bedding planes. Based on the microphotographs, this sample is a Dunham crystalline carbonate rock, specifically a dolomite.

Figure 25 is a microphotograph of the thin section of dolomite at Squaw Canyon's SC-2 sample. Precursor sediment and fabric has been destroyed due to the recrystallization. This dolomite

shows a nonplanar fabric, anhedral crystals and a lack of pore space as seen in Figure 25. There are traces of skeletal grains in two other thin sections.

Figure 25. Squaw Canyon dolomite thin section SC-2. The crystal in the middle-right is over 2 mm long from top to bottom. This photograph was used for the point count analysis.

Figure 25 is representative of the SC-2 sample at Squaw Canyon and was used for the point count analysis. The point count analysis at all locations provides grain size histograms and grain size cumulative percentage charts for each sample. These charts are used to determine the mean, median, mode, sorting and skewness statistical measures for grain sizes in the samples. The methodology described by Prothero and Schwab (1996, p. 88) was used to determine the statistical measures for each sample.

Table 1 provides the results of the statistical measures for sample SC-2. Skewness, reported in the tables, is a statistical measure of the symmetry of a distribution whereby in an asymmetrical or skewed distribution, the median and mean shift from the mode (Prothero and Schwab, 2001, p. 88). Coarser grains being less well sorted than finer grains yields a negative skewness (*i.e.*, median and mean left of mode) while finer grains being less well sorted than coarser grains results in positive skewness (*i.e.*, median and mean right of mode). Figure 26 shows the grain size histogram and grain size cumulative percentage charts for sample SC-2.

Statistical Measures	Value	Description
Mean	-0.50 ϕ	Arithmetic Average
Median	-0.60 ϕ	Distribution Split In Half
Mode	-0.50 ϕ	Most Frequently Occurring
Sorting	0.89 ϕ	Moderately Sorted
Skewness	0.36	Strongly Fine Skewed

Table 1. Statistical measures for Squaw Canyon sample SC-2.

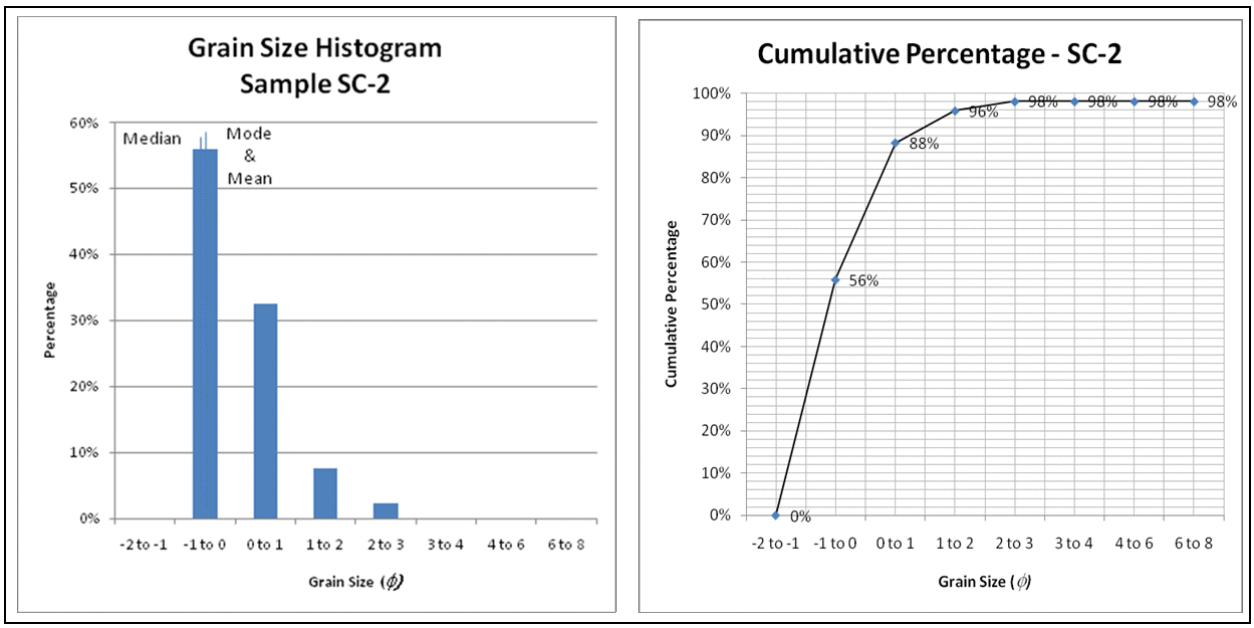

Figure 26. Squaw Canyon SC-2 grain size histogram and grain size cumulative percentage charts.

Squaw Canyon sample SC-2 is classified as a crystalline nonplanar dolomite of closely packed and curved anhedral crystals, crystal supported with no porosity, consisting mostly of very coarsely crystalline crystals.

VIRGIN RIVER GORGE TEXTURAL ANALYSIS SAMPLE VR-3

Two samples were taken at the Virgin River Gorge study location. Here, WNB is 3.8 m thick, the upper 0.5 m consisting of coarser grained sediment with water escape pipes, weathering to light gray. Only sample VR-3 will be discussed here. For more detailed statistics, discussion and additional samples, the reader is referred to Stansbury's thesis (2010).

Sample VR-3 was taken 114 cm up from the base of WNB (Figure 14) on the roadcut side of the exposure. Sample VR-3 is in the lower section of the bed. This is a recent exposure weathering to light brown. There are large crystals, up to 2.5 mm, throughout the sample and the sample is heavily fractured with calcite infilling.

Sample point counts were performed against a representative slide (Figure 27). Slides with large crystals were not used for the point count as the large crystals are more representative of a d_{max} size than the average texture of the location. It should be noted that no bioclastic debris was identified in this sample.

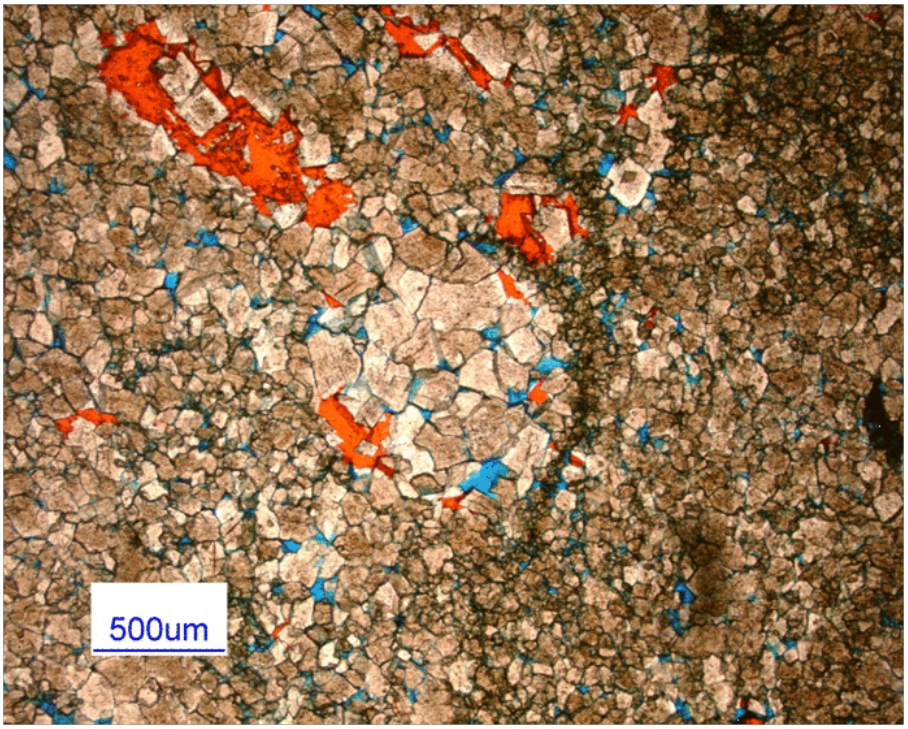

Figure 27. Virgin River Gorge thin section VR-3 microphotograph used for the point count analysis.

Table 2 contains the statistical measures for sample VR-3 from the point count. The grain size histogram and cumulative percentage chart is presented as Figure 28.

Statistical Measures	Value	Description
Mean	3.07 ϕ	Arithmetic Average
Median	3.10 ϕ	Distribution Split In Half
Mode	3.5 ϕ	Most Frequently Occurring
Sorting	1.08 ϕ	Poorly Sorted
Skewness	-0.09	Near-symmetrical (unskewed)

Table 2. Statistical measures for Virgin River Gorge thin section VR-3.

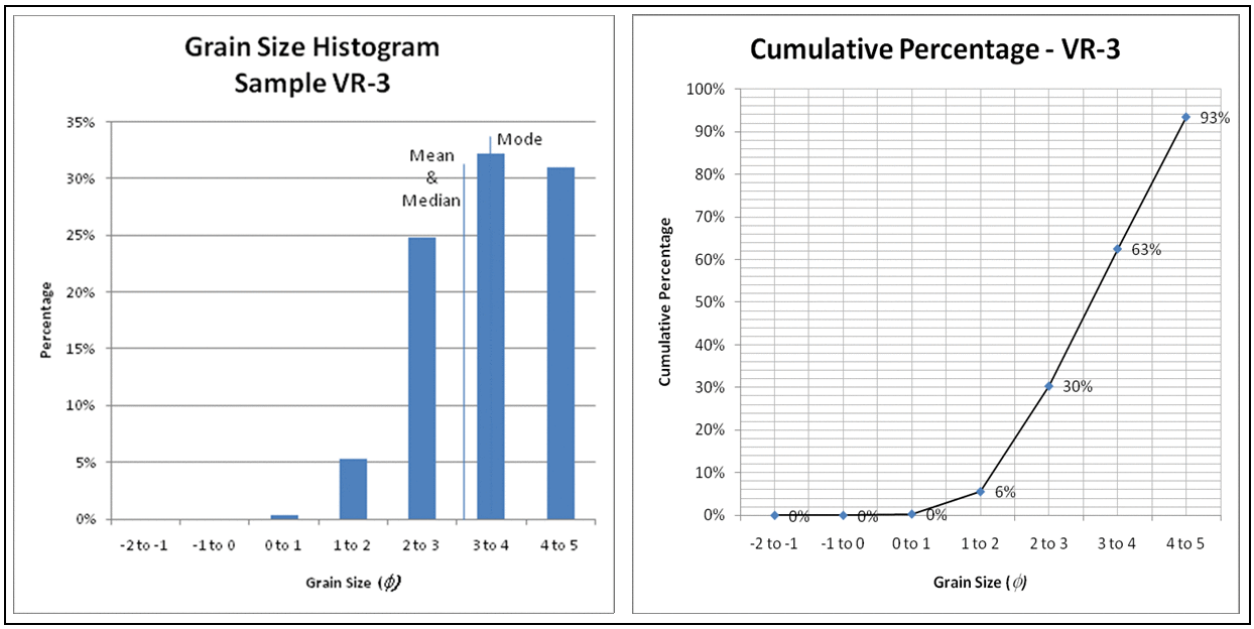

Figure 28. Virgin River Gorge VR-3 grain size histogram and grain size cumulative percentage charts.

Sample VR-3 is classified as crystalline with a planar-s to planar-e fabric consisting mostly of medium crystalline subhedral to euhedral rhomb crystals; crystal supported with inter-crystalline areas filled with calcite or porous.

MORMON MOUNTAINS TEXTURAL ANALYSIS SAMPLE MM-2

At this location, WNB shows a coarsening upward texture from the base to about 2.5 m and then transitions to a fining upward texture through the next 2.0 m. Two samples were taken at the Mormon Mountains location, Figure 16. Sample MM-2 is from the lower section of WNB.

Just over 50 cm from the base of WNB, sample MM-2 was collected and is a crinoidal lime packstone, weathering to light gray with heavy fossil content including crinoids and a high acid fizz. A representative microphotograph of the MM-2 sample is presented in Figure 29. Included in this slide is what are appear to be a rugose coral (upper right center), a crinoid columnal plate (center) with an arm plate above, various calcite crystals (upper right corner twinning), possible foraminifera (dark small oval shapes) and other skeletal debris.

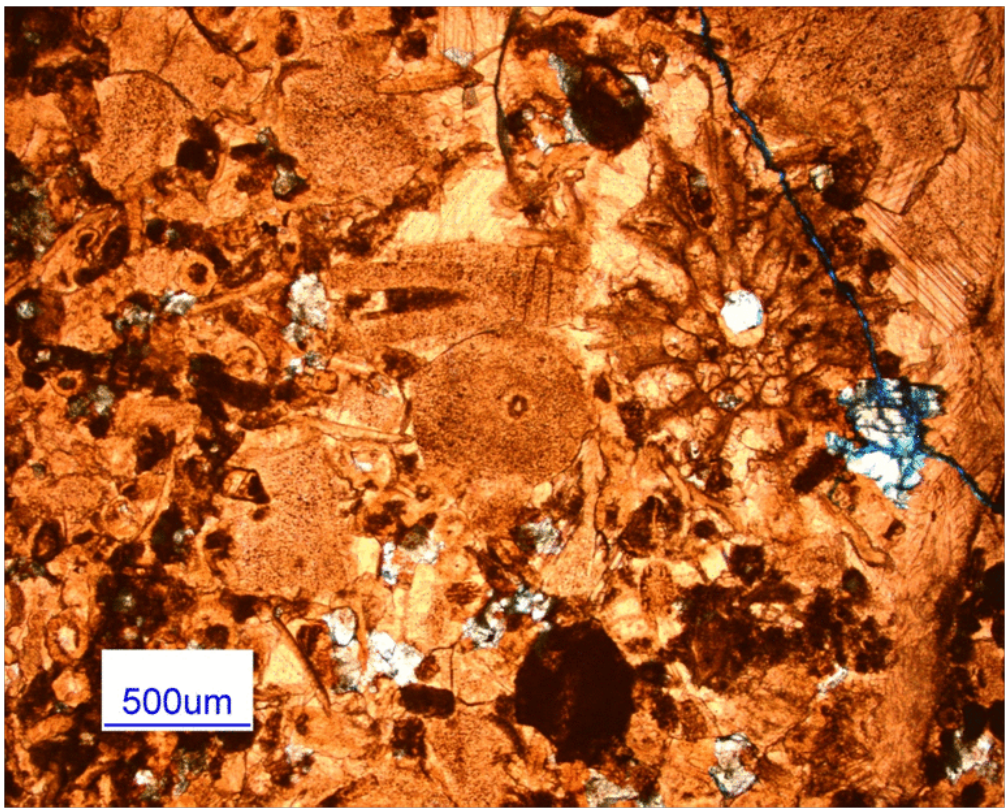

Figure 29. Mormon Mountains microphotograph of thin section MM-2. This photograph shows the variety of skeletal debris in the limestone at Mormon Mountains from rugose coral to crinoid plates.

On the micro-photograph of Figure 29, three hundred and thirty grid points were counted. Statistical measures for sample MM-2 are presented in Table 3 which is followed by the grain size histogram and cumulative grain size percentage charts of Figure 30. For purposes of this analysis, the sparite will be considered pore space and is not included in the grain size count percentages. In some places under points in the point count, inter-granular contacts occurred or no clear grain may be identified. Where this occurs, the point is assigned a silt sized matrix point.

Statistical Measures	Value	Description
Mean	1.30 ϕ	Arithmetic Average
Median	1.25 ϕ	Distribution Split In Half
Mode	2.5 ϕ	Most Frequently Occurring
Sorting	2.67 ϕ	Very Poorly Sorted
Skewness	0.29	Fine Skewed

Table 3. Statistical measures for Mormon Mountains thin section MM-2.

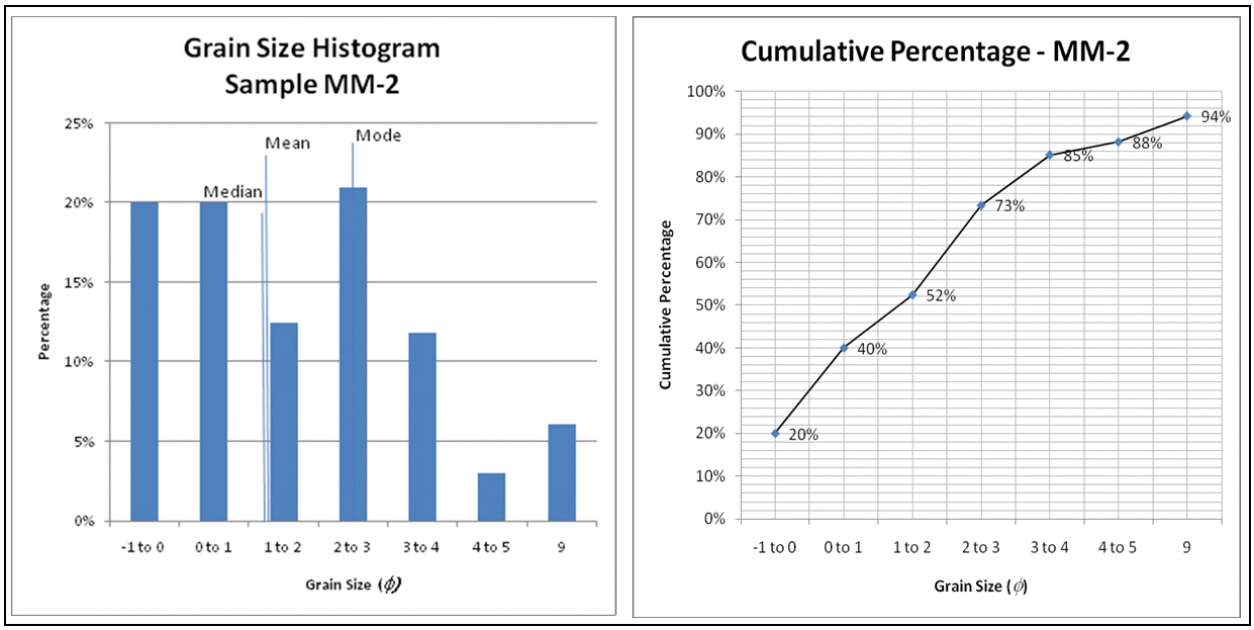

Figure 30. Mormon Mountains MM-2 grain size histogram and grain size cumulative percentage charts.

Is this sample a packstone or a grainstone? By definition, both packstones and grainstones are grain supported, as is the case here. The question then becomes, is there matrix or not? A grainstone contains <1% of material with diameters less than 20 μm, which is medium silt from 6.3ϕ to smaller 10ϕ clay grain sizes. 20 μm grains are easily identified in the scale of Figure 29. Smaller grains appear to be dark without the ability to see crystal boundaries. In this sample, many of the dark round shapes may be foraminifera tests and where clear shape is identifiable, they have so been counted. However, some of the dark spaces have no particular body shape or shadow that would imply a biologic origin and may be small amounts of matrix. The point count analysis identified 6% of the points in sample MM-2 as matrix points. This would exceed the grainstone test of <1% matrix and, therefore, is categorized as a packstone.

Sample MM-2 from the base of WNB at Mormon Mountains is a very poorly sorted fine- to coarse-grained, clast supported packstone composed of both skeletal debris and calcite re-crystallization. Grain size distribution is variable from very-fine sand to very-coarse sand sized grains yielding a fine skewed grain distribution.

MEADOW VALLEY MOUNTAINS TEXTURAL ANALYSIS

The Meadow Valley Mountains section is the farthest distal location of WNB where textural analysis was performed. Two locations were studied, Medow1 and Medow2, from which three samples were taken. Two of the samples were taken from Meadow1, samples MV-2 and MV-3, and sample MV2-1 was taken from the second location at Medow2 (Figure 18).

The samples at this location demonstrate the varied macro characteristics of the flow at Meadow Valley Mountains as shown in the bed form graphic of Figure 19. Two flow packages with

inverse grading and vertical particle sorting macro characteristics show further micro characteristic variation from packstone to dolomite. Each sample is discussed below with the statistical analysis provided for MV2-1 which was taken from the plane bedded section of location Meadow2. Refer to Figure 19 for the sample locations within WNB.

Sample MV-2 (Figure 31) is from the inverse graded base section of WNB and is a poorly sorted crinoidal microspar wackestone composed mostly of 5- to 20 μm-sized calcite crystals with some skeletal grains. Pore space is filled with sparite as in other samples. Grain size distribution is primarily very-fine silt sized with some fine- to very-fine sand, is strongly coarsely skewed and matrix supported.

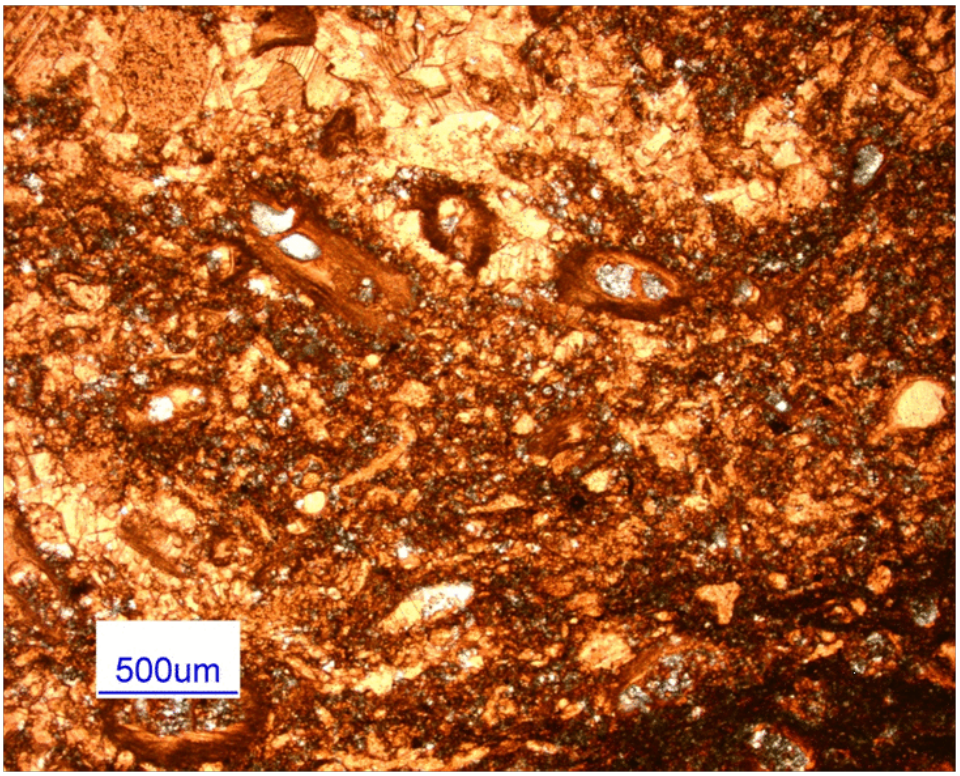

Figure 31. Meadow Valley Mountains thin section MV-2 microphotograph.

The Meadow Valley Mountains sample MV2-1 (Figure 32) is from the plane bedded traction section of the middle of WNB (Figure 19). Only the point count analysis details for sample MV2-1 are presented here. Table 4 provides the results of the point count and Figure 33 is the histrogram and cumulative grain size chart.

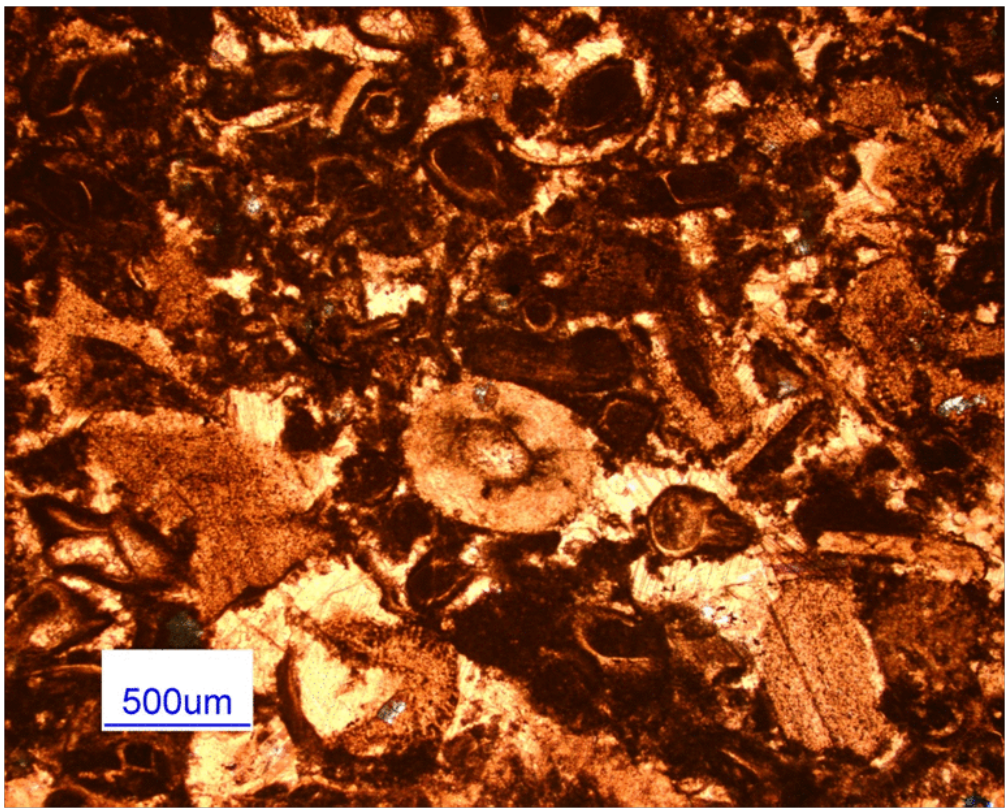

Figure 32. Meadow Valley Mountains MV2-1 thin section microphotograph. Ample skeletal fragments and calcite re-crystallization exist in this slide.

Statistical Measures	Value	Description
Mean	2.25 ϕ	Arithmetic Average
Median	1.75 ϕ	Distribution Split In Half
Mode	9 ϕ	Most Frequently Occurring
Sorting	2.68 ϕ	Very Poorly Sorted
Skewness	0.39	Strongly Fine Skewed

Table 4. Statistical measures for Meadow Valley Mountains thin section MV2-1.

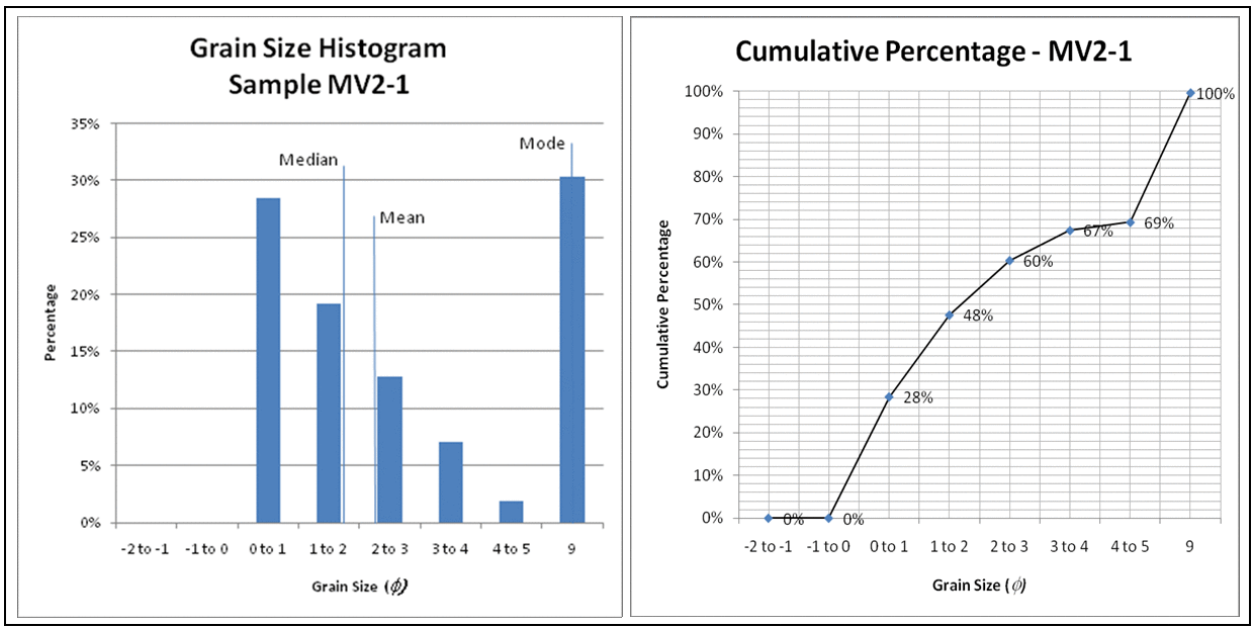

Figure 33. Meadow Valley Mountains thin section MV2-1 grain size histogram and grain size cumulative percentage charts.

Sample MV2-1 is a very poorly sorted packstone composed of medium- to coarse-sand sized skeletal debris with a micritic (8-10ϕ) matrix. There is virtually no pore space in this slide as the packstone is very tight. Grain size distribution is primarily fine- to coarse-sand sized with substantial matrix, grain supported and is strongly fine skewed.

The third sample, MV-3, was taken at location Medow1 at 5.5 m from the base of WNB, roughly 0.5 m from the top of the deposit. This section of WNB is very coarse, weathering to light gray and, interestingly contains heavy chert slabs just below and above the sample location. This sample is very different from the previous Meadow Valley Mountains samples, but is clearly part of WNB as overlying this section is an abrupt transition to the coarse, dark gray rhythmites of the Anchor Formation.

Figure 34, the microphotograph of sample MV-3, shows large dolomite crystals and finely- to very-finely crystalline matrix, and is taken to be representative of the overall textural characteristics of the MV-3 sample location. The dark crystalline points were counted as very-finely crystalline (8 to 10 ϕ) and the larger and lighter crystalline points were counted as finely crystalline (4 to 6 ϕ).

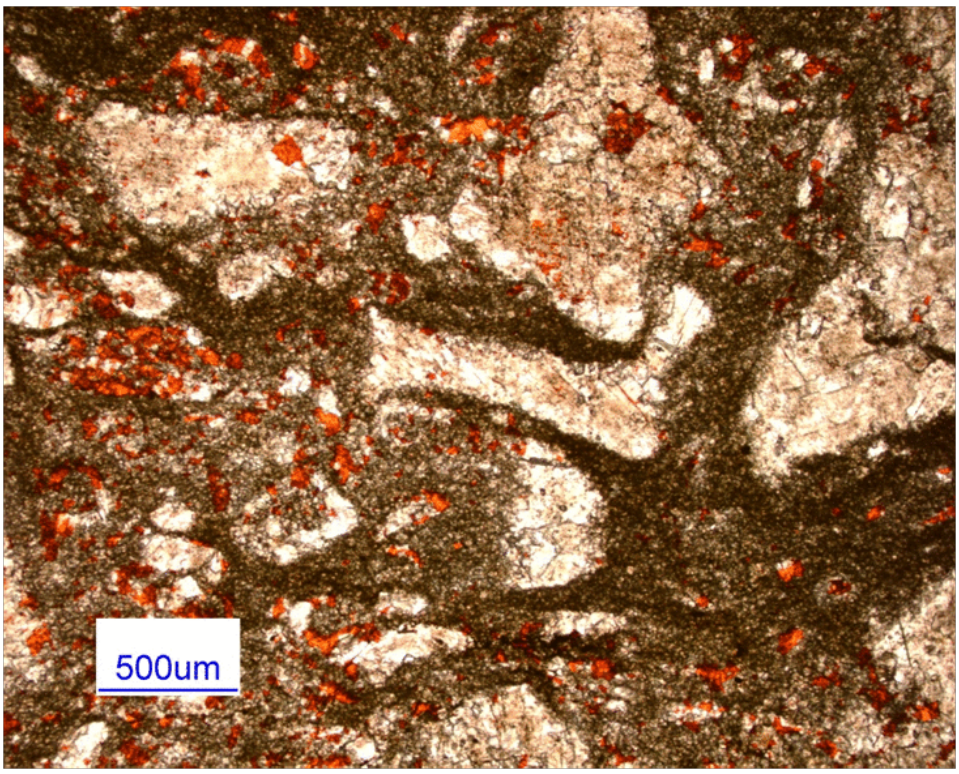

Figure 34. Upper section of thin section MV-3, large dolomite crystals "float" in a crystalline matrix.

Upper WNB at Meadow Valley Mountains contains a variety of dolomitized fabrics from dolomitized calcite crytals to skeletal debris to outstanding rhombs. Sample MV-3 is a finely- to very-finely crystalline dolomite matrix with coarse- to very-coarse grained clasts lacking pore space and demonstrating matrix support.

CONCLUSION

How does an underwater debris flow end? Specifically, does an underwater debris flow end by becoming frictional and freezing, or does it end by becoming turbulent, ingesting fluid and transforming into a tractive current resulting in the deposition of large volumes of sediment? The purpose of this study was to analyze the stratigraphy, bedforms and textures at four locations for the Whitmore Nautiloid Bed flow event in the upper Whitmore Wash Member of the Redwall Limestone, northern Arizona through southern Nevada, to answer the proposed questions.

STRATIGRAPHIC CORRELATION

The stratigraphic correlation had two primary objectives: 1) ensure the bed being studied is stratigraphically correlated throughout the study area, and 2) answer the question of the hypothesis that the bed should thicken distally. Whitmore Nautiloid Bed (WNB) was correlated throughout the study area as it is identified at the base of the rhythmic Thunder Springs Member in Arizona. As WNB progresses into Nevada, the bed characteristics are traced into the Anchor Limestone of the Monte Cristo Group. The easterly proximal end of WNB at Squaw Canyon is a

consistent 2.0 m thick inflating distally to 3.8 m at Virgin River Gorge, 8.4 m at Mormon Mountains and 6.0 m at the most distal end of the study area at Meadow Valley Mountains. Further west and distally at Las Vegas Range North, Nevada, WNB is reported to be a preserved dune feature 7.5 m thick. The reduction in bed thickness from Mormon Mountains to Meadow Valley Mountains is interpreted to be the result of the flow re-concentrating and forming two concentrated flow packages. This conclusion is based on the reappearance of hyperconcentrated bedforms at Meadow Valley Mountains. The bed then inflates again to the Las Vegas Range location where only concentrated bedforms have been identified. The hypothesis is positively confirmed as the bed does inflate as it progresses distally.

BEDFORM ANALYSIS

The hypothesis states that WNB should ultimately transform from a hyperconcentrated flow into a concentrated flow and finally into a turbulent flow by ingesting fluid and inflating. A wide variety of tractive current structures should form in the bed and become more abundant in the distal direction because of reduced sediment concentration and increased turbulence. Specifically, as the flow moves distally, an increase in vertical particle sorting should appear. The most distal section of this study at Meadow Valley Mountains did not discover the end of the flow deposit. Nor was the terminal end of the flow identified at Las Vegas Range. Further study west of Las Vegas Range should be performed to identify the terminus of the flow.

The hyperconcentrated regimes of the flow at Squaw Canyon and Virgin River Gorge have no indication of bedforms and are generally massive. The Mormon Mountains location has multiple bedforms demonstrating vertical particle sorting and is classified as a concentrated density flow. Coarsening-upward, fining-upward, tractive current plane beds and multiple massive beds from flow surges are identified bedforms at the Mormon Mountains location. The distal end of the study area at Meadow Valley Mountains also has bedforms including inverse graded beds, massive beds, tractive current plane beds and chert beds indicative of particle sorting. Here the deposit is interpreted to be two concentrated flow deposits, one overlying the other, with mixed bedforms of hyperconcentrated and concentrated character. West of the study area and still more distal, a large dune is identified with indications of tractive current deposition at the Las Vegas Range.

This study has found a wide variety of tractive current structures, becoming more abundant as the flow moves distally. This is due to the decreasing sediment concentration that allow for vertical particle segregation because of flow dilution and loss of fluid pressure resulting in the formation of tractive current and suspension structures, thus confirming the hypothesis.

TEXTURAL ANALYSIS

The focus of the textural analysis was to address the question: Do matrix supported textures give way distally to clast supported textures? The two proximal locations, Squaw Canyon and Virgin River Gorge, were both dolomitized and precursor fabrics were destroyed. The dolomitization at Squaw Canyon is extreme and the conclusions on precursor sediments and fabric is speculative. Based on dolomite crystal sizes, it is interpreted that Squaw Canyon had a precursor clast supported texture while the major precursor texture at Virgin River Gorge, with smaller grains than Squaw Canyon, was matrix supported. There is an upper section to the Virgin River Gorge

deposit, the top 0.5 m, which is interpreted to be clast supported but is likely due to the removal of fines as the deposit settled, compressed and dewatered. At the Mormon Mountains location, clast support and vertical particle sorting is evident in coarsening-upward, fining-upward and tractive beds. No concentrated bedforms are described in the deposit. The most distal study area at Meadow Valley Mountains exhibits both hyperconcentrated and concentrated flow bedforms and as such, has both matrix and clast supported textures.

The hypothesis that matrix supported textures should give way distally to clast supported textures is not confirmed through the study locations – with caveat. The issue is more complex than the general statement of matrix support giving way to clast support distally. Heavy sediment concentrations may form typically hyperconcentrated beds (e.g., inverse grading, massive) in both hyperconcentrated and concentrated flow regimes. What this study has found is that the basis for the hypothesis is correct. Simply stated, hyperconcentrated beds are matrix supported and concentrated beds are clast supported. The study found that hyperconcentrated beds may exist in concentrated flow regimes. The flow may deposit hyperconcentrated and concentrated beds at the same location in a concentrated flow regime due to sediment re-concentration. This distorts the statement that matrix support gives way distally to clast support, because the determining factor is not the location within the lateral extent of the flow that dictates fabric, but what type of deposition was occurring at that location within the flow.

SUMMARY

So then - How does an underwater debris flow end? - is the major question in this study. Although the terminal end of WNB was not discovered, it is determined that WNB ended in the study area by flow transformation and not by frictional freezing. WNB is traced throughout the study with no discontinuity, inflates distally, exhibits increased vertical particle sorting distally and matrix or clast support is driven by the type of deposition and not the location of the deposition in the flow deposit.

The terminal end of the Whitmore Nautiloid Bed flow event was not discovered in any of this study's locations. No outrunner blocks, clearly turbulent flow regime deposits or terminal flow discontinuities were identified. The transition to the end of the flow has been studied but the actual flow termination point has yet to be discovered. In a distance of approximately 80 km, from Squaw Canyon, AZ to Las Vegas Range, NV, it is estimated that the flow velocity decreased roughly 3 m/s, from 5 m/s at the Squaw Canyon hyperconcentrated deposit to 2 m/s at the cross-bedded dune deposit of Las Vegas Range. Assuming a steady flow velocity decrease and no topographic barriers, this distance offers a suggested flow terminus in the range of an additional 50 km. Further study is proposed for the area west and north of Las Vegas, NV to find the terminal end of the WNB flow event. This would include the areas just east of Nellis Air Force Range and north of Pahrump, NV. Future, similar studies need to be performed to completely answer the primary question as it pertains to the Whitmore Nautiloid Bed flow event.

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