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FLOW DYNAMICS OF AN ENORMOUS SUBAQUEOUS DUNE
WITHIN THE ANCHOR LIMESTONE, LAS VEGAS RANGE,
CLARK COUNTY, SOUTHERN NEVADA

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Limestone, cross-bedding, subaqueous dune, bedform analysis, flow depth, flow velocity, hydrodynamics, Anchor Limestone, Redwall Limestone, Las Vegas Range, Grand Canyon, Nevada.

ABSTRACT
Very large cross-beds with a measured height of 7.5 m occur in the middle of the Anchor Limestone (Lower Mississippian, Las Vegas Range, southern Nevada) and are composed of pebble-granule-sand, crinoid grainstone. The bedform is understood to be the preserved remnant of an enormous, subaqueous, 3-dimensional dune with original height estimated conservatively at 15 m with length of about 800 m. Dunes produced in laboratory flumes and dunes observed in natural shallow-water straits allow scaling of the hydrodynamics of the tractive current that produced the large-scale cross-beds within the gigantic subaqueous dune. The depositional environment of the dune is interpreted to be a marine slope with a water depth of 140 m. Flow thickness exceeded 15 m and flow velocity is estimated conservatively at 2.5 m/s toward the west. The large scale of this bedform attests to the rapid, catastrophic emplacement of coarse lime sediments in this section of the Anchor Limestone. This enormous dune is interpreted to be the distal tractive current deposit formed by the fluid turbulence generated by breakdown of a hydroplaning, fast-moving, hyperconcentrated sediment gravity flow after it had traversed northern Arizona.

INTRODUCTION
A regionally extensive limestone bed occurs within the Redwall Limestone (Lower Mississippian) in the Grand Canyon region (northern Arizona, southwestern Utah and southern Nevada). Austin [3] described the bed as 2 to 14 m thick composed of lime packstone and grainstone. The bed’s extraordinary fossil content influenced Austin [3] to call it “Whitmore Nautiloid Bed” (WNB). This persistent stratigraphic unit occurs at the top of the Whitmore Wash Member of the Redwall Limestone (Arizona terminology of McKee [17]) and in the middle of the Anchor Limestone (Nevada terminology of Stevens et al. [26]).

The Anchor Limestone is more than 3 times thicker in the Las Vegas Range of Nevada (140 m according to Page [22]) than its equivalent strata are to the east in Grand Canyon of Arizona (36 m according to McKee [17]). Poole and Sandberg [23] presented models of platform and slope facies for the westward-thickening Mississippian strata in the western United States. The depositional environment of the Mississippian strata in southern Nevada is interpreted to be a deeper marine slope with depositional surface dipping westward, whereas the depositional environment towards the east, including Grand Canyon, is interpreted to be a shallow marine platform with essentially level depositional surface [23].

Whitmore Nautiloid Bed (WNB) contains abundant orthocone nautiloids buried by a catastrophic sedimentary event having a sediment volume exceeding 100 km³ and bed area of more than 30,000 km² [3]. The sedimentary event was interpreted by Austin [3] to be a high-sediment-concentration, laminar flow (i.e., hyperconcentrated density current) with velocity of more than 5 m/s. The hyperconcentrated flow appears to have hydroplaned westward through a shallow-marine platform in Arizona before encountering a deeper marine slope in southern Nevada [3]. The hyperconcentrated flow deposit is uniformly 2 m thick in the uppermost Whitmore Wash Member (lower Redwall Limestone of Arizona). Westward in southern Nevada the flow deposit occurs within the Anchor Limestone and thickens significantly to as much as 14 m. In southern Nevada the bed is interpreted by Austin [3] as deposited by a high-sediment-concentration, turbulent flow (i.e., concentrated density current).

The extent of Whitmore Nautiloid Bed (WNB) is currently being investigated [3]. As part of defining the areal extent of the sedimentary event, potential exposures of WNB are being studied. I was asked by Dr. Steve Austin to conduct reconnaissance field investigation of WNB in the distal area of the high-
sediment-concentration, fast-moving flow in southern Nevada at the north end of the Las Vegas Range (Figure 1) in Clark County, Nevada. From the regional stratigraphic correlation I was directed to investigate the middle of the Anchor Limestone about 26 m above the base of the formation. The flow unit called Whitmore Nautiloid Bed east of the Las Vegas Range is about 9 m thick, composed of multiple, horizontal, graded-to-massive flow units of light-gray-weathering crinoidal grainstone within the thinner, dark-gray-weathering beds of the Anchor Limestone (Lower Mississippian) in Clark County, Nevada. I was expecting to see a similar succession of horizontal beds at the north end of the Las Vegas Range. At one outcrop in the North Las Vegas Range I discovered very large, west-dipping limestone cross-beds within the middle of the Anchor Limestone. The purpose of this investigation is to describe these large-scale cross-beds and infer the hydrodynamic conditions responsible for their formation.

SEDIMENT DENSITY FLOWS
Mulder and Alexander [20] recently revised nomenclature for sediment density flows. In order for a sediment density flow to begin, sediment must be taken into suspension by a catastrophic trigger event [18]. As the flow proceeds, the sediment concentration and dynamics change and three flow classifications have been adopted. A single flow may progress through each stage of flow classification, as is believed to be the case for WNB. The three flow classifications are (1) hyperconcentrated flow, (2) concentrated flow and (3) turbidity flow [20]. Subdivision into the flow classifications is based on sediment volume concentration, which influences the dominant particle support mechanisms, i.e. grain-to-grain interaction or fluid turbulence. These particular flows contain minimal clay-sized particles that would be needed for matrix support. Therefore, they are defined as non-cohesive density flows and are not considered debris flows.

Very high sediment concentrations are experienced in the early stages of a sediment gravity flow. Non-cohesive sediment flows with sediment volume concentrations ranging from 25% to more than 40% have been classified as hyperconcentrated flows by Mulder and Alexander [20]. Characteristics of these flows are based on friction dominated grain interactions. This accounts for frictional freezing deposition with inverse grading, a consequence of an upward velocity gradient in the flow and a laminar flow regime [10, 20], and fluid escape, collapse and deformation structures [15]. Large sediment clasts may be found within these deposits just above the laminar flow regime. The high concentration of sediment and the effects of two-layer flow (a basal fluidized layer and a lower permeability upper layer) traps water below the slurry allowing the flow to hydroplane [19]. This reduces basal erosion and provides for high-velocity, long-run-out flows. These characteristics have all been identified in the eastern section of WNB by Austin [3].

Hyperconcentrated density flows may transform into concentrated density flows [6, 20]. As the concentration of sediment by volume decreases below 25% and intruded water dilutes the flow, the upper part of the flow becomes turbulent and particle fall-out and sorting will occur. The dilution of the flow allows trapped basal fluids to escape, which prevents the flow from hydroplaning [20]. Elimination of the hydroplaning effect increases basal friction causing the flow to erode and sculpt bedforms. Depositional characteristics may include stratification, parallel lamination, Bouma Tbc sequences, thickness changes and bedforms, specifically dunes [2, 6, 12, 14, 16, 20, 25].

As the flow continues to dilute, the dominant particle-support mechanism becomes turbulence. The transition from concentrated flow to turbidity flow, based on sediment concentration, is not well defined. Turbidity flow, sensu stricto, is defined at a sediment volume concentration of 9% by volume or less [4]. Turbidity flow, sensu lato, introduced by Mulder and Alexander [20], spans the concentration from 9% upward into the lower concentrated density flow regime. This transition is most easily identified by the characteristics of the deposit. A turbidity flow cannot transport large clasts, and turbidity flow deposits are composed mainly of fine-grained sediment that can be transported in suspension. Bouma Tabc sequences are sometimes missing [21, p. 57]. However, bedforms and sedimentary structures are more dependent upon sedimentation rate and not enough is known to use these as reliable distinguishing features [20].

DUNE DESCRIPTION
Figure 2 is an oblique areal photograph of the studied cross-bed outcrop in the lower half of the Anchor Limestone at the north end of the Las Vegas Range. The dune bedding structures of the WNB in the Anchor Limestone at Las Vegas Range North are 26 m above the base of the Anchor Formation. The
Figure 1. Location map of very large limestone cross-beds. The flag indicates the location of the dune outcrop in the Anchor Limestone of Las Vegas Range, approximately 2 km west of Highway 93, about 35 km west of the town of Moapa, Nevada. GPS coordinates of the outcrop are N 36° 39.244', W 114° 56.518' with an elevation of 952.7 m at an accuracy of 2.2 m (North American Datum 1927).

Figure 2. Oblique areal photograph of Whitmore Nautiloid Bed in the northern Las Vegas Range. The arrows indicate the preserved 9 m thick bed in the Anchor Limestone, the approximate base of the Anchor Limestone and where WNB dips underground. The bed is dipping from left to right (east to west) at approximately 15°.
outcrop strike of WNB varies slightly but averages about 15° relative to true north with a structural dip of 15° west. Cross-stratification has been preserved by replacement chertification of fines within the dune structure, indicating particle sorting. Tractive currents are also indicated by indistinct laminations of grain size in the preserved bed. Cross-stratification angles, identified by the chert beds, are about 8° and are consistent with aqueous dune formation [24]. Evidence of moderate sorting is seen in the abundant crinoidal debris that does not exceed approximately 15 mm diameter. This subaqueous dune structure is preserved in a 9-m-thick section of cross-bedded, pebble-granule-sand crinoid grainstone about 26 m above the base of the Anchor Formation.

Figure 3 shows a relatively good view of detail of the side of the dune viewed nearly along the strike of the bed. The base of the dune is 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 [5]. No other dune structure can be identified in the down dip direction as the structure is buried beneath slope debris approximately 100 m westward. To the left in Figure 3, 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 [24]. Flow direction is interpreted to be nearly straight west with bearing of 280°.

The top of the preserved dune is approximately 2 m higher than the exposure in Figure 3. Detail of the base of WNB is shown in Figure 4. 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 (Figure 4) 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 inflated and became diluted in the concentrated regime.

The measured section of the outcrop is 9 m. 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 scour. More likely, this is an indication of the 3-D structure of the dune where the outcrop is presenting a change in thickness associated with a scour pit and curved lee face [7, 8]. Utilizing the dune classification scheme of Ashley [2], this bedform is interpreted as a very large, subaqueous, 3-dimensional dune.

Very large modern subaqueous dunes are on the order of >100 m spacing and have heights of >5 m. Ashley [2] identifies very large subaqueous dunes in three modern examples: (1) 3-D dunes with spacing of about 125 m in the Icelandic River, (2) 2-D subaqueous dunes with spacings of 75-125 m in the Lougher Estuary, Wales, and (3) very large subaqueous dunes with spacings of 50-300 m in the Torres Strait, Australian continental shelf. Additionally, Rubin and McCulloch [25] have studied very large 2-D subaqueous dunes in San Francisco Bay, California.

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 unweathered, 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 [14], may be interpreted from the indistinct parallel lamination of larger particles (Figure 5). 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 within the event bed in the Las Vegas Range. 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
Figure 3. Oblique side view of the base of the dune bedform. 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 into a horizontal surface. The top of WNB is not visible in the photograph. Notice the downward sloping angle of the chert beds towards the right of the outcrop. This is interpreted as the lee (downslope) side of the dune with flow direction to the right (westward).

Figure 4. Bottom boundary of dune bedform in WNB within Anchor Limestone. Coarse, light-gray-weathering grainstone of WNB overlies the fine, dark-gray-weathering wackestone about 26 m above the base of the Anchor Limestone at the northern end of Las Vegas Range.

Figure 5. Indistinct parallel laminations of coarser granules within WNB. The light-gray laminations, composed of large grains are indicative of traction deposition.
to be the depositional product of a tractive current at the base of a non-hydroplaning concentrated density flow.

FLOW DYNAMICS
The objective of this section is to estimate the water depth and flow velocity associated with the deposition of this very large dune. This is accomplished by estimating dune spacing, from which water depth may be derived. Flow velocity may then be estimated by scaling from observational data. The observational data is based on water flowing over a sediment surface creating bedforms. As shown by Kranenburg [13], the water flow velocity may be evaluated by placing an arbitrary coordinate system on the head of the sediment flow. This coordinate system is stationary with the sediment flow head and allows for evaluation of water flow velocity as if the water were flowing over the sediment flow (Figure 6). This interpretation reconciles the issue that the sediment flow is actually moving through the water with the observational results of water flowing over the bedforms.

![Figure 6. Flow relative to a moving front. A stationary coordinate system may be assumed for the flow head resulting in analysis as if the water were flowing over the sediment flow. Flow parameters are velocity \( U_f \) of the flow and velocity \( U_r \) behind the flow head [13].](image)

Depositional environment
As previously defined, the original dune height is conservatively estimated at 15 m. Dune spacing is estimated from dune height using Equation 1 [9]:

\[
H = 0.06775^{0.8909} \ldots \ldots (1)
\]

The relationship between dune height, \( H \), and dune spacing, \( L \), is based on observational analysis of 1,491 subaqueous marine bedforms from Flemming [9]. This provides a dune spacing estimate of 790 m.

Water depth may be approximated using the relationship between dune spacing, \( L \), and water depth, \( d \), as in Julien and Klaassen [11]:

\[
\frac{L}{d} = 6.25 \ldots \ldots (2)
\]

This relationship is based on laboratory and field data from Julien and Klaassen [11]. Solving for \( d \) yields an estimated water depth of 126 m.

Flow velocity
Boguchwal and Southard [5] performed extensive analysis on scale modeling of bed configurations. Their results are standardized to a water temperature of 10° C from dimensionless values for depth, velocity and sediment mean size. The paleoecology of corals in the Anchor Limestone indicates a water temperature of 25° C. Therefore, water temperature corrections are made to convert 25° C values to 10° C for use in Boguchwal and Southard [5] charts. The results are then converted back to 25° C to obtain estimates relevant to Anchor Limestone.
Mean flow depth, $d_{10}$, at 10° C is used to find the mean flow velocity, $U_{10}$, at 10° C from Boguchwal and Southard [5] for a temperature corrected mean grain diameter of 0.64-0.80 mm. Correction of estimated water depth at 25° C is based on Equation 3 [5]:

$$d_{10} = d \left( \frac{\mu_{10}}{\mu} \right)^{\frac{3}{32}} = 126 \left( \frac{1.30}{0.90} \right)^{\frac{3}{32}} = 162 \text{ m. . . . . (3)}$$

where $\mu_{10}$ is the viscosity of water at 10° C and $\mu$ is the viscosity of water at 25° C. Viscosity values are from Amyx, Bass and Whiting [1]. Sufficient bed regime boundary data for viscosity corrected mean sediment size is not available. Additionally, Boguchwal and Southard’s analysis is based on quartz sands with a specific gravity of 2.65 gm/cm$^3$, which is lighter than the specific gravity of calcium carbonate sands at 2.71 gm/cm$^3$. However, viscosity correction for the mean sediment size and increased specific gravity would both result in increasing the mean flow velocity for bedform boundaries [5].

**Figure 7.** Extended bedform boundary diagram after Boguchwal and Southard [5]. The bedform boundaries, where $D_{10}$ is 0.64-0.80 mm, were extended to allow the estimate of mean flow velocity, $U_{10}$, for a viscosity corrected depth, $d_{10} = 162$ m, as depicted by the upper horizontal dashed line.

Data from Boguchwal and Southard [5] were used to create a bedform boundary diagram of Figure 7. The boundaries were extended using a linear regression via least squares to allow estimates for deep water. The ripple/dune regression line and the dune/upper-regime plane bed regression line bound the flow regime for stable dunes. Estimates of $U_{10}$ are obtained where the 162-m $d_{10}$ flow depth intersects these boundaries. From the chart, a lower velocity of 0.57 m/s and an upper velocity of 5.40 m/s are obtained.

These velocities must then be corrected back to the original depositional environment of 25° C. This is done using the viscosity correction of Boguchwal and Southard [5]:

$$U = U_{10} \left( \frac{\mu}{\mu_{10}} \right)^{\frac{3}{32}} \quad \ldots \ldots \ (4)$$

The corrected minimum velocity for dune formation is then estimated to be 0.50 m/s and the maximum velocity for dune stability is 4.78 m/s. At lower velocities, 2-D dunes would be created. As the velocity increases, the dunes will transition from 2-D to 3-D dunes where the crests are less continuous and more irregular [5].
Observational data is based on the water velocity over the bedform. Therefore, water velocity over the flow, \( U_i \), from Figure 6, is used to approximate flow velocity, \( U_f \). Notice that \( U_i \) will be faster than the actual flow velocity \( U_f \) depending upon the relationship between \( d_r \), total water depth and \( d_t \), partial water depth above the flow. Observational data and above estimated water depth correspond to \( U_i \). Using \( U_i \), an estimate for \( U_f \) may be obtained from the conservation of mass \( q \) as illustrated by Kranenburg [13]:

\[
q = U_i \cdot d_r = U_i \cdot d_t \quad \text{or} \quad U_i = \frac{U_i \cdot d_r}{d_t} \quad \ldots \ldots \ldots (5)
\]

The minimum flow depth would have to be at least as high as the original dune height, estimated at 15 m, \( d_t \) of Figure 6. Therefore, it is assumed that the total water depth, \( d_t \), is 141 m; partial flow depth, \( d_r \), is 128 m; and water flow velocities above the sediment flow, \( U_i \), range from 0.50 m/s to 4.78 m/s. Solving the conservation of mass equation provides estimates of flow velocities from 0.45 m/s to 4.27 m/s. These are considered minimum boundary velocities as grain diameter and grain density considerations would increase these values.

DISCUSSION

Subaqueous bedforms of this magnitude in limestone are unique in the geologic literature. Common thought is that carbonate, non-terrigenous sedimentary rocks form chemically and biochemically by autochthonous processes [24]. By implication, it is presumed that limestones require great periods of time to form. For example, Redwall Limestone of Grand Canyon is commonly thought to have taken millions of years to deposit. However, recent studies are proving otherwise [3].

Whitmore Nautiloid Bed in the Anchor Formation at Las Vegas Range is further evidence of catastrophic emplacement of limestone. Cross-beds preserved in this section are interpreted to be the deposit of a concentrated density flow. Further interpretation is that this flow initiated as the result of a significant triggering event east of Grand Canyon on a platform facies and is now preserved as part of the Mississippian System.

Analysis of the hydrodynamic environment of emplacement of the cross-beds indicates a water depth of approximately 141 m. This depth is estimated from studies of dune height/dune spacing and dune spacing/water depth of Flemming [9] and Julien and Klaassen [11] respectively. Because these studies have evaluated flow depth above the bedform, this depth has also been corrected to a total depth using the conservation of mass equation from Kranenburg [13]. Additionally, this depth is a reasonable estimation for a slope facies [21] as interpreted by Poole and Sandberg [23].

Estimating the flow velocity of the concentrated density flow is slightly more difficult. Much analysis has been performed utilizing flume data and observations of flow velocity and bedform sizes. Due to the large magnitude of this flow, available data must be extrapolated to account for the greater depth and higher velocity of emplacement.

The objective of bedform analysis is to identify independent flow variables that may be used as a predictive bedform mechanism. Normal fluid flow analysis involves the use of boundary shear stress, \( \tau_0 \), at the bedding surface. When shear stress equals some critical shear value, \( \tau_c \), the sediment grains will begin to roll or move. Boundary shear stress, then, is a component of traction transportation and deposition. However, from a bedform analysis perspective, \( \tau_0 \) can lead to ambiguity. For the same value of \( \tau_0 \), given differences in certain variables, more than one bed state at a given flow depth is possible [5]. Thus, \( \tau_0 \) is not an independent variable that may be used to predict bed state. Rather, in beds with rugged flow-transverse bedforms, form drag (i.e. skin friction) on the main roughness elements becomes dominant. However, skin friction cannot be measured directly and estimations contain considerable uncertainty. Therefore, a better independent bedform analysis variable is flow velocity \( U \) [5].

Flow characterization for bedform analysis is more easily performed using flow velocity, \( U \), and flow depth, \( d \). In addition, mean grain size, \( D \), is an important, independent variable. To predict properly bedform state, these three independent variables may be used, as in Figure 7. Water density changes very little from 10° C to 30° C and may be eliminated from consideration. However, water viscosity changes in this temperature range do make a significant impact. As an example, in Equations 3 and 4, the ratios of viscosity between actual and chart standardized viscosities are used to correct either the chart values to actual values that would be expected in the field (Equation 4) or actual values to those standardized in the chart (Equation 3) [5]. Utilizing this methodology allowed for the previous estimation of the stable dune flow velocity range from 0.50 m/s to 4.78 m/s, prior to the conservation of mass correction, using the \( D_{10} \) chart for mean grain size from 0.64-0.80 mm [5].
Those estimations ignored two other important factors, sediment grain density and mean grain size. Boguchwal and Southard’s [5] analysis was based on quartz grains. Because calcium carbonate grains are heavier, they would require a greater \( \tau_c \) or \( U \) to begin movement. Therefore, any estimates made using the charts of Boguchwal and Southard [5] would underestimate the actual flow velocity for calcium carbonate sediment grains.

The correction for mean grain size from actual, \( D \), to chart standardized \( D_{10} \), is done using the equation of Boguchwal and Southard [5]:

\[
D_{10} = D \left( \frac{D_{10}}{\mu} \right)^{\frac{1}{2}} \quad \ldots \ldots (6)
\]

Using a mean grain size for WNB at the north end of the Las Vegas Range of 1.5 mm equates to a viscosity corrected value for \( D_{10} \) of 1.92 mm. Similar to sediment grain density, utilizing the chart with a \( D_{10} \) of 0.64-0.80 mm would underestimate the actual velocity because larger grain sizes would require higher velocities for movement. Boguchwal and Southard [5] present a plot using a \( D_{10} \) range from 1.8 – 2.5 mm. However, there are few data points and the data do not allow for definition of a dune/upper-regime plane bed boundary. For these reasons, the smaller \( D_{10} \) chart was used for these estimations and will, inherently, underestimate the actual flow velocity.

To understand the magnitude of this underestimation, the lower-regime plane bed/dune boundary of the 1.8-2.5 mm \( D_{10} \) chart yields a flow velocity of approximately 0.4 m/s at 0.1 m depth. The 0.64-0.80 mm \( D_{10} \) chart yields a flow velocity of 0.35 m/s at the same depth for the ripple/dune boundary. (Note that the lower dune boundary for the larger grain size is bounded by lower-regime plane beds and not with ripples. However, this will still allow for the definition of the stable dune regime.) This equates to a flow velocity increase of nearly 15% for the larger \( D_{10} \) grain size lower dune boundary. Because the flow regime boundaries were tentatively placed [5], and assuming, the lower dune boundary is shifted to a higher velocity to accommodate larger grain sizes, the 15% increase in \( U_{10} \) correlates to a 16% increase in minimum \( U_{hi} \) per Equation 5. For the lower dune boundary of the larger grain size, this would increase the minimum flow velocity from 0.45 m/s to 0.52 m/s. The upper dune boundary is too speculative to apply this process. All things considered, it is best to estimate conservatively the flow velocity to lie within the 0.45 m/s to 4.27 m/s range, utilizing the smaller \( D_{10} \) of 0.64-0.80 mm.

At the lower end of this velocity range, 2-D dunes would be stable whereas the upper velocity range would allow and require 3-D dune stability. The preserved dune formation of WNB in Las Vegas Range is interpreted to be a 3-D dune. Arbitrarily assuming that the transition from 2-D to 3-D dunes occurs halfway through the velocity range would suggest that these dunes were formed above approximately 2.4 m/s. Reasonably, this would be a conservative estimate for the distal flow rate of WNB per previous discussion. It should also be noted that extrapolations of the Boguchwal and Southard [5] data to these depths have not been reconciled with any field data.

CONCLUSION

Unusually large cross-beds have been preserved in limestone at the distal end of a hyperconcentrated flow at the northern end of the Las Vegas Range, southern Nevada. These beds are interpreted to be a preserved record of a concentrated density flow that transitioned from the hyperconcentrated density flow of Whitmore Nautiloid Bed in Grand Canyon, Arizona [3]. The large scale of these bedforms attests to the rapid, catastrophic emplacement of lime sediments in this section of the Anchor Limestone of Nevada.

Hydrodynamic analysis of the bedform has provided estimates for the environmental conditions during deposition. The preserved dune height is 7.5 m, which leads to a complete, conservative dune height of approximately 15 m. Based on this dune height, dune spacing of approximately 800 m is inferred [9]. These dunes are classified as very large, subaqueous 3-dimensional dunes [2]. No known studies of the hydrodynamic conditions responsible for subaqueous dunes with calcium carbonate sediments of this magnitude have been performed.

The depositional environment of this section of WNB is interpreted to be a slope facies [23]. Water depth is estimated to be approximately 140 m based on the application of analysis from Julien and Klaassen [11] and Kranenburg [13]. Flow thickness must exceed 15 m and the minimum flow velocity for emplacement is estimated to be 2.5 m/s. These estimates of flow dynamics are derived from scaling of modern laboratory flume and shallow-water, natural dune observations.
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