Paleowind velocity and paleocurrents of pluvial Lake Manly, Death Valley, USA

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A B S T R A C T

Pluvial lake deposits are found throughout western North America and are frequently used to reconstruct regional paleoclimate. In Death Valley, California, USA, we apply the beach particle technique (BPT) of Adams (2003), Sedimentology, 50, 565–577 and Adams (2004), Sedimentology, 51, 671–673 to Lake Manly deposits at the Beatty Junction Bar Complex (BJBC), Desolation Canyon, and Manly Terraces and calculate paleowind velocities of 14–27 m/s. These wind velocities are within the range of present-day wind velocities recorded in the surrounding area. Sedimentary structures and clast provenance at Desolation Canyon and the Manly Terraces indicate sediment transport from north to south. Lake level, based on the elevation of constructional features, indicates that the hill west of the BJBC was an island and that the BJBC spits formed during simple lake regression. The data are consistent with the hypothesis that the present wind regime (velocity and direction) formed the pluvial Lake Manly features.

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Introduction

Lake Manly, the pluvial lake that occupied Death Valley during cooler, wetter climate conditions, is a key component in climate models of the western USA and subsequently the northern latitudes (Fig. 1; e.g., Matsubara and Howard, 2009; Peterson et al., 2010). However, at one of the best known and most accessible outcrops of Lake Manly—the Beatty Junction bar complex (BJBC)—the age (Caskey et al., 2006; Machette et al., 2001; Owen et al., 2010) and paleoshoreline configuration (Hunt and Mabey, 1966; Orme and Orme, 1991; Galvin and Klinger, 1996; Klinger, 2001) remain confusing. The age of the BJBC is considered either Marine Isotope Stage (MIS) 6 (186–120 ka; e.g., Phillips and Zreda, 1999; Owen et a., 2010) or MIS 2 (30–10 ka; e.g., Caskey et al., 2006; Owen et al., 2010). Hunt and Mabey (1966) describe the BJBC as gravel bars that formed on the east side of an island in Lake Manly. Orme and Orme (1991) inferred that these bars formed by waves generated by >31 m/s south winds across a transgressing Lake Manly eroded the same hill to the west. Galvin and Klinger (1996) also inferred formation in a rising lake and erosion of the same hill, but that the BJBC formed by intermittent south winds that produced north- and eastward currents east of a projecting peninsula (Klinger, 2001).

In this study we present field observations at the BJBC, Desolation Canyon and the Manly Terraces in an effort to determine the wave height and direction and, ultimately, wind speed that formed these Lake Manly deposits. We selected the BJBC because Orme and Orme (1991) had previously determined paleowind velocity there. The Desolation Canyon and the Manly Terrace locations were selected because: 1) the pluvial lake deposits are formed from resistant volcanic rocks that are more suitable for the beach particle technique (BPT) of Adams (2003, 2004) and determining paleowind velocity, 2) these are the largest distribution of contiguous Lake Manly deposits, and 3) outcrops of Ordovician Eureka Quartzite there provide a unique rock type to study longshore transport.

We combine these data with observations elsewhere in Death Valley (Blair, 1999; Knott et al., 2002), to infer that storm-generated west-southwest and topographically funneled north winds with velocities and directions similar to present-day winds generated waves across ancient Lake Manly. These waves were topographically funneled and generated east- and south-propagating waves and southerly longshore drift along the eastern shore of pluvial Lake Manly. Our study shows that the present-day wind regime is sufficient to form the Pleistocene constructional lake forms.

Background

Pluvial Lake Manly was located at the southwestern edge of the Great Basin in Death Valley, California, USA (Fig. 1). Unlike Lake Lahontan or Lake Bonneville to the north, Lake Manly’s history and formation is more enigmatic (Machette et al., 2001). Evidence of Lake Manly is found at isolated locations throughout Death Valley (Machette et al., 2001). In this study we focus on two of the larger, more accessible and better studied locations: the BJBC and the Desolation Canyon/Manly Terraces areas. Even though these deposits are 25 km apart, Owen et al. (2010) obtained similar cosmogenic
radionuclide ages on both features, suggesting that these deposits formed at the same time.

The BJBC is along the Beatty Cutoff Road about 2.5 km north of California Route 190 junction (Blackwelder, 1954; Hunt and Mabey, 1966). Hunt and Mabey (1966) described the BJBC as bar deposits extending from a hill to the west (Fig. 2) that is composed of Pliocene (Wright and Troxel, 1993) conglomerate. Based on stratigraphic and sedimentological data, Orme and Orme (1991) interpreted the BJBC as transgressive barrier bars formed by south winds. They noted that the elevation of the crest of the highest bar decreased 4 m to the east over its 500 m length. They suspected that tectonism may be the cause of the elevation change. In addition, they attributed the increase in pebble flatness to the east to greater wave energy away from the hill west of the BJBC rather than longshore drift from west to east.

Galvin and Klinger (1996) and Klinger (2001) interpreted the BJBC as a sequence of spits that were developed by southerly wind-driven waves against the hill to the west of the BJBC in the transgressing Lake Manly. The four spits (A, B, C, and D) formed from north to south at elevations of 44.97 m, 45.97 m, 36.30 m and 33.78 m above mean sea level (asl), respectively (Galvin and Klinger, 1996; Klinger, 2001). Wright and Troxel (1993) and Klinger (2001) also noted the presence of another Lake Manly deposit at 19.1 m asl (Fig. 2) herein named spit E. According to Galvin and Klinger (1996), the paleogeography at the BJBC was a peninsula that projected south into Lake Manly. This configuration necessitates that spit A, which is to the north of and lower in elevation than spit B, formed first; otherwise the higher elevation spit B would have prevented the southerly waves from reaching the lower elevation spit A (Galvin and Klinger, 1996).

Desolation Canyon and the Manly Terraces are two other prominent Lake Manly deposits found at the north end of the Artists Drive structural block (Fig. 3; Clements and Clements, 1953; Hunt and Mabey, 1966; Knott and Machette, 2001). At Desolation Canyon, Lake Manly deposits form a spit and tombolo that are deposited around outcrops of Tertiary andesite and basalt (Knott and Machette, 2001). The Manly Terraces are 300 m wide and 850 m long with the shoreline moving water. Orme and Orme (1991) derived paleowind velocities represented by the maximum-size clasts moved by the waves. The paleowind velocity is derived from wave competency as represented by the maximum-size clasts moved by the waves. The maximum-size clasts reflect the basal shear stress generated by the moving water. Orme and Orme (1991) derived paleowind velocities for the BJBC by calculating bottom velocities using the Sverdrup–Monk–Bretschneider method that uses mean clast size. They concluded that present-day south winds of 9 m/s and 14 m/s measured in Death Valley were insufficient to generate waves large enough to move the largest particles at the BJBC. They also concluded that to
initiate particle motion a sustained wind speed of \(>31\) m/s was required to form large enough waves to move clasts at the BJBC (Orme and Orme, 1991, p. 344).


**Methods**

Clast dimensions were measured at multiple sites at the BJBC, Desolation Canyon, and the Manly Terraces. Because competence was the goal, the clasts that were measured represent the largest clasts that could be found. The location, general rock type, along with the a-, b-, and c-axes lengths were recorded for each clast. Clast dimension listed are for the b-axis dimension (Table 1). At Desolation Canyon and the Manly Terraces, the distribution of Eureka Quartzite clasts was also observed to determine longshore drift direction.

Calculations of paleowind velocities were based on the BPT method of Adams (2003, 2004) using the equations therein. The clast dimensions are the most important measurement for the calculations. The clast measurements allowed for the estimation of the critical shear stress, average velocity, breaking wave height, deep-water wave height, wind stress factor, and ultimately the wind speed required to generate the waves that move the clasts.

Determination of paleowind velocity also requires determination of fetch length. We constructed a hypothetical lake with an elevation of 45 m asl (Fig. 4). Lake Manly was elongated in a north–south direction and fetch length is dependent upon wind direction. The logical approach to determining fetch length is to begin with the present wind direction; however, wind direction in the western Basin and Range is not simple. Based on the work of Laity (1987) and Sharp and Glazner (1997) our observations at the Manly Terraces and Desolation Canyon, and our interpretation of the weather data (see Discussion below), we assumed a westerly to southwesterly wind direction at the BJBC and a northwesterly wind direction at Desolation Canyon/Manly Terraces to determine the fetch length. With these general directions, the maximum fetch length was determined visually (Fig 4). The fetch was then rotated at 3° intervals to determine if a longer fetch was possible.

The slope of the surface over which the particles are transported is also critical. The surface slopes of Lake Manly features vary from horizontal to 12°. The most frequent slope angles were between 3° and 4°. For the calculations, we assumed a slope of 3° in order to separate wave-driven movement of clasts from gravity movement. Adams (2003) stated that for a 10–100 km fetch, wave periods range from 3 to 8 s under fetch-limited conditions. We assumed this range of
probable wave periods in our calculations along with a particle density of 2.9 g/cm³ (Table 1).

We used two different sets of wind data. The first wind data set is the daily wind summary data from Remote Automatic Weather Stations (RAWS) predominantly operated by the Bureau of Land Management and available from the Western Regional Climate Center (http://www.raws.dri.edu). RAWS wind data for the period 1/1/2007–12/31/2010 is available as daily mean wind speed and wind direction based on hourly observations. For simplicity, these data are represented by wind rose diagrams (Figs. 1 and 4). Lorenz et al. (2011) found that RAWS data were representative of synoptic wind direction and comparable to local, portable wind measurements at Racetrack Valley in northwest Death Valley National Park (Fig. 1).

Each of the above RAWS wind data sets has data gaps; however, these data gaps are incomplete hourly data rather than missing "days" of data. Each RAWS station has wind speed and direction observations for all 1461 days of the designated time frame. The exception to this is the Hunter Mountain RAWS station where there are no wind data between May 21, 2010 and August 1, 2010. The second set of wind data is hourly mean wind speed and direction from a National Oceanic and Atmospheric Administration (NOAA) station at the China Lake Naval Air Weapons Station (China Lake; Fig. 1). We selected data from China Lake for the calendar year 2007 to be consistent with Lorenz et al. (2011). Wind speed was recorded at least hourly at China Lake with the exception of June 23–27 when wind data was sporadically collected. These data were used to determine wind events as defined by Adams (2003).

Other weather stations exist in the Death Valley area; however, many of these are in close proximity to the stations shown (Fig. 1) with no significant difference in observations. A NOAA CRN weather station exists at Stovepipe Wells (http://gis.ncdc.noaa.gov) about 25 km west of the BJBC, but the wind direction data are not archived. Two NOAA Cooperative Network (NOAA-COOP) weather stations exist at Cow Creek and Furnace Creek in central Death Valley (http://wrcc.dri.edu/coopmap); however, wind data are not archived from these stations either.

### Results

#### Paleowind velocity

The dimensions of 191 clasts were measured from Lake Manly deposits at the BJBC, Desolation Canyon, and the Manly Terraces. Clasts ranged from oblate to equant with the highest percentage of oblate (most rounded) clasts found at the BJBC. The median length of the intermediate clast dimension at the Manly Terraces was 152 cm (n = 21) whereas the same dimension at the BJBC was 10.9 cm (n = 99) and Desolation Canyon (n = 71) was 12.7 cm. Using the BPT method.

<table>
<thead>
<tr>
<th>Field site location (UTM)</th>
<th>Fetch Length (km)</th>
<th>Direction</th>
<th>Probable period (s)</th>
<th>Clast size Median (cm)</th>
<th>Max (cm)</th>
<th>Calculated wind speed (m/s) (mph)</th>
</tr>
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<tbody>
<tr>
<td>Beatty Bar 24 NW-SE 8</td>
<td>20</td>
<td>14</td>
<td>20</td>
<td>14</td>
<td>14</td>
<td>32</td>
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<tr>
<td>Desolation 42 NW-SE 8</td>
<td>24</td>
<td>11</td>
<td>20</td>
<td>21</td>
<td>21</td>
<td>49</td>
</tr>
<tr>
<td>Canyon 42 NW-SE 3</td>
<td>24</td>
<td>13</td>
<td>20</td>
<td>17</td>
<td>17</td>
<td>39</td>
</tr>
<tr>
<td>Manly Terraces 42 NW-SE 8</td>
<td>24</td>
<td>15</td>
<td>27</td>
<td>23</td>
<td>23</td>
<td>52</td>
</tr>
<tr>
<td>Teraces 42 NW-SE 3</td>
<td>24</td>
<td>15</td>
<td>27</td>
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<td>23</td>
<td>52</td>
</tr>
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</table>

Figure 3. Portion of the 7.5' Furnace Creek topographic quadrangle (contour elev. in feet) showing the paleoshoreline Lake Manly deposits and Eureka Quartzite at Desolation Canyon and the Manly Terraces in central Death Valley relative to the Black Mountains Fault Zone. Note that the paleoshoreline here is based on outcrop and is at ~40 m asl due to tectonics. The gray arrow shows the annual wind direction (Laity, 1987). The black arrows show the direction of wind-driven waves and longshore drift derived from field observations. Box shows the location of Fig. 6.
of Adams (2003, 2004), the calculated paleowind velocities required to move clasts of these dimensions ranged from 14 to 27 m/s (Table 1).

Wind direction and longshore drift

We completed a geologic map of the BJBC to elucidate the stratigraphic relations among spits A, B, C and D (Fig. 5). Our mapping shows that spits B, C and D form a contiguous deposit. In contrast, we found that the east end of spit A is overlain by alluvial fan deposits with a subdued bar-and-swale topography equivalent to the Qg3 deposits of Hunt and Mabey (1966). The area between spit A and spit B is covered by Qg2 and Qg3 deposits. In a stream cut at its east end, spit B is overlain by fine-grained deposits interpreted as a playa. These playa deposits are overlain by alluvial fan deposits with a well-developed desert pavement that are equivalent to the Qg2 deposits of Hunt and Mabey (1966).

Clast imbrications in the roadcut and stream cut were generally trending north-south, as described previously by Orme and Orme (1991). However, acceptable outcrops of Lake Manly deposits were limited to the highest bar (spit B of Galvin and Klinger, 1996) where the best incisions and cuts through the bar are oriented north-
south; alternately oriented cuts or incisions are poor, which effectively prevented determination if clasts are imbricated in any other direction (i.e., east–west) or if the north–south imbrication is an apparent trend direction.

At the Desolation Canyon spit (Fig. 3), foreset beds were found to dip south and climb to the south (Fig. 6). The crest of the tombolo to the west of this spit is oriented north–south and is convex to the west. Clasts composing the Desolation Canyon spit and tombolo are a mixture of the Tertiary andesite and basalt that crop out north of these lake features. Both the spit and tombolo are north of outcrops of the Eureka Quartzite; no quartzite clasts were observed in the spit or tombolo.

The Manly Terraces, which are south of the Desolation Canyon spit and tombolo (Fig. 3), are incised by active stream channels allowing the observation that foreset beds dip to both the east and south. Clasts were dominantly equant in shape and a mixture of Tertiary basalt and Eureka Quartzite; Eureka Quartzite clasts were found only east and south of the bedrock outcroppings.

Discussion

Beatty Junction Bar Complex

There is some confusion regarding the shoreline configuration when the BJBC spits were formed (Fig. 2). Hunt and Mabey (1966, p. 69) noted that the hill west of the BJBC was an island when the spit was built. In contrast, Galvin and Klinger (1996) hypothesized that the hill to the west was part of a south-projecting peninsula. This peninsula configuration means that spit A (44.97 m asl) must have formed before spit B (45.97 m asl) because spit B and the peninsula prevented waves generated by southerly winds from reaching spit A (Galvin and Klinger, 1996). Klinger (2001) supported this hypothesis with a cross section showing superposition of the spits with spit A overlying spit B.

We could not confirm the superposed relations between spits A and B (Fig. 5). The few outcrops between spits A and B are alluvial-fan deposits with no outcrops of lake deposits. Plotting the 45.97-m (150.8-ft) contour of the spit B highstand on a topographic map of the BJBC shows that the hill to the west would be an island rather than a peninsula (Fig. 2). We entertained the alternative hypothesis that the neck of the Lake Manly peninsula was subsequently eroded; however, we dismissed this hypothesis because erosion of the peninsula neck would result in erosion of spit A also and the spit is clearly present.

Based on the topography and spit crest elevations from Klinger (2001), our hypothesis is that the hill to the west was an island, as Hunt and Mabey (1966) inferred. An island configuration would allow waves around the north side where spit A (44.97 m asl) formed. Thus, spit A is not required to form before spit B (45.97 m asl). Spit A could have formed during either lake regression or
transgression or at the same time as spit B. Adams and Wesnousky (1998) found that constructional, highstand features formed at the Lake Lahontan highstand had up to 2.6 m in elevation difference.

If our hypothesis that the hill to the west was an island when the BJBC formed is correct, then we infer that the simplest explanation of the BJBC spits is that they formed as Lake Manly regressed rather than the complex sequence previously proposed to form and preserve the BJBC. Orme and Orme (1991) did not consider spit A; however, they inferred that Lake Manly receded rapidly in order to preserve spits C and D. If spits A, C, D and E formed during lake regression from the elevation of spit B, then it is not necessary for rapid lake recession to occur and the lower-elevation features are preserved as lake level drops. At Lake Lahonton, a pluvial lake in west-central Nevada north of Death Valley, Adams and Wesnousky (1998) noted that many of the preserved surficial nearshore features formed during lake recession with only a few transgressive features preserved.

In a more complex process dependent upon the presence of a peninsular, Galvin and Klinger (1996) implied that Lake Manly transgressed to 44.97 m asl to first form spit A along its north paleoshoreline. Then, the water level rose an additional ~1 m to 45.97 m and formed spit B offshore rather than at the paleoshoreline, thereby preserving spit A. Lake Manly subsequently receded with pauses to form spits C, D and E (Fig. 2). With the hypothesized island configuration, spits A and B may have formed simultaneously as waves wrapped around the island (Fig. 2) or as Lake Manly rose or receded. The southwesterly to westerly winds shown by the present-day wind roses would also drive waves around the northern side of the island and facilitated formation of spit A.

Galvin and Klinger (1996) hypothesized that the spits formed during transgression as waves easily eroded sediment from the hill to the west. Subsequently, this erodible sediment was lacking during regression. We found the conglomerate that composes the hill to the west (Fig. 5) remarkably homogeneous and poorly cemented. Thus, the sediment deficit hypothesis may still be true; however, we did not find the induration or composition conditions that might support this hypothesis.

In summary, our observations support the hypothesis that Lake Manly rose to an elevation near 45.97 m asl, making the hill to the west of the BJBC an island. Lake Manly then receded with significant pauses at 44.97 m, 36.30 m, 33.78 m and 19.11 m to form spits A, C, D and E, respectively (Fig. 2). Funneled north winds and west-southwest winds drove waves around the island to form spit A. Another variation of this working hypothesis is that spit A formed before spit B during lake transgression as waves moved around the island to the west or at the same time as spit B.

**Wind velocity**

We calculated wind velocities of 14 to 27 m/s using the BPT method of Adams (2003, 2004), Orme and Orme (1991; p. 344) calculated that the winds required to make waves high enough to initiate clast movement at the BJBC were >31 m/s. The calculated wind velocity differences might be attributable to calculation method. Orme and Orme (1991) measured 90 rocks at two locations along spit B at the BJBC where clasts are reworked from sedimentary rock and found a mean b-axis diameter of 1.6–6.4 cm. In contrast, we measured clasts at spits A–D and used a maximum b-axis diameter of 20 cm at the BJBC. We also found larger clasts at Desolation Canyon and the Manly Terraces, which should logically have resulted in higher wind velocities than those calculated by Orme and Orme (1991); however, our wind velocity was less. This difference is likely due to the calculation methods where the BPT method uses both median and maximum dimensions to account for grain pivot whereas the Sverdrup–Monk–Bretschneider method used by Orme and Orme (1991) uses mean grain size only.

The question remains, however, are these velocities reasonable? Are wind velocities 14 to 27 m/s in Death Valley today and how often do they occur? Wind direction and velocity in the southern Basin and Range is difficult to characterize due to the steep, north-south trending, topographic relief that is counter to the east–west synoptic wind regime—and Death Valley is no exception (Fig. 1). Adams (2003) was fortunate to have wind velocity and direction data from stations located within the limits of pluvial Lake Lahontan. Wind data from within Death Valley itself is not archived at RAWS or NOAA climate data sites in the valley leaving regional wind data as proxies for wind direction and velocity. Within the suspected time frame of Lake Manly (ca. 180 ka or ca. 30 ka), the present topography has not changed appreciably, so large-scale topographic changes that would impact wind regime need not be considered.

Regional winds are generally westerly in the southwestern US (Fig. 1) with the highest velocity winds during the spring (Laity, 1987 after Berry et al., 1981). Winds in Death Valley vary seasonally with lower velocity, southerly winds during the summer months and higher velocity, northerly winds during the spring and winter months (Laity, 1987). Laity (1987) characterized the annual wind
direction in Death Valley as from the north (Fig. 1). Northerly winds in Death Valley are consistent with the 2007–2010 winds recorded at the Oriental Wash RAWS site (Fig. 1), which is located in a valley bottom north of Death Valley. In addition, Sharp and Glazner (1997) point out that the sand source for the Mesquite Flat dune field (Fig. 1) is from the dry lake sediments to the north—indicating dominant north winds. The Mesquite Flat dunes, however, are a star dune suggesting that wind direction is variable and funneled westerly winds are common as illustrated by the Hunter Mountain wind data (Fig. 1). The dominant wind direction at the Panamint Mountain station is west-southwest or parallel to the orientation of the valley where the station is located. The same relations exist between wind direction and valley orientation for the Hunter Mountain and Oriental Wash stations (Fig. 1) suggesting topographic funneling of winds in the Death Valley region.

Racetrack Valley, northwest of Death Valley, is a 4-km-wide, north–south trending valley with 630 m of relief (Fig. 1) where Lorenz et al. (2011) collected local wind, temperature and precipitation data using portable automated weather stations. They found that the local wind direction and velocity were from the south but were generated by westerly winds topographically funneled by local topography. They concluded that, in spite of the topographic conditions, the data from the surrounding RAWS stations were useful and similar to the local climate data they collected with portable weather stations. If we accept the conclusions of these studies (Laity, 1987; Sharp and Glazner, 1997; Lorenz et al., 2011) that wind direction and speed is strongly influenced by topography and variable in the Death Valley region (Fig. 1) but that RAWS and other regional stations may be used to represent regional wind condition, then we can compare our calculated wind speed of 14 to 27 m/s to regional weather station data.

Average wind velocities during 2007–2010 at the five RAWS stations near Death Valley (Panamint, Hunter Mountain, Oriental Wash, Horse Thief Springs, and Mojave River Sink) ranged from 0.6 near Death Valley (Panamint, Hunter Mountain, Oriental Wash, Horse Thief Springs, and Mojave River Sink) ranging from 0.6 to 4.1 m/s with maximum wind speeds ranging from 34.8 m/s (Panamint Mountain) to 11.6 m/s (Hunter Mountain). These maximum wind speeds represent the average speed over 1 h. Adams (2003) suggested that wind-generated waves that move clasts must be sustained and require “wind events” that he defined as three consecutive hours when hourly wind speed exceeded 9 m/s.

Do sustained wind events occur in the Death Valley region? The closest weather station where hourly wind velocity is archived is at China Lake about 100 km west of Death Valley. The hourly wind velocity archived from China Lake showed that during 2007 the monthly maximum wind velocity ranged from 11 m/s in November to 19 m/s in February. A total of 83 wind events occurred at China Lake in 2007 with at least one wind event each month. In comparison, Adams (2003) identified 58 wind events at the Salt Lake City airport during the two-year period of 1986–87 (29 events/year) and 203 wind events at Fallon Naval Air Station in the 8 yr from 1992 to 1999 (25 events/year). Clearly, it’s windier in the Death Valley region. As Adams (2003) observed, however, a wind event may not capture the full picture of the wind regime. For example, three wind events occurred during a 36-hour period from February 25 to 26 (Fig. 7). During that time, 74 wind velocity measurements were made with only three measurements below the 9 m/s threshold and the median wind velocity was 12 m/s. Between 13:56 and 19:56 on February 25 and between 03:12 and 07:56 on February 26, the wind velocity was >14 m/s. In effect, the wind exceeded 9 m/s for nearly 36 h with a maximum velocity of 19 m/s.

Regional weather stations near Death Valley recorded monthly maximum wind velocities ranging from 11 to 34 m/s. Eighty-three sustained wind events where wind velocity exceeded 9 m/s occurred at China Lake during 2007 with a maximum velocity of 19 m/s. These average and discrete wind velocities are within the range of the wind velocities that we calculated (14 to 27 m/s). Thus, we infer that the wind velocities present today could have formed the Lake Manly features.

In contrast, Orme and Orme (1991) found that present-day winds were insufficient to move Lake Manly clasts. In their study, they state that winds of 9 and 14 m/s were recorded by the National Park Service for predominantly southerly winds (SSE–SSW) in Death Valley. They assumed that these values were representative of the Death Valley wind conditions. Based on Lorenz et al.’s (2011) conclusion that regional RAWS data was representative of local (i.e., Death Valley) wind regimes, we infer that the more temporally and spatially comprehensive data set from the RAWS stations that surround Death Valley is an equivalent, if not improved, representation of the Death Valley wind regime and sufficient to move Lake Manly clasts.

Wind direction

Orme and Orme (1991), who focused on southerly present-day winds, observed that high-velocity southwesterly winds might produce 1.8-m-high, short-period waves that may have moved clasts at the BJBC. As a result, they posed the question of whether or not the wind direction was different when the BJBC was formed. Wind directions in the western Basin and Range are highly influenced by topography as the wind roses show (Fig. 1) and as observed by Lorenz et al. (2011). West of Death Valley (Panamint and Hunter Mountain), wind direction is dominantly from the south and southwest; however,
north and east of Death Valley (Oriental Wash and Horse Thief Spring), the dominant wind direction is from the north (Fig. 1). These varying wind directions are expressed by the Mesquite Flat dunes at the northern end of the Panamint Mountains (Fig. 4). Sharp and Glazner (1997) inferred that the source for the dunes is the playa surface north of the dune, implying north winds; however, the Mesquite Flat dunes are a star dune complex, which forms by variable wind directions. Thus, the wind direction in Death Valley is variable.

The 36-hour high wind storm described above also illustrates the variability of wind direction during a storm event (Fig. 7). During that storm, initial winds were 13 m/s from 280°. At the end of this particular storm, when wind velocity dropped below 9 m/s, 36 h later, the wind direction had shifted 70° toward the south to 210°. As a result, these data support the hypotheses put forth by Orme and Orme (1991) and Galvin and Klinger (1996) that occasional strong winds from the south may have formed the BJBC. Imbrication directions at the BJBC might help resolve wind direction, however, we found the outcrops at the BJBC where Orme and Orme (1991) and Galvin and Klinger (1996) made their observations limited and therefore cannot eliminate other wind directions or confirm a single wind direction.

Orme and Orme (1991) observed that the crest of spit B at the BJBC decreased in elevation by 4 m from west to east and that pebble flatness increased to the east. They explained the elevation difference as tectonic tilting and the shape change as higher wave energy away from the hill to the west. The most active and closest fault to the BJBC is the Northern Death Valley fault zone, which is 2 km to the southwest (Wright and Troxel, 1993). Here the fault is dominantly strike slip with scarps at the fault of <1 m high with the adjoining hills only a few meters high (Brogan et al., 1991). Thus, it is unlikely that the BJBC is tectonically tilted 4 m at a distance of 2 km from the fault. If the tilting of spit B is not tectonically tilted, then the elevation change of spit B may just as easily be due to easterly longshore drift. The flattening of the clasts to the east is just as reasonably due to reworking of clasts from west to east, which would be consistent with an elevation decrease in that direction.

We propose an alternative hypothesis and interpretation that the decrease in elevation from west to east of spit B and the flattening of clasts in that same direction indicates west-to-east reworking of clasts in the BJBC. Reworking and moving of clasts to the east would require more southwesterly to westerly winds. This westerly-southwesterly wind direction is consistent with present-day wind directions recorded at the Panamint Mountain RAWS station and the variable wind directions forming the Mesquite star dune complex. A more westerly wind direction would also explain the formation of spit B by wind-driven waves around the north end of an island (Fig. 2).

Outcrops and observations at both Desolation Canyon and the Manly Terraces indicate that north-to-south and west-to-east waves transported Eureka Quartzite clasts with longshore drift to the south (Figs. 3 and 4). The west-to-east transport direction is consistent with the hypothesized westerly wind direction at the BJBC. The north-to-south longshore drift at the Manly Terraces and north to south wave direction is also consistent with the northerly annual winds (Laity, 1987) topographically funneled to the south.

Topographically funneled winds from the north are also consistent with Blair’s (1999) description of south-dipping foresets in Lake Manly deposits at Warm Springs Canyon (Fig. 4). At Mormon Point, foresets dip south and nearshore gravels are also transported to the south (Kolb et al., 2002). In addition, north winds are consistent with the putative wave-cut benches at Shoreline Butte in southern Death Valley (Noble, 1926). These benches face north and it seems unlikely that these benches would form by south-to-north waves driven by south winds (Fig. 4).

A marked anomaly in our hypothesis is the Lake Manly deposits at the Three Bare Hills about 5 km southeast of the BJBC (Fig. 4). There, Hunt and Mabey (1966, p. 69) described foreset beds dipping 10° northwest and a bar crest that arcs over 90°. This wide sweep of the bar crest and the position of the deposit behind prominent hills may explain the unusual configuration and foreset dip; however, we did not explore this location and this is an obvious object of future work.

Conclusions

Wind direction and velocity in the western Basin and Range are strongly influenced by topography (Fig. 1) and storm movement (Fig. 7). We used the BPT method to determine wind velocity on constructional landforms of Lake Manly. The largest, wave-rounded clasts were found at the Manly Terraces where the substrate consists of Tertiary conglomerate. At the BJBC, the smaller clasts were reworked from the adjoining Tertiary conglomerate. Based on the BPT method, wind speeds required to generate waves that moved clasts on constructive Lake Manly features in Death Valley were 14–27 m/s. These velocities are within the range of average maximum wind velocities (11–34 m/s) from 2007 to 2010 and wind event velocities at China Lake during 2007. Adams (2003) calculated Pleistocene wind velocities of 9–27 m/s at Lake Lahonton to the north of Death Valley. Thus, we infer that the wind velocities that formed the Lake Manly deposits were similar to the present-day wind velocities in the region and that Death Valley is windier.

Orme and Orme (1991) calculated an initiation velocity of >31 m/s using the Sverdrup–Monk–Bretscher method that used mean clast size. The BPT method uses both median and maximum clast size to account for clast shape. This methodology difference may account for the lower wind velocity that we calculated.

We explain the difference in clast sizes between our study and Orme and Orme (1991) as differing clast source (reworked conglomerate vs. basalt) and number of clasts measured. At Desolation Canyon and the Manly Terraces, sedimentary structures and the southerly transport of Eureka Quartzite clasts (Fig. 3) infer wave propagation from the north-northwest and west with a longshore drift to the south, which is consistent with other observations of wave transport in southern Death Valley (Fig 4).

Plotting of the surveyed crest elevation (45.97 m asl) of the highest spit (spit B) as the water level of Lake Manly indicates that the hill to the west of the BJBC was an island. Hunt and Mabey (1966) made this same observation. The island configuration would allow waves around the north end and formation of spit A at 44.97 m asl. Spits A and B could have formed synchronously or as Lake Manly receded or rose. Because the elevation difference between spits A and B is only a meter, we hypothesize that spits A and B formed synchronously. We hypothesize that the remaining spits (C, D and E) simply formed as Lake Manly receded rather than during shoreline transgression, as required if the hill to the west was a peninsula.

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