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Beryllium-10 terrestrial cosmogenic nuclide surface exposure dating of Quaternary landforms in Death Valley

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ABSTRACT
Quaternary alluvial fans and shorelines, spits and beach bars were dated using 10 Be terrestrial cosmogenic nuclide (TCN) surface exposure dating in Death Valley. The 10 Be TCN ages show considerable variance on individual surfaces. Samples collected in the active channels date from ~ 6 ka to ~ 93 ka, showing that there is significant inheritance of 10 Be TCN within cobbles and boulders that were dated, which suggests that slopes erode and sediment is transferred very slowly in most regions within Death Valley. Comparisons of 10 Be TCN ages on alluvial fan surfaces with chronostratigraphies based on soil development and optically stimulated luminescence dating show that minimum 10 Be TCN ages within sample sets on individual surfaces most closely approximate to the age of landforms that are younger than ~ 70 ka. Alluvial fan surfaces older than ~ 70 ka have begun to undergo significant erosion so that the majority of 10 Be TCN ages for data sets on individual surfaces underestimate the true age of the surface due to erosion and exhumation of fresh cobbles and boulders. The spread of 10 Be TCN ages for beach bars near Beatty Junction and shorelines ~ 8 km south of Furnace Creek is large, ranging from ~119 ka to ~ 385 ka and ~ 109 ka to ~ 465 ka, respectively. However, new and previously published luminescence ages, soil development and geomorphic context suggest that these landforms formed during high lake level stands in marine isotope stage 2 (~ 22-18 ka), but these younger ages my reflect soil development and material elluviated into the bar deposit long after deposition. This suggests that the cobbles and boulders dated with 10 Be methods have inherited 10 Be TCNs, which have been derived from older shorelines or associated landforms. These results highlight the problems associated with using surface cobbles and boulders to date Quaternary surfaces in Death Valley and other similar dryland settings. Moreover, this study emphasizes the need to combine multiple, different dating methods to accurately date landforms in Death Valley and similar settings.

1. Introduction
Death Valley constitutes one of the most dramatic landscapes in North America, and is famous...
for its faulted mountain fronts, spectacular alluvial fans, and extensive saline playa. The valley is recognized for being the hottest (maximum recorded temperatures of 56.7°C at Furnace Creek on July 13, 1913), driest and lowest location (85.5 m below sea level at Badwater) in North America. In February 1933, President Herbert Hoover made Death Valley a National Monument and it was designated a biosphere reserve in 1984, and became a U.S. National Park in 1994.

Despite its fame and environmental significance, relatively little work has been undertaken to date landforms in Death Valley. This is partially because of the difficulty in defining the ages of landforms by the standard technique of radiocarbon dating due to the absence of organic matter in sediments. Nevertheless, relative ages of landforms have been determined by numerous researchers using a combination of morphological, relative weathering and soil characteristics (Denny, 1965; Hunt and Mabey, 1966; Bull, 1968; Hooke, 1972; McFadden et al., 1989, 1991; Hook and Dorn, 1992; Nishiizumi et al., 1993; Ku et al., 1998; Machete et al., 2001, 2008; Klinger, 2001; Klinger and Piety, 2001; Knott et al., 2005; Frankel and Dolan 2007). In recent years, however, the newly developing methods of optically stimulated luminescence (OSL) and terrestrial cosmogenic nuclide (TCN) surface exposure dating have allowed many of the landforms to be dated within the valley (Frankel et al. 2007a; Machette et al., 2008; Frankel et al., 2010a, b). Successful application of these methods requires detailed considerations of the geomorphic, climatic, and tectonic origin of the landforms that are being dated, as well as an understanding of the theory, chemistry and physics behind the methods that are applied to avoid misinterpreting ages.

As part of a larger study to determine slip rates on the Death Valley- Fish Lake Valley fault system that bounds the northwestern edge of the valley, we undertook an intensive program of $^{10}$Be TCN and OSL dating, which included determining > 70 $^{10}$Be TCN and ~ 30 OSL ages on landforms throughout Death Valley (Frankel, 2007a, 2010a,b). In this paper, we utilize much of these data and report an additional 44 new $^{10}$Be TCN and two new OSL ages to determine ages for selected landforms in Death Valley. We then assess the methods and problems associated with the application of $^{10}$Be TCN methods in this region and similar environments.

The application of TCN methods can prove problematic since the TCN ages on surface clasts (pebble, cobbles and boulders) may provide significant over-estimates of the true age of the landforms if the clasts have acquired significant TCN concentrations prior to final deposition (inheritance). Alternatively, TCN ages on rock surfaces might under-estimate the true age of the landform if the rock surface or clast had been recently exhumed or weathered. Various methods, such as determining multiple ages on surfaces and analyzing TCN depth profiles, have been used to help assess these problems. Most presume that these geologic processes are stochastic and that when ages cluster, these processes have not significantly affected TCN concentrations and that the model ages reflect the true age of the landforms. However, defining ‘significant clustering’ of ages and/or the age within a distribution that most accurately represents the true landform age can be very subjective. Here, we examine these problems and highlight the limitations of applying these methods in Death Valley and drylands.

2. Regional setting
Death Valley is located along the western margin of the Great Basin in the southwestern USA (Fig. 1). The valley is a pull-apart basin in the transition between the extensional Basin and
Range Province and the strike-slip faults comprising the eastern California shear zone (Burchfiel and Stewart, 1966). The valley formed since the Miocene by displacement along a down-to-the-west normal fault in a step-over between the right-lateral southern Death Valley and northern Death Valley fault zones (Burchfiel and Stewart, 1966; Hamilton, 1988; Wernicke et al., 1988; Burchfiel et al., 1995; Miller and Pavlis, 2005). Death Valley is bounded by the Cottonwood and Panamint Mountains, and Last Chance Range to the west; and the Grapevine, Funeral and Black Mountains to the east. The Panamint Mountains rise > 3000 m above sea level, to the highest point, Telescope Peak, at 3,368 m. The bedrock is very diverse and ranges in age from Proterozoic to Cenozoic and includes metamorphic crystalline basement, dolomites, limestones, quartzite, sedimentary siliclastics and volcanic ashes (Hunt and Mabey, 1966).

The present-day arid climate results from the rain shadow produced by the Sierra Nevada, Inyo Mountains, and Panamint Mountains (Poage and Chamberlain, 2002). From 1961-2008 the weather station at Furnace Creek in the central part of Death Valley recorded an average yearly temperature of 24.8°C with an average high in January and July of ~ 19°C and ~ 47°C, respectively, and an average annual precipitation of 57 mm (Western Regional Climate Center, 2010). Geochemical and sedimentological analysis of sediment cores show that the late Quaternary climate was dominated by two wet, cold periods and two warm, dry intervals (Li et al., 1996; Lowenstein et al., 1999). The evidence suggests that perennial lakes existed in the central basin during the penultimate glacial advance from ~ 128 to 186 ka and during the last glacial maximum from ~12 to 35 ka when the climate was cooler and wetter (Lowenstein et al., 1999).

The gross geomorphology of Death Valley can be broadly divided into three physiographic provinces: the playa floor of the valley; extensive alluvial fans that form a bajada along valley-bounding range fronts; and steep, long, essentially bare bedrock hillslopes that rise to high mountain peaks and are incised by deep canyons. The alluvial fans of Death Valley are commonly featured in textbooks as classic examples and were examined during some of the early, seminal work on these landforms (e.g., Bull, 1968). Owing to its position below sea level, the valley is internally drained and the fluvial source is the Amargosa River.

3. Previous work
The long history of Quaternary geology and geomorphology research in Death Valley began with observations by Gilbert (1890), who recognized ancient shorelines along the Black Mountains and suggested a large lake once occupied the region. These observations were expanded on by Nobel (1926), who noted several lake-shore terraces upon a basalt hill near the southern end of Death Valley, a feature now known as Shoreline Butte. The first extensive study of Death Valley was undertaken by Blackwelder (1933) who described the evidence for the lake recognized by Gilbert (1890), coining the name Lake Manly in honor of W.L. Manly who led, and heroically rescued, the first party of western emigrants who entered Death Valley in 1849 (Means, 1932).

Modern geomorphic research in Death Valley began with focus on the widespread alluvial fans as a keystone for the Quaternary stratigraphy of the valley and arid regions throughout western North America (Denny, 1965; Hunt and Mabey, 1966). This work continued both in Death Valley and throughout southwestern North America, resulting in a relatively consistent alluvial
fan stratigraphy for the region; however, subtle differences in the nomenclature exist between researchers, as illustrated in Table 1 (Denny, 1965; Hunt and Mabey, 1966; Reynolds, 1969; Hooke, 1972; Moring, 1986; Bull, 1991; Hooke and Dorn, 1992; Nishiizumi et al., 1993; Klinger, 2001a, d; Frankel and Dolan, 2007; Machette et al., 2001, 2008). From the late 1980s to the early 2000s, a series of detailed studies of the Quaternary geology and geomorphology was undertaken that resulted in a string of doctoral theses, field guides, and USGS publications (e.g., Troxel, 1986; Knott, 1998; Anderson, 1998; Professional Soil Scientists Association of California, 1998; Wright and Troxel, 1999; Klinger, 2001; Machette et al., 2001).

Sohn et al. (2007) undertook the first comprehensive OSL dating study of Quaternary landforms in Death Valley. This work showed that Q3b alluvial fan deposits had OSL ages from ~ 4 to ~ 7 ka, Q3a alluvial fan deposits had OSL ages from ~ 11 to ~ 17 ka, and Q2d alluvial fan deposits have OSL ages of ~ 25 ka along the Black Mountains.

Zreda (1991, cited in Orme and Orme, 1991), Trull et al. (1995), Nishiizumi et al. (1993), and Phillips and Zreda (1999) determined the first TCN ages in Death Valley using $^{36}$Cl, $^{26}$Al, $^{10}$Be, and $^3$He to date lake and alluvial fan features. Knott (unpublished data, 1998) followed this study by dating a landslide deposit along the western Black Mountains using $^{10}$Be methods. Next, Frankel et al. (2007a) provided the first comprehensive study using TCNs for Death Valley, focusing on dating faulted alluvial fans using both $^{36}$Cl and $^{10}$Be. Recently, Machette et al. (2008) used $^{36}$Cl TCNs in 12 depth profiles to establish the age of some of the most extensive Quaternary alluvial fans in Death Valley. Their intermediate-age (Qai) alluvial fans ranged from ~ 40 to 100 ka, with a mean age of about 70 ka, and an older phase of alluvial-fan deposits (Qao) were dated to ~ 170 ka. In addition, Frankel et al. (2007b) and Ganev et al. (2010) determined $^{10}$Be on four offset alluvial fans in Fish Lake valley showing that the fans range from ~ 71 ka to ~ 121 ka. Frankel et al. (2010a, b) dated Holocene alluvial fans near Badwater and at Mormon Point and a late Pleistocene alluvial fan south of Mud Canyon, which will be discussed in more detail below.

4. Methods

Seven study areas were chosen to examine the characteristics of some classic landforms in Death Valley, which included alluvial fans, active channels, and shorelines, spits and beach bars of Lake Manly (Fig. 1). Several of the study areas provided useful data for defining rates of displacement along the Death Valley-Fish Lake fault zone. The results of these tectonic geomorphic studies are described in Frankel et al. (2007a, 2010a, b).

Landforms were mapped in the field on base maps produced from high-resolution airborne lidar digital topographic data. The detailed processing of the lidar data is described in Frankel et al. (2007b). We use the fan characteristics defined by Bull (1991) and nomenclature of Klinger (2001a) to define the Quaternary stratigraphic units in our study area (Table 1). Samples for $^{10}$Be TCN dating were collected from surfaces within each of the study areas to help define the ages of landforms and to test the applicability of the method. In addition two OSL samples were collected from one of the Lake Manly beach bars ~8 km south of Furnace Creek.

4.1. Be-10 terrestrial cosmogenic dating
Samples were collected from surface boulders and cobbles for $^{10}$Be TCN dating. Where possible, large boulders (> 1 m high) were preferentially sampled from sites that showed the least evidence of erosion. For surface boulders ~ 250 g of rock was chiseled off the upper ≤ 5 cm surface. Whole cobbles were collected where boulders were absent. The location, geomorphic setting, size, shape, and weathering characteristics of each sample were recorded and are listed in Table 2. The inclination from the sampling site to the surrounding horizon was measured to quantify topographic shielding, which in most locations was negligible.

Boulder and cobbles samples were crushed and sieved to obtain a 250-500 µm grain size fraction. The 250-500 µm size fraction was processed using four acid leaches: aqua regia for > 9 hours, two 5% HF/HNO$_3$ leaches for ~ 24 hours, and one 1% HF/HNO$_3$ leach for 24 hours. Lithium heteropolytungstate heavy liquid separation was applied after the first 5% HF/HNO$_3$ leach. Atomic absorption spectrometry (AAS) Be carrier was added to the pure quartz. The quartz was dissolved in 49% HF and HNO$_3$ and passed through anion and cation exchange columns along with chemical blanks to extract Be(OH)$_2$. The Be(OH)$_2$ was oxidized to BeO through ignition at 750°C and mixed with Nb powder and loaded in steel targets for the measurement of the $^{10}$Be/$^{9}$Be ratios by accelerator mass spectrometry (AMS). AMS measurements were made at the Center for Accelerator Mass Spectrometer at the Lawrence Livermore National Laboratory. Details for standards, blanks and age calculations are shown in the footnotes of Table 2.

### 4.2. Optically stimulated luminescence dating

Samples were collected by hammering opaque plastic tubes, ~ 20 cm-long, into freshly cleaned natural exposures. The tubes were sealed and placed in light-proof photographic bags until the initial processing at the University of Cincinnati. Laboratory preparation follows the methods described in Seong et al. (2007). The luminescence signals were measured using a Riso TL/OSL reader (model DA-20). Luminescence from the quartz grains was stimulated using an array of blue light emitting diodes (470 nm, 50 mW/cm$^2$) filtered using a green long-pass GG-420 filter. Detection was through a Hoya U-340 filter. All quartz aliquots were screened for feldspar contamination using infrared stimulation with infrared light emitting diodes (870 nm, 150 mW/cm$^2$). All OSL signals were detected using a 52 mm diameter photomultiplier tube (9235B). The equivalent dose ($D_e$) measurements were determined on multiple aliquots using the single aliquot regenerative (SAR) method protocol developed by Murray and Wintle (2000). Growth curve data were fitted using linear and exponential trend curves. The $D_e$ value for every aliquot was examined using Riso Analysis 3.22b software. Aliquots with poor recuperation (>10%) were not used in the age calculations. Equivalent doses of all aliquots were averaged for each sample then divided by the dose rate giving a mean age (Table 3). Calculation uncertainties and methods used to calculate dose rates are explained in the footnotes in Table 3.

### 5. Study areas

Detailed studies areas are described from North to South, with the alluvial fan sites listed first (Figs. 1 and 2).

#### 5.1 North Ubehebe Crater Alluvial Fans

A succession of faulted fans is present along the western Grapevine Mountains piedmont near North Ubehebe Crater in northern Death Valley. Frankel and Dolan (2007) first described one of these alluvial fans, which is part of what we informally call the North Ubehebe Crater alluvial fans, and they used high-resolution airborne laser swath mapping (ALSM) digital topographic
data to quantify the roughness of different age alluvial fan units to aid in regional mapping (Fig. 3). The alluvial fans at this location are composed of a combination of sheet-wash and debris flow deposits, and at least seven alluvial fan units (Q4, Q3c, Q3b, Q3a, Q2c, Q2b and Q2a) can be recognized in this study area (Frankel and Dolan, 2007). Ten quartzite pebbles were collected for TCN dating from the Q2b surface, which has been displaced by the northern Death Valley fault zone. The surface clasts had a mean diameter of 7 cm and ranged from 2 to 13 cm in size.

5.2. Big Dip canyon
Impressive alluvial fans are present at the mouth of Red Wall and Big Dip Canyons radiating from the western flank of the Grapevine Mountains (Fig. 4). Reynolds (1969), Brogan et al. (1991) and Klinger (2001) first examined these alluvial fans. Klinger (2001) mapped six alluvial units, which, based on soil development, he argued ranged in age from late Pleistocene to recent (the active channels), and he documented 250 to 330 m of dextral offset by the northern Death Valley fault zone. The displacement has since been refined to 297 ± 9 m based on lidar digital topographic data (Frankel et al., 2007a). Frankel et al. (2007a) used 16 TCN $^{10}$Be surface samples and three $^{36}$Cl depth profiles to date the Q2c surfaces on the Big Dip Canyon fan to $70+22/-20$ ka and $75 +18/-16$ ka, respectively. Approximately 55 ka of $^{36}$Cl inheritance was removed from the depth profiles to determine the $^{36}$Cl age for this surface. To examine the potential inheritance in active channel cobbles, we collected three cobbles (Sc6A, B and C) from the active channel (Q4b) adjacent the sampling site for $^{10}$Be TCN dating of Frankel et al. (2007a: Fig. 4) at the Big Dip Canyon fan.

5.3 North Junction
Large alluvial fans are also present near North Junction (Figs. 2 and 5). Brogan et al. (1991) mapped offsets across a Q3a surface on a fan along the mountain front. A Q3a surface near the mountain front has well preserved channels and is faulted by several strands of the northern Death Valley fault that offset the channels by ~ 3 m (Fig. 5). We collected quartzite cobbles (DVDFC3A, B, C and D) from the Q3a surface of the alluvial fan and its active channel (Q4b; Sc5A and B) to date using $^{10}$Be TCN and to examine any inheritance of TCN.

5.4 South Junction
Small faulted remnants of Q3b alluvial fan surfaces are present at South Junction. Brogan et al. (1991) first mapped the offsets along these alluvial fans. The Q3b surface and channels are offset several meters by several stands of the northern Death Valley fault. We collected quartzite cobbles (DVDFC2A, C, D and E) from this Q3b surface and its active channel (Q4b; Sc4A, B and C) to dating using $^{10}$Be TCN and to examine inheritance of TCN.

5.5. Mud Canyon
An impressive succession of alluvial fans is present in the Mud Canyon area. Brogan et al. (1991) mapped offsets along the northern Death Valley fault zone in this region. Frankel et al. (2010a) examined this region in more detail to determine rates of displacement along the northern Death Valley fault zone using high-resolution airborne lidar digital topographic data, $^{10}$Be TCN and OSL dating. The OSL dating of Frankel et al. (2010a) shows that the Q3a surface dates to 14-20 ka. However, the $^{10}$Be TCN dating could not be used to date the surfaces successfully since the spread of ages is considerable (~ 38 ka to ~ 153 ka). Moreover, $^{10}$Be TCN in active stream channels shows that inherited TCN concentrations in this area are relatively
high, with ages ranges from ~8 to ~30 ka. We examine these data in more detail below and provide new $^\text{10}$Be TCN ages for cobbles from a Q3a surface in the southeastern part of this study area (Fig. 7).

5.6. Beatty bar
A series of bars and spits, collectively called the Beatty Junction bar complex by Klinger (2001), are present north of Beatty Junction. These provide some of the best evidence for Lake Manly and have been examined in numerous studies (Blackwelder, 1954; Hunt and Mabey, 1966; Orme and Orme, 1991; Wright and Troxel, 1993; Galvin and Klinger, 1996; Klinger, 2001a,c). The Betty Junction bar complex comprises four approximately east-west trending ridges and spits (A, B, C, and D; Galvin and Klinger, 1996; Klinger, 2001c). The main and highest bar (B) is the youngest and is exposed in a road cut and an excavation just west of the road. The bars and ridges are composed of sand and gravel, which have meter-size beds that mimic the topography of the ridges. The gravels are imbricated indicating transport direction from the south and west. Galvin and Klinger (1996) hypothesized that the ridges formed in order of increasing crest elevation (D, C, A, and B).

A case for a Late Pleistocene age as been made for the relative age of the beach ridges based on stratigraphic relationships, preservation of the landforms and soil characteristics (Galvin and Klinger, 1996; Klinger, 2001c). However, the numerical ages for the highest bar are equivocal. Anderson (1998; unpublished data) provides a thermoluminescence (TL) age of $24.0 \pm 2.5$ ka and an OSL age of $\sim 68$ ka for fine-grained sediment ponded behind the main gravel spit near its eastern end (Table 4). The dated sediment was interpreted to have formed in the playa behind the spit, thus these ages post-date the formation of the spit. In contrast, Zreda (cited in Orme an Orme, 1991) and Phillips and Zreda (1999), used $^{36}$Cl TCN to date gravel clasts on the spit and for a depth profile through the gravel at the crest of the same spit that give a surface age of $153 \pm 13$ ka and 20 to 85 ka, respectively.

To test the difference between ages determined on the highest bar (B) we collected two samples for OSL dating from exposures in the bar and quartzite cobbles from the surface of the crest of the bar for $^\text{10}$Be TCN dating (Fig. 8).

5.7. Manly shorelines
A series of wave-cut shorelines are present on the lower slopes of the Black Mountains ~8 km south of Furnace Creek (Fig. 1). The surfaces of these shorelines are armored with small pebbles and cobbles, and desert pavements are present on some stretches. The most prominent wave-cut surface is at an elevation of about 10 m below sea level. We collected cobbles (MANLY-1, -2, -3, -4, -5 and -6) from this surface to help determine the timing of its formation.

5. Dating results
The $^\text{10}$Be TCN and OSL ages for the samples dated in this study are listed in Tables 2 and 3. Table 5 shows the ages from previous studies, which have been calculated using the same methods as described above. All the $^\text{10}$Be TCN ages are minimum ages since we do not make any correction for erosion. Since we have obtained several $^\text{10}$Be TCN ages > 350 ka, however, the rate of erosion must be relatively small. Using the method of Lal (1991), the mean erosion rate of the three oldest samples (MANLY-1, KF-0417-12 and -13) was obtained to provide a rough
estimate of erosion. This produced values of 5.4 ± 0.6 m/Ma, which is consistent with rates determined in other semi-arid environments (e.g., Small et al. 1997; Seong et al., 2007; Owen et al., 2009) and previous estimates of catchment-scale denudation in Death Valley and neighboring Panamint Valley (Jayko, 2005). If we assume that all the samples we collected erode at that rate, then, a calculated age of 10 ka, would underestimate the true age by ~ 5%, an age of 50 ka by ~ 24%, and an age of 100 ka by ~ 50%. However, since most of the clasts (cobbles and boulders) we collected retained their original rounded depositional shapes and given the arid to semi-arid climate in the region throughout the Late Quaternary it is highly unlikely that these experienced any significant erosion.

Currently there is much debate regarding the appropriate scaling models and geomagnetic corrections for TCN production to calculate TCN ages (e.g., Pigati and Lifton, 2004; Staiger et al., 2007; Balco et al., 2008). We, therefore, use constant (time-invariant) local production based on Lal (1991) and Stone (2000), but acknowledge that uncertainties in absolute production rates for the latitude and altitudes of Death Valley may be up to ≤ 15% difference in apparent ages among scaling models for the Holocene and ≤ 10% for the late Pleistocene. Irrespective of these issues, scaling factors have far less impact on relative chronologies for events in a limited geographic area, such as our study area in Death Valley.

All our $^{10}$Be TCN ages show considerable variance on individual surfaces (Tables 2 and 5). For example, the Q2b surface in the North Ubehebe Crater study area has $^{10}$Be TCN ages ranging from ~ 27 ka to ~ 191 ka, the Q3a surface in Mud Canyon has ages that range from ~ 8 to ~ 133 ka, the Q3a surface at North Junction has ages ranging from ~ 26 ka to ~ 51 ka, and the Q3b surface at South Junction has ages from ~ 6 ka to ~ 134 ka. Moreover, samples collected in the active channels (Q4a) range from ~ 6 ka to ~ 93 ka. Similarly, the spread of $^{10}$Be TCN ages for the Beatty Junction bar complex and the Manly shorelines study area is large, ranging from ~119 ka to ~ 385 ka (mean = 218 ka; 1 σ [standard deviation] = 125 ka) and ~ 109 ka to ~ 465 ka (mean = 209 ka; 1 σ = 142 ka), respectively. There is no correlation between samples size (boulder/cobble) and age within an individual surface (Tables 2 and 5). To fully assess the spread of $^{10}$Be TCN ages on the alluvial fan surfaces, we plot all the $^{10}$Be TCN ages determined in this and previous studies for Death Valley as probability distributions (Fig. 10).

Both OSL samples have ages that are within error of each other showing that the sands were deposited at ~ 19 ka. This provides confidence in the OSL dating.

6. Discussion
TCN ages on surfaces are affected by several geological factors, including weathering, exhumation, prior exposure and shielding of the surface by sediment and/or snow. With the exception of prior exposure, these factors generally reduce the concentration of TCNs in surfaces, which results in an underestimate of the true age of the landforms. Episodes of prior exposure result in an overestimate of the true age. Uneven distribution of these geological processes can produce a large spread in apparent exposure ages on a landform. These effects are commonly assessed by collecting multiple samples on a surface. If multiple surface samples possess similar apparent ages, the data suggest that the dated samples were not derived from older surfaces and/or were not weathered or exhumed; hence the ages are likely representative of the true age of the surface. In the typical case where a wide range of the ages are obtained for a
single landform, the most likely explanation suggests post-depositional exhumation of fresh boulders to the surface and/or derivation of samples from deposits or slopes that have experienced prior exposure to cosmic rays, thus containing inherited TCN concentrations. The large spread of ages on individual surfaces in Death Valley reflects the dominance of geologic processes in controlling the concentrations of TCNs in clasts and sediment.

The very large spread of ages for the cobbles and boulders in the active channels (Q4a surfaces) clearly indicates that the \(^{10}\text{Be}\) TCN concentrations in the sampled clasts have a significant inherited component (Fig. 10A). The minimum age for any clast in this and Frankel et al.’s (2007a, 2010a,b) studies is 2 ka, but the mean is 24 ka and standard deviation is 27 ka (strongly skewed toward younger ages). This suggests that clasts within older alluvial fan surfaces will have a significant component of inherited \(^{10}\text{Be}\) TCNs.

Table 6 shows the \(^{10}\text{Be}\) TCN ages for alluvial fan surfaces that were dated in this study and in Frankel et al. (2007a; 2010a,b). These are compared the age estimates of Klinger (2001), that were based on soil characteristics, and OSL ages of Sohn et al. (2007) and Frankel et al. (2010a,b). These data show that the mean \(^{10}\text{Be}\) TCN ages of Q3a, Q3b and Q3c surfaces are considerably older than the estimated ages of the surfaces based on OSL and soil methods (Fig. 10B). However, the youngest \(^{10}\text{Be}\) TCN ages for each surface are consistent with the estimated ages, which indicate that the sampled clasts likely have significant inherited TCNs. The prevalence of inherited \(^{10}\text{Be}\) TCNs in samples suggests that sediment transfer to alluvial fans from adjacent hillslopes is slow and/or the residence time of sediment on valley sides (floodplains) or channel bottoms is great (many millennium to tens of millennium).

These results highlight the problems of applying TCN methods to surface samples to date alluvial fans in Death Valley. Machette et al. (2008) highlighted that the use of TCN depth profiles may help assess and overcome the problems of inheritance. Moreover, Frankel et al. (2007a) showed that both surface clasts and depth profiles could be used to define ages with confidence in some settings. However, Frankel (2010b) showed that depth profiles could not be determined on Q3 surfaces because the amount of TCN inheritance in sediment is several orders of magnitude greater than the concentrations of TCN acquired in situ.

The distribution of \(^{10}\text{Be}\) TCN ages for Q2c has a similarly a large range, but the younger \(^{10}\text{Be}\) TCN ages are close to the age estimate of the surfaces based on other methods (Fig. 10C). The spread of \(^{10}\text{Be}\) TCN ages for Q2b, based on only one study area (North Ubehebe Crater), are also large, but the youngest ages are significantly younger than age estimates based on other methods. This suggests that erosion may be significant on these surfaces, exhuming clasts and exposing them late in the evolutionary history of the fan. Inheritance may also be a problem for some clasts on the Q2b surfaces as highlighted by the samples (KF-0218-2 and -3) that are older than 160 ka. The Q2b surface age would be 41 ± 9 ka if the two oldest samples were eliminated from the data set. This would be a significant underestimate of the age, and thus argues for significant erosion of this surface. The surface erosion interpretation suggested by the TCN ages is supported by abundant incised channels that traverse Q2b and the development of a convex hillslope-type system on alluvial fans of this age in the North Ubehebe Crater area thus providing geomorphic evidence for extensive erosion of Q2b (Fig. 3; e.g., Frankel and Dolan, 2007).
The large spread of $^{10}$Be TCN ages for the Beatty Junction bar complex (~119 ka to ~385 ka; mean = 218 ka; $\sigma$ = 125 ka) and the Manly shorelines (~109 ka to ~465 ka; mean = 209 ka; $\sigma$ = 142 ka) study areas also suggests that geologic factors have a strong influence on these surfaces. The OSL dates (Table 3) for the Beatty Bar are similar to the TL date, but are significantly different than the OSL date of Anderson (1998) (Table 4). Moreover, the soil development characteristics are consistent with a late Pleistocene age (Galvin and Klinger, 1996; Klinger, 2001c); however, correlating soil development on alluvial-fan deposits with soils developed on a gravel spit is equivocal. Li et al. (1997) and Lowenstein et al. (1999) interpreted sediment cores from near Badwater as consistent with a “deep” Lake Manly during marine isotope stage (MIS) 2 and towards the end of MIS 6. However, core recovery of MIS 2 sediments was poor and the faunal data is consistent with a saline mudflat rather than a fresh water lake (Forester et al., 2005). In addition, Machette et al. (2008) and Knott et al. (2002; 2004) found no evidence of an MIS 2 lake above -46 m and -30 m, respectively, on morphologically similar alluvial-fan deposits dated between 100 and 40 ka by Machette et al. (2008).

The disparate geochronology at the Beatty Bar leads to two possible interpretations of the TCN data. If the Beatty Bar was deposited during MIS 2, then the OSL dates (Table 3), TL dates of Anderson (1998) and soil development represent the correct age of the deposit at the Beatty Bar and a high lake level stand during MIS 2 at +45 m (~130 m deep lake) and that the TCN-dated cobbles have ~170 ka inherited $^{10}$Be. This interpretation is consistent with the interpretation of core data by Lowenstein et al. (1999).

Alternatively, if the Beatty Bar was deposited during MIS 6, then the TCN $^{10}$Be-dated cobbles have ~20 ka inherited $^{10}$Be and the OSL dates (Table 3) and the soil development reflect material elluviated into the bar deposit long after deposition. These elluviated materials would have been bleached (reset) and record younger dates. This interpretation is consistent with observations by Machette et al. (2008) and Knott et al. (2002; 2004) that no lacustrine deposition or erosion is observed on 100-40 ka alluvial-fan deposits at Hanaupah Fan and Mormon Point, respectively, above elevations -46 m and -30 m respectively. An MIS 6 age for the Beatty Bar is also consistent with the faunal ostracode data indicating a saline lake during MIS 2 (Forester et al., 2005).

Like the Beatty Bar, the Manly shorelines dates may be interpreted as either MIS 2 or MIS 6 even though the Manly shorelines have the oldest date for any Lake Manly-related deposits at ~465 ka. The Manly shorelines are significantly lower than the Beatty Junction bar complex at an altitude of ~10 m below sea level, compared to ~45 m asl for the Beatty Bar. Assuming the Beatty Junction bar complex was formed during MIS 2, the Manly shorelines would have been intermittently covered by water during MIS 2 according to Anderson and Wells (2003). Consequently, the surface of the Manly shorelines would have been reworked by wave action. This suggests that the clasts that were dated using $^{10}$Be TCN methods on the Manly shorelines were reworked from the previous MIS-6 high stand and/or slope debris and had significant prior exposure.

Alternatively, if the Beatty Bar has a MIS 6 age, the mean TCN $^{10}$Be date of 209±142 ka at the Manly shorelines is consistent with clasts having variable amounts of inherited $^{10}$Be deposited in an MIS 6 lake. This interpretation is consistent with observations by Machette et al. (2008) and
Knott et al. (2002; 2004) that the MIS 4 and MIS 2 lake shorelines never rose above -46 m and -30 m, respectively. This is also consistent with the interpretation by Forester et al. (2005) that the MIS-2 lake was a saline mudflat and not a freshwater lake.

In sedimentary environments where reworking of material is common, like deltas, the youngest dates are generally considered the best indicator of the age of the deposit (Stanley and Hait, 2000; Knott and Eley, 2006). If this practice is applied to the TCN $^{10}B$ dates at the Beatty Bar and Manly shorelines, the interpreted TCN ages of these deposits would be $\sim$119 ka and $\sim$109 ka, respectively.

Machette et al. (2008) dated a lacustrine delta complex on Hanaupah Canyon fan west of Badwater using a $^{36}Cl$ depth-profile to 130 ka, which is consistent with deposition during a high stand of Lake Manly at the end of MIS 6. The dated deposits are at an altitude of $\sim$ 30 m asl, which relates to a lake with a maximum depth of $\sim$ 115 m. Machette et al. (2008) also showed that remnants of shoreline deposits are present at higher elevations ($> 67$ m asl) on the southern margin of the Hanaupah Canyon fan complex are cut across older alluvium and may be related to an MIS 6 or, more likely, an MIS 8 or earlier high stand.

Our results highlight the problems of using surface clasts to date landforms in Death Valley. This underscores the potential problems of applying such methods in other similar semi-arid and arid settings where there is significant prior exposure and slow sediment transfer. Armstrong et al. (2010) showed similar problems for piedmont mountain front deposits along the eastern Sierra El Mayor in northern Baja California. Despite the potential problems of using TCN methods to define ages on alluvial fan surfaces in Death Valley, a combination of TCN surface and depth profile methods, along with other Quaternary dating techniques, such as OSL geochronology, may provide useful determinations of landform age to investigate tectonic rates and other processes in this region (e.g., Frankel et al., 2010a,b).

7. Conclusions

The $^{10}Be$ TCN ages from individual alluvial fan surfaces in Death Valley show considerable variance. In particular, samples collected in the active channels date from $\sim$ 6 ka to $\sim$ 93 ka. This shows that there is significant inheritance of $^{10}Be$ TCN in clasts that ultimately form alluvial fans in Death Valley. This is probably because bedrock hillslopes erode slowly and clasts reside in channels and floodplains for long periods in this semi-arid to arid region; hence, this material is exposed to cosmic rays and acquires a component of inherited TCNs. Comparisons of $^{10}Be$ TCN ages on alluvial fan surfaces with chronostratigraphies based on soil development and OSL dating show that minimum $^{10}Be$ TCN ages within sample sets on individual surfaces more closely approximate the age of the surface for landforms younger than $< 70$ ka. However, alluvial fan surfaces older than $> 70$ ka have undergone significant erosion that the majority of $^{10}Be$ TCN ages for data sets on individual surfaces underestimate the true age of the surface due to erosion and exhumation of fresh clasts.

The $^{10}Be$ TCN ages for Beatty Junction bar complex and the Manly shorelines range from $\sim$119 ka to $\sim$ 385 ka and $\sim$ 109 ka to $\sim$ 465 ka, respectively, or during MIS 6. The youngest dates may represent the age of the deposit, as is frequently the case in reworked deposits, and many clasts have a substantial inherited $^{10}Be$ TCN. An MIS 6 age for these deposits is consistent with
mapping and dating by Machette et al. (2008) at Hanaupah fan as well as mapping and observations at Mormon Point (Knott et al., 2002; 2004) and faunal interpretation of the Badwater core (Forester et al., 2005). This suggests that OSL dates (Table 3) records of younger eluviated materials. In contrast, new OSL and previously published and preliminary OSL and TL ages and soil development allow interpretation that these landforms formed during MIS 2 (~22-18 ka). This suggests that the clasts dated with $^{10}$Be methods are derived from older shorelines and/or associated landforms and have inherited $^{10}$Be TCNs.

Our results highlight the significant problems associated with using surface cobbles and boulders to date surfaces using $^{10}$Be methods in Death Valley and likely for other similar semi-arid and arid settings. We suggest that a combination of TCN surface and depth profile methods, together with other techniques such as OSL dating and geologic mapping, are needed to accurately determine late Quaternary numerical landform chronologies in semi-arid environments such as Death Valley, which are essential for tectonic, geomorphic, paleoenvironmental, landscape development and archaeological studies.

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References


and paleoclimates from salt cores, Death Valley, California, Palaeogeography, Palaeoclimatology, Palaeoecology 123, 179–203.


**Figures**

**Fig. 1.** Regional location/setting for Death Valley (BM - Black Mountains; CM - Cottonwood Mountains; DSV - Deep Springs Valley; EV - Eureka Valley; FM - Funeral Mountains; GM - Grapevine Mountains; LCR - Last Chance Range; SV - Saline Valley; YM - Yucca Mountain).

**Fig. 2.** Map of Death Valley showing the locations of Quaternary surfaces that have been dated using numerical methods and the study areas examined in this paper.
Fig. 3. High-resolution airborne LiDAR digital topographic image for the North Ubehebe Crater study area (adapted from Frankel and Dolan, 2007) showing locations for the $^{10}$Be TCN sampling.

Fig. 4. High-resolution airborne LiDAR digital topographic image for Big Dip Canyon showing the locations of sampling sites for $^{10}$Be TCN dating. The green circles show the sites sampled by Frankel et al. (2007a) together with a probability distribution plot for their ages. The red circles show the locations of the samples (Sc6A, B, C) sampled from the active channel together with photographs of the active channel and typical sampled clasts.

Fig. 5. Dating sites at the North Junction alluvial fans. A) View of the Q3a fan together with $^{10}$Be TCN ages. B) View of active channel with examples of the typical clasts that were dated using $^{10}$Be TCN methods. C) High-resolution airborne LiDAR digital topographic image of the sampled areas.

Fig. 6. High-resolution airborne LiDAR digital topographic image of the South Junction study area showing the location of the sampling sites and views of the Q3b surface, and the active channel with typical clasts that were sampled for $^{10}$Be TCN dating.

Fig. 7. High-resolution airborne LiDAR digital topographic image for South Junction and Mud Canyon (adapted from Frankel et al., 2010a) showing the sampling locations for $^{10}$Be TCN (white circles) and the OSL dating sites (black circles) of Frankel et al. (2010a). Q3a surfaces are shaded in pale grey. The white lines show the trace of the northern Death Valley fault. The inset photographs show a typical surface for Q3a where samples KF-0416-1 to KF-0416-6 where sampled and an example of one of the sampled clast, showing both the exposed and underside surface (lower panel).

Fig. 8. The highest bar (B) of the Beatty Junction bar complex showing A) the surface and example of the cobbles that were dated together with $^{10}$Be TCN ages and B) sampling locations for OSL dating in excavations.

Fig. 9. Views of Manly shorelines ~ 8 km south of Furnace Creek. A) View NW across Death Valley showing the location of the shoreline from where $^{10}$Be TCN samples were collected. B) Surface of the shoreline that was sampled. C) Views of several of the sampled cobbles on surface of the shoreline.

Fig. 10. Probability distribution plots for $^{10}$Be TCN ages for A) Q4b, B) Q3a, Q3b, Q3c and C) Q2a and Q2b units. The number of samples and number of locations used in each probability plot is highlighted by n and s. Q4b are samples BWF082, 083, 084 and 085, and Bwater6, 7 and 8 from Frankel et al. (2010b) for active channels south of Badwater; and samples Q3a are from from Mud Canyon including samples KF-0416-1 to 6 and Sc1A, B, C, and from Frankel et al. (2010a) samples DVFC1A to E and KF-0506-1 to 10. Q3b are from samples DVFC2A, C, D and E from South Junction; and from Frankel et al. (2010b) including samples KFMP-101, 103, 105, 106, 110 and 112 from Mormon point. Q3c are from Badwater fans including samples Bwater1 to 5 and BWF086, 088 and 089 from Frankel et al. (2010b). Q4a are samples from North
Junction and Big Dip Canyon, and include samples Sc5A and B, and Sc6A, B and C, respectively. Sc2a and B, Sc3A, B and C, and Sc4A and B from Frankel et al. (2010a) for active channel in the Mud Canyon area. Q2b are samples KF-0218-2, 3, 4 and10, and KF-0404-1 to 6 from Ubehebe Crater.

Tables

Table 1
Correlation Quaternary stratigraphic unit in Death Valley (adapted from Klinger, 2001d and Machette et al., 2008); and generalized descriptions for Late Quaternary stratigraphic units (after Klinger, 2001b).

Table 2
Locations for $^{10}$Be TCN samples, sample sizes, topographic shielding factors, concentrations, and analytical results and ages.

Table 3
Summary of OSL dating results from extracted from sediment, sample locations, radioisotopes concentrations, moisture contents, total dose-rates, $D_E$ estimates and optical ages.

Table 4
Numerical ages from the highest spit of the Betty Junction bar complex (adapted from Machette et al., 2001).

Table 5
Location and $^{10}$Be TCN ages for samples collected from Q4b and Q3a surfaces in the Mud Canyon region (from Frankel et al., 2010a), Badwater (after Frankel et al., 2010b) and Big Dip Canyon (after Frankel et al., 2007a). All ages were calculated or recalculated using the same methods as in our study.

Table 6
Summary of $^{10}$Be ages for surfaces in this study and Frankel et al. (2007a,b, 2010a,b) and OSL ages.
Beryllium-10 model ages were calculated with the CRONUS-Earth online calculator, version 2.2 (Balco et al., 2008; http://hess.ess.washington.edu/).

Propagated error in the model ages include a 6% uncertainty in the production rate of Be. Isotope ratios were normalized to Be = 6.183 ± 0.833 x 10^-11.

### Table 2

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Lake Manly shorelines

Quartzite

Be = 6.183 ± 0.833 x 10^-11