I, Harrison J Gray, hereby submit this original work as part of the requirements for the degree of Master of Science in Geology.

It is entitled:
Geomorphic response to transpression and alluvial fan chronology of the Mecca Hills, a case study along the Southern southern San Andreas fault zone.

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Geomorphic response to transpression and alluvial fan chronology of the Mecca Hills: a case study along the southern San Andreas Fault zone

A thesis submitted to the Graduate School of the University of Cincinnati in partial fulfillment of the requirements for the degree of Master of Science in the Department of Geology Of the College of Arts and Sciences by Harrison J. Gray

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ABSTRACT

Geomorphic analysis was undertaken to better understand the landscape evolution of the Mecca Hills, a zone of transpressional uplift along the southern end of the San Andreas fault, in southern California. Terrestrial cosmogenic nuclide (TCN) $^{10}\text{Be}$ geochronology, TCN $^{10}\text{Be}$ derived catchment-wide erosion rates, and digital elevation model based geomorphic indices were used to define the ages of landforms, determine the rates of catchment-wide erosion, and to assess the relative influence of tectonic uplift on catchments within the Mecca Hills. Ages for major geomorphic surfaces based on $^{10}\text{Be}$ surface exposure dating of boulders and $^{10}\text{Be}$ depth profiles define the timing of surface formation to $8.2 \pm 0.5 \text{ ka (Qyf1 surface)}$, $67.2 \pm 5.3 \text{ ka (Qvof2 surface)}$, and $280 \pm 24 \text{ ka (Qvof1 surface)}$. Comparison of $^{10}\text{Be}$ measurements from active channel deposits (Qac) and terraces (Qt) illustrate a complex history of erosion, sediment storage, and sediment transport in this environment. Beryllium-10 catchment-wide erosion rates range from $19.9 \pm 3.2$ to $149 \pm 22.5 \text{ m Ma}^{-1}$ and reveal a mean rate of $58.9 \pm 10.8 \text{ m Ma}^{-1}$, significantly less than the global mean $^{10}\text{Be}$ catchment-wide erosion rate of $218 \text{ m/Ma}$. Geomorphic indices, including the stream length gradient index, ratio of catchment area to volume, and mountain front sinuosity, demonstrate spatial and temporal heterogeneous geomorphic response, forced by rapid tectonic uplift throughout the Mecca Hills.
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INTRODUCTION

Southern California is one of the most well-known diffuse transform plate boundaries. The landscape evolution of this region, like many others, acts as a function of climatically controlled erosive geomorphic processes and vertical and horizontal tectonic displacement (Whipple, 2004). Defining the Quaternary geomorphic history along the San Andreas fault zone is essential to help develop landscape evolution and tectonic models for this active zone. Moreover, case studies of geomorphically and tectonically active areas, such as along the San Andreas fault zone, serve as observational foundations that focus future research efforts on tectonic geomorphology and landscape evolution (Keller et al., 1982; Dorsey and Roering, 2005). Yet few studies have been undertaken to quantify rates of landscape evolution in this region, especially along the southern end of the San Andreas fault zone. To develop a Quaternary geomorphic history for a stretch of the southern Andreas fault zone towards helping to develop a landscape evolution story for the Pacific – North American plate boundary, we undertook a geomorphic study of the Mecca Hills close to the southernmost end of the fault zone. The Mecca Hills are a rapidly uplifting transpressive segment of the southern San Andreas fault zone. We conducted a fourfold approach utilizing: 1) geomorphic mapping; 2) terrestrial cosmogenic nuclide (TCN) $^{10}$Be geochronology to assess ages of geomorphic surfaces; 3) TCN $^{10}$Be in sediment to quantify catchment averaged rates of erosion; and 4) GIS to calculate geomorphic indices and catchments metrics across the Mecca Hills.

REGIONAL SETTING

The Mecca Hills are a result of transpression along a stretch of the southernmost part of the San Andreas fault within the Coachella Valley of southern California (Fig. 1). The Coachella valley
is a northern extension of the Salton Trough, a pull-apart basin tied to rifting in the Gulf of California (Axen and Fletcher 1998). The San Andreas fault along this segment exhibits a “sawtooth” geometry in map view consisting of low-relief strike-slip segments bounded by high-relief transpressive segments (Sylvester and Smith, 1976; Sylvester, 1988; Bilham and Williams, 1989; Spotila, 2007). The transpressive segments, known geographically as the Indio, Mecca, and Durmid Hills, demonstrate significant deformation and uplift (Diblee, 1954; Sylvester and Smith, 1976). Of these transpressive segments, the Mecca Hills demonstrates the greatest cumulative deformation (Sylvester and Smith, 1976; Sheridan and Weldon, 1992) and potentially preserves the greatest history of tectonic activity on the southern San Andreas Fault since ~740 ka (Rymer, 1992; Hurford and Hammerschmidt, 1985).

The Mecca Hills were originally mapped at a regional scale by Diblee (1954) and at a local scale by Ware (1958) in which the main stratigraphic units were defined, which include the Palm Spring Formation, the Mecca Formation, and the Ocotillo Conglomerate (Sylvester and Smith, 1976). Discovery of vertebrate fossils in the Mecca Hills by Hays (1957) and Ware (1958) indicated a late Cenozoic age for the Palm Spring Formation. Detailed mapping and stratigraphic work by Sheridan and Weldon (1994) and Boley et al. (1994) built on and expanded the mapping of Sylvester and Smith (1976) and added to the paleomagnetic work of Chang et al. (1986). Discovery of the Bishop Ash bed by Ware (1958) and chemical confirmation by Merriam and Bischoff (1975) provided further proof of late Cenozoic age for these formations, specifically with the Bishop Ash dated to 767.1 ± 0.9 ka (Izett and Naeser, 1976; Reid and Coath, 2000; Crowley et al., 2007). Detailed structural geologic studies by Sylvester and Smith (1976) proposed a model of partitioned transpression, that they called a ‘palm tree’ structure, which
helped lay the foundations towards future models of transpressional deformation (Fossen and Tikoff, 1998). Further work by Sheridan and Weldon (1992) re-interpreted the structural geology and suggested an alternate model of compression involving upward and inward motion of stratigraphy by cataclastic flow against a bedrock buttress. Work by Patt (2000) examined the Quaternary geology and conducted the first geomorphic analysis of the Mecca Hills.

METHODS

Geomorphic Mapping

We followed the mapping, unit descriptions, and conventions of Patt (2000; Table 1, Fig. 2), who utilized and slightly modified the relative weathering methodology proposed by Burke and Birkeland (1979) and McFadden et al. (1989). Alluvial stratigraphies were developed by distinguishing geomorphic units by the following criteria: 1) number, pitting, splitting, and relief of boulders; 2) degree of desert varnish, and extent of desert pavement development; 3) percent vegetation cover and plant diversity; and 4) soil development and solum depth (Table 1). The numbering scheme used for geomorphic surfaces was adopted from the designations of Patt (2000) who used a scheme loosely based on regional alluvial chronologies (McFadden et al., 1989; Bull, 1991; Hooke and Dorn, 1992; Wells et al., 1990). Based on the relative weathering system, Patt (2000) designated the oldest alluvial surface as Qvof1 and named the next youngest surface as Qvof2. Patt (2000) designated the most recently abandoned alluvial fan surface as Qyf1 and river fill terraces as Qt1 while naming the active alluvial fan deposits as Qac.

The Qvof1, Qvof2, Qyf1, Qt1 surfaces were targeted for geochronology due to their widespread presence and significance in the Mecca Hills’ alluvial stratigraphy as noted by Patt (2000). Fieldwork was undertaken to verify the mapping of Patt (2000) and to collect samples for TCN
Digital mapping was limited to the continuous extent of surfaces sampled for geochronology to avoid over extrapolation of age results. Mapping was performed remotely using ArcGIS 10.1 Education Edition and aerial photography from CalAtlas (State of California 2013). Digital mapping results are presented in Figure 3 and the regional geology adapted from Patt (2000) is shown in Figure 2 with geomorphic Qvof1, Qvof2, and Qyf1 surfaces based on relative weathering correlation and demonstrates the extent of geomorphic surfaces beyond our sampled region. Faults within the Mecca Hills were not mapped in this study, we instead refer to data from the USGS fault and fold database (U.S. Geological Survey and California Geological Survey, 2013) Patt (2000), and structures from Sylvester and Smith (1976) (Figs. 2 and 3).

Example photos of the mapped geomorphic surfaces are presented in Figure 4.

**TCN $^{10}$Be Surface Exposure Dating**

Surface exposure ages for geomorphic units/surfaces within the Mecca Hills were determined by $^{10}$Be TCN geochronology (Table 2). Samples on major geomorphic surfaces were collected from boulders that demonstrated minimal weathering and erosion as evidenced by strong desert varnish, a lack of physical weathering features such as fracturing and disintegration, and that were well inset into the ground surface with no possibility for toppling, and in addition boulder were located away from topographic lows and/or hillslopes (Figs. 4 and 5; see supplemental Fig. 2). Sample sizes ranged from 300 to 1000 g, collected by hammering off 1-5 cm-thick layers from horizontal boulder tops using a hammer and chisel, avoiding the sides of the boulders. The samples were crushed and sieved to the 250-500 µm particle size and treated with aqua regia to remove carbonates and organic material. Following this, the samples were placed in a 24 hour 5% hydrofluoric solution to etch, dissolve, and disintegrate non-quartz minerals and the resulting
sample was rinsed and agitated with a high velocity 10% Lauryl Amine and CO$_2$ spray to pulverize and evacuate feldspathic minerals. The samples were then subjected to further quartz purification using magnetic separation employing a Frantz Magnetic Separator, and further separated using heavy liquid (lithium heteropolytungstate - LST). The resulting pure quartz was subject to a 1% HF acid etch to remove any meteoric Be before complete dissolution using concentrated solution of 10 parts 49% HF and one part HNO$_3$ scaled to the weight of the pure quartz extract. The dissolved quartz was desiccated and underwent repeated treatment with application of 25% HClO$_4$ while on a hot plate set to high heat to remove fluorides. The sample was rehydrated in an HCl solution and passed through cation and anion exchange columns to concentrate Be and remove Al and Ti ions. Beryllium was precipitated from the purified Be solution by addition of NHOH to produce a Be(OH)$_2$ gel. This gel was dried and combusted at 700°C before being mixed with Nb powder and loaded in cathode targets for accelerator mass spectrometry (AMS) at PRIME lab in Purdue University and at Lawrence Livermore National Laboratory to determine $^{10}$Be/$^{9}$Be ratios. Ages were derived from AMS determined $^{10}$Be concentrations using the online CRONUS calculator (Balco et al., 2007). Age results including various models for age determinations are present in Table 2 following reporting methods suggested by Frankel et al. (2010). Our preferred age is obtained with the time-dependent scaling model (Lal, 1991/Stone, 2000).

Age results were grouped based on mapped geomorphic surfaces and analyzed using a normal kernel probability density estimate (NKDE; Fig. 6) and a mean weighted square deviation (MWSD) test (McDougall and Harrison, 1988; Powell et al., 2002; Streule et al., 2009). Surface ages and errors based on boulder data are the weighted mean of all ages that pass the MSWD test and the 1-$\sigma$ standard deviation of those ages. For surfaces that do not pass the MSWD test, the
surface age and error is the weighted mean and standard deviation of all ages from that surface. The NKDE analysis, also known as a probability distribution function plot of the sum of the individual Gaussian distributions, illustrates the scattering of boulder surface exposure ages for a given geomorphic surface. Curves were produced using Camelplot MATLAB code developed by Balco (2009). We assumed zero erosion for all surface exposure age calculations. TCN $^{10}$Be surface exposure ages on boulders were compiled from studies in southwestern North America, recalculated using Lal (1991)/Stone (2000) modeling scheme, and plotted as an NKDE plot to discern episodes of deposition (supplemental Fig. 1).

**TCN Depth Profiles**

Beryllium-10 TCN depth profiles were determined for the Qvof1, Qvof2, and Qyf1 surfaces to define surface ages (Fig. 7, Table 3). Samples were collected, from 1.5 to 2 m deep pits or natural exposures that were enlarged to a depth about 1 m, at equal intervals with depth from the surface (Table 3). Beryllium-10 concentrations were determined following extraction procedure described in the $^{10}$Be TCN surface exposure dating section above. Erosion rates were computed using MATLAB 2009 and TCN depth profile simulator MATLAB code developed by Hidy et al. (2010).

**Catchment-wide erosion rates**

Catchment-wide erosion rates for the Mecca Hills were determined using TCN $^{10}$Be concentrations in active-channel alluvial sediment (Lal and Arnold 1985; Granger et al 1996; Bierman and Steig 1996). (Fig. 5, Table 4). Samples were collected throughout major drainage networks focusing on Painted, Thermal, and Box Canyons (Figs. 3 and 5). Approximately ~1 kg
of sediment from the trace of the active channel and were collected in the upper, middle, and lower reach of drainage systems. Beryllium-10 concentrations were determined by Be isolation and AMS measurement as described in the previous section. Upstream catchments of sample locations were delineated and extracted using standard flow routing algorithms in ArcGIS 10.0 on USGS National Elevation Dataset DEMs (nationalmap.gov). Catchment-wide $^{10}$Be production rates were calculated using the methods and MATLAB v. (2009) code of Dortch et al. (2011). Individual $^{10}$Be production rates (Lal 1991) were calculated on a pixel by pixel basis using the scaling factors of Stone (2000) and averaged over the entire catchment. Production rates were corrected for topographic shielding on a pixel by pixel basis by calculating maximum angle to the horizon and using this as the shielding estimate (see Dortch et al., 2011). Basin geomorphic parameters of catchment area, total relief, mean slope, and catchment area (from Portenga and Bierman, 2011) were calculated from sampled catchments and compared in a linear regression against erosion rate to compare the Mecca Hills against the global dataset (Fig. 8).

**Geomorphic Indices**

Catchment geomorphic metrics were calculated using tools available with ArcGIS 10 with the spatial analyst extension. Ten m per pixel digital elevation models (DEM) were acquired from the national elevation data set provided by the U.S. Geological Survey (2013). Catchments were delineated by computing flow direction and flow accumulation rasters to create a hydrologic network and then defining a catchment as one connected to the main drainage trunk streams, which included Box, Painted and Thermal canyons (Figs. 3 and 5). A threshold for catchment size of $10^6 \text{ m}^2$ was chosen as the minimum catchment size as this is considered the size of
catchment where fluvial processes overcome hillslope processes as the dominant form of sediment erosion and transport (Wobus et al., 2006) and this size is less sensitive to lithologic controls and stochastic processes. This criterion produced 39 catchments from which we calculated and compared geomorphic indices.

The ratio of catchment volume to area (RVA) was obtained by first determining the volume of delineated catchment in cubic meters and then by dividing this value by the sum of pixels within the catchment boundaries multiplied by the pixel area (Frankel and Pazzagila, 2006). The catchment volume was determined by clipping individual delineated catchments from a 10 m DEM. The elevation data from the catchment bounding ridgeline was then extracted and used to derive a triangular irregular network (TIN) effectively generating a capping surface connecting catchment ridgelines. The TIN was then clipped to catchment 2D geometry and converted to a raster. The original clipped catchment DEM was subtracted from the capping raster and then summed by pixel and multiplied by pixel area to produce a single value of catchment volume in cubic meters. This value was divided by the number of pixels within the catchment boundaries multiplied by catchment area and displayed graphically in Figure 9.

Stream length gradient (SL) index values were computed across the entire drainage network for the Mecca Hills and then averaged per catchment. The SL index is computed by multiplying the slope of a river by the distance to the drainage divide (Hack, 1967). First, the drainage network was extracted in ArcGIS using the spatial analysis from flow direction and flow accumulation rasters following standard flow routing methods. The drainage network was clipped from a 10 m
DEM to minimize the accidental inclusion of hillslopes in the slope calculation and smoothed to reduce the magnitude of any possible errors within the DEM. The slope was then calculated by applying a 3 x 3 moving window, which divided the difference in pixel elevations by the distance between them. The length to the drainage divide was then determined by counting the pixel distance to the furthest upstream point of zero flow accumulation using the flow length tool in the spatial analyst. These values were then multiplied and averaged throughout individual catchments within the Mecca Hills, which are displayed in Figure 9.

Mountain front sinuosity, $S_{mf}$, was calculated across the eastern range front of the Mecca Hills (Fig. 9) using the equation of (Bull and McFadden, 1979) such that:

$$S = (1)$$

where $L_{rangefront}$ is the length along the mountain front determined by tracing the slope break between hillslopes and range front alluvial deposits across the southwestern edge of the Mecca Hills and $L_{straightline}$ is the straight line distance from end to end of the range front. Mountain front sinuosity values are presented in Figure 5.

RESULTS

Geomorphic Mapping

Geomorphic mapping of the Qvof1, Qvof2, and Qyf1 surfaces are presented in Figure 5 with insets showing detailed mapping of sampling locations. The minor Qyf2 surface was mapped to
differentiate it from the Qyf1 surface in the Painted Canyon study site (Fig. 5b). Our mapping is
agrees with the interpretations of Patt (2000). Descriptions and summaries of alluvial surfaces
are presented in Table 1.

The Qvof1 surface demonstrates the greatest relative age based on our multi-parameter approach
(Burke and Birkeland, 1976; McFadden et al., 1989; Patt, 2000). The Qvof1 surface has an
extremely well developed desert pavement and rock varnish (5YR 2/1 to N2) and is composed of
polymictic granite (60-70%), gneiss (10-20%), and infrequent greenschist (10-20%). The
sediment was probably derived from the nearby Little San Bernardino, Cottonwood, and
Orocopia Mountains. Surface boulders are not common and when present are heavily pitted and
often split; surface clasts are poorly sorted and subrounded to angular, highly rubified, and soils
have significant carbonate development; the solum depth is 30 cm. Granitic boulders often
appear completely decomposed and ventifacts are present. Plant diversity is high relative to other
alluvial surfaces and vegetation is sparse.

The Qvof2 surface presents a lesser degree of relative weathering than Qvof1. Desert pavement
is less developed as indicated by the lighter brown varnish (5YR 3/4) and occasional clast
layering at the surface. The lithology of the Qvof2 surface is very similar to the Qvof1 surface
with clast composition approximately 60-70% granite, 10-20% gneiss and 10-20% schist.
Boulders are moderately pitted and some are split with fresh faces; surface clasts have sporadic
rubification, no ventification, and less carbonate development than the Qvof1 surface along with
lower vegetation diversity.
The Qyf1 surface demonstrates the youngest relative age of sampled surfaces in the Mecca Hills. Desert pavement has not developed and rock varnish is minimal with no rubification of clasts. There is no soil developed on this surface. Similar to Qvof1 and Qvof2 surfaces, lithology is dominantly granitic but also contains notable gneiss and schist (10-20%) among poorly sorted subrounded sediment. Boulder splitting and pitting is rare if existent and no ventifacts are present. Vegetation is not diverse, exhibiting only the infrequent smoke tree, *Dalea spinosa* and Creosote bush *Larrea tridentata*. The Qyf1 surface is indistinguishable from the Qt1 surface outside of surface morphology.

**SL Index**

SL index values range from 7144 in the western Mecca Hills to 1308 in the south easternmost catchment. SL index values generally increase toward the northeast and in catchment close to active mapped faults. The SL index is a commonly utilized tool for geomorphologists interested in differentiating changes in fluvial geometry in response to changing lithology and/or tectonics (Hack, 1973; Bull and McFadden, 1976; Bull and Knuepfer, 1987). Recent studies have shown success in the evaluation and implementation of the SL index and the dominating influence of the tectonic contribution to the value change over the lithologic signal (Troiani et al., 2008; Font et al., 2010; Selim et al., 2012; Gao et al., 2013). Although other workers indicate that differentiating the lithologic signal from the tectonic is intractable (Troiani and Seta, 2008). We chose to evaluate the SL index averaged within individual catchments to overcome potential issues associated with the subjective application of SL index measurement. Because catchments
within the Mecca Hills are smaller than those utilized in other studies and the highest order streams in each individual catchment differ, a catchment-wide average allows for a reproducible measurement that is less susceptible to individual DEM errors. The SL index has shown success in smaller scale catchments (Troiani and Seta, 2008). We assume that because lithology is consistently assorted sands and siltstones of the Palm Spring and Mecca Formations, and that the underlying crystalline bedrock is rare (Patt, 2000), the relative changes in the SL index are dominated by the signal produced by tectonic activity.

**Ratio of Catchment Volume to Area**

RVA values range from a high of 0.41 in a tributary catchment of Painted Canyon drainage and to a low of 0.03 in a tributary catchment of Box Canyon in the Northeastern Mecca Hills. RVA generally increases toward the northwest in a similar manner to the SL index values although a greater emphasis is present in the western regions of the Mecca hills. RVA is greatest in higher relief catchment bounding topographic high points. The ratio of catchment volume to area (RVA) was first proposed and used by Frankel and Pazzaglia (2005) as a method to evaluate the maturity of a catchment and to compare tectonically active versus erosionally exhumed mountain ranges. RVA is roughly analogous to the valley width to height ratio developed by Bull and McFadden (1977) and commonly used in geomorphic studies (Keller, 1986; Mayer, 1986; Zuchiewicz, 1998; Burbank and Anderson, 2011; Ul-Hadi et al., 2012). The RVA has the advantage over the valley width to height ratio in that it more likely reflects tectonic uplift (Frankel and Pazzagila, 2005), yet eliminates the subjectivity of choosing a location upstream from the mountain front while integrating hillslope and fluvial processes across a catchment. We
chose to use the RVA metric over the valley width to height ratio as within the Mecca Hills, the valley width to valley height ratio value for rivers varied greatly within any given distance upstream from the main mountain front causing results to be equivocal. The RVA has the advantage over the valley width to height ratio as it encompasses hillslope and fluvial processes acting over an entire catchment as opposed to a single cross sectional area (Frankel and Pazzagila, 2006).

Mountain Front Sinuosity

$S_{mf}$ values are 1.11 for the Mecca Hills, 1.38 for the Cottonwood Mountains, 1.60 for the Little San Bernadino Mountains, and 1.67 for the Orocopia Mountains. $S_{mf}$ is a commonly utilized index to ascertain the tectonic activity of a mountain range (Bull and McFadden, 1979; Keller and Pinter, 2000; Azor et al., 2002; Burbank and Anderson, 2011). The sinuosity of a mountain front acts as a function of uplifting tectonics, which straighten the range front, and erosional processes, which erode mountain facets and valleys causing the sinuosity to increase. Often the index is used as a reconnaissance tool to evaluate the tectonic activity of mountain ranges from aerial photographs or topographic datasets (Keller and Pinter, 2000).

Surface Exposure Dating

Sample locations for surface exposure ages are shown in Figure 5, age results in Table 2 and in Figure 6 as NKDE plots. Each cumulative NKDE plots (Fig. 3) exhibit a bimodal distribution with a primary and secondary peak for $Qvof1$ and $Qvof2$ surfaces and an asymmetrical curve for
Qvf. Qyf1 and Qvof2 surfaces pass the MSWD test. Sample MH-19 from the Qyf1 surface dataset and samples MH-43, -46, -49, -50, and -51 from the Qvof2 surface dataset are considered outliers according to the MSWD test results. The Qvof1 surface does not pass the MSWD test with the removal of samples from the dataset. MSWD test results show an age of 8.2 ± 2.1 ka for the Qyf1 surface and an age of 67.2 ± 2.1 ka for the Qvof2 surface. The age for the Qvof1 surface is inconclusive; however, the primary peak in the NKDE plot is at ~217 ka and the weighted mean of boulder surface exposure ages is 266 ± 100 ka. MSWD values for each surface are presented in Table 1 with 1-σ uncertainty. The samples removed from each dataset during the MSWD test lie under the secondary peak seen in the NKDE plots (Fig. 6). A hypothesized extension of the Qvof1 surface in the central Mecca Hills (Fig. 5) was sampled (samples MH-HG-2 to -5, -6, and -7), however age results do not pass the MSWD test and are significantly younger than surface exposure ages for the Qvof1 surface further north. Boulders in the active channel of Box Canyon (Qac; Table 1) produce a non-MSWD weighted mean age of 8.4 ± 16 ranging in age from 6.6 ± 0.9 to 36.0 ± 3.2 ka. The first level river terrace present in the central Mecca Hills (Qt1) produces a weighted mean age of 9.0 ± 4.8 ka that does not pass the MSWD test. In addition, boulders present on a strath terrace at the uppermost reaches of Box Canyon produces two boulder surface ages of 39.3 ± 3.4 ka and 13.3 ± 1.8 ka.

Depth profile data for the sampled surfaces are shown in Table 3. We use the Bayesian most probable age from each profile result as our preferred depth profile age. A value of 1.00 for topographic shielding correction was used because each location had a very low horizon («20°) and a value of 1.00 for cover as no snow or vegetative cover was present or expected. We use a reference spallogenic production rate of 4.39 ± 0.19 g⁻¹ a⁻¹ based on estimated production rates
for North America (Balco et al., 2008; Lifton et al., 2009; Briner et al., 2012) and to maintain consistency with surface exposure age calculations. Following Hidy et al. (2010), we assumed values of 5 m for depth of muon fit, 160 ± 5 neutrons, and 2.2-2.5 g cm$^{-3}$ for sediment density. Additional parameters chosen for each depth profile stimulation are described and justified in the discussion sections.

**Erosion Rates**

Erosion rate measurements and sampling locations are presented in Figure 5. Figure 8 compares erosion rates with select geomorphic parameters. We chose the geomorphic parameters of mean catchment slope, catchment area (size), mean catchment elevation, and total catchment relief, following results from Portenga and Bierman (2011) and to allow to comparison with global datasets of erosion rate. Erosion rate values range from a minimum of 20 ± 3 m Ma$^{-1}$ in the northernmost catchment to a maximum value of 89 ± 20 m Ma$^{-1}$ at the mouth of Box Canyon. Erosion rates increase nearer to the San Andreas fault. Average erosion rate across all samples is 49.6 ± 10 m Ma$^{-1}$. Erosion rates correlated strongest with mean catchment slope producing an R$^2$ value of 0.47 for all samples and 0.89 with the removal of sample MH-7 (see discussion below; Fig. 8). Erosion rates are very weakly correlated with catchment area with an R$^2$ value of 0.025 and an R$^2$ of 0.18 when erosion rates from Box Canyon were excluded (MH-3,-6,-7). A linear regression of catchment mean elevation, versus erosion rate revealed a weakly correlated (R$^2$ of 0.14) inverse relationship with or without the inclusion of Box Canyon samples (Fig. 8). Total catchment relief, taken as catchment maximum elevation minus catchment minimum elevation,
displayed the weakest correlation of tested geomorphic parameters, with an $R^2$ value of 0.001.

**DISCUSSION**

**Geomorphic Mapping**

The geomorphic surfaces examined in this paper are regionally extensive and represent periodic deposition during the ongoing deformation and uplift of the Mecca Hills (Fig. 2, Fig. 5). The extent of surface Qvof1 and the present eroding back of the surface by the Painted Canyon and Box Canyon catchments suggests that the surface may have had a previously greater extent. The surface we and others (Patt 2000) have mapped as Qvof1 shows significant topography possibly due to deflection from tectonic activity. Likewise, the abandonment of surface Qvof2 and further creation of Qvof2 capped terraces through river incision implies a greater continuous extent of the surface than is evident at the present. The cause of this abandonment and incision may also be a result of post depositional tectonic deformation consistent with the interpretations of other studies in the region (Sylvester and Smith 1976; Sheridan and Weldon 1992). The youngest surface Qyf1 does not seem to have had a previously greater extent than the older surfaces Qvof1 and Qvof2 based on its current morphology and lack of incision.

We interpret the depositional environment of the three major surfaces as a flash flood controlled regime producing extensive alluvial fans and fanglomerate based on the surface lithologies. The coarse and poorly sorted nature of the sediment composing the surfaces would require a high energy environment to generate the critical shear stresses necessary to move cobble and boulder
size material. In the current climate of the Salton Trough, the only feasible high energy mechanism is flash flooding in which sediment is rapidly and episodically transported from the nearby Little San Bernadino, Cottonwood, and Orocopia Mountains towards the basin floor, leaving behind extensive alluvial fans. Past climates, such as during glacial periods, may have caused the region to be both colder and wetter owing to the southward migration of the jet stream (Owen et al. 2003). This may have shifted the dominant sediment transport process towards river flow and gradual aggradation (Bull, 1991; Miller, 2010) We interpret that the geomorphic surfaces are composed of fanglomerates originally deposited via flash flood events as alluvial fans forming a Bajada complex. The ages of the surfaces as derived from $^{10}$Be surface exposure dating therefore reflect abandonment ages when a change in stream power, such as during climate change (Fig. 6), causes drainage systems to shift from aggradation to incision.

**Geomorphic Indices**

**SL index**

The distribution of catchment averaged SL index values from 7144 in the northwestern Mecca Hills to a low of 1308 in the southern province suggests that tectonic activity due to transpression is greater in towards the northwestern and central regions of the Mecca Hills. This is consistent with previous studies of tectonic deformation (Sylvester and Smith, 1976; Sheridan and Weldon, 1992). Whereas the distribution of relative tectonic motions based on the SL index does not quantify the rates of deformation, it is reasonable to suggest that rates of deformation in the northwestern segments of the Mecca Hills are greater than those in the southeast. The absence of currently identified river terraces amenable to Quaternary geochronology makes defining rates of
deformation intractable. However, unidentified locations may preserve this information. Additionally, future study examining deformation of stratigraphy within the Mecca Hills would allow for a further test of this apparent relative difference in tectonic deformation.

**Ratio of Catchment Volume to Area**

Consistent with the conclusions of Frankel and Pazzagila (2006), we interpret higher RVA values as proxies for relative strain rate and tectonic uplift. RVA values for the Mecca Hills are greatest in the region between the San Andreas and Painted Canyon faults (Fig. 9b). Sylvester and Smith (1976) identified this region, the “central block,” as the major region where compression is accommodated, a finding consistent with the interpretations of Sheridan and Weldon (1992). Based on these models, we expect the uplift rates to be greater in this central block as compared to other regions of the Mecca Hills. These greater uplift rates should increase the gradients and incisional power of rivers, leading to greater relief and high RVA values. RVA values from the Mecca Hills support this finding by displaying the greatest values in the central block and lower values in the surrounding regions. Interestingly, Painted Canyon in the central Mecca Hills, and a tributary catchment of Box Canyon in the northeastern Mecca Hills displays higher RVA values than the fringes of the Mecca Hills, suggesting that uplift may be spreading to the outer regions. The regions of higher RVA values corroborate with the higher SL catchment average values suggesting that the same function, be it tectonic or lithologic, is acting on catchments within the Mecca Hills.

**Mountain Front Sinuosity**
The lower $S_{fm}$ values for Cottonwood, Little San Bernadino, and Orocopia mountains suggest Mecca Hills is more tectonically active than the surrounding environment (Fig. 9c). This is consistent with the recent and rapid deformation suggested by other workers in the area (Rymer 1991; Sheridan and Weldon 1992; Boley et al 1994) and supports a hypothesis that the Mecca Hills is experiencing rapid uplift compared to its surroundings.

Surface Exposure and Depth Profiles Ages

Qvof1 Discussion

The two strong peaks in the NKDE plot for the Qvof1 surface is problematic towards obtaining a single surface abandonment age as the source of the age scatter could be the result of multiple variables such as post-depositional mixing of underlying sediment (Hooke, 1967), in situ boulder erosion (Putkonen and Swanson, 1996), or the possibility of recycled alluvial fan material introducing boulders with significant $^{10}$Be inheritance (Anderson et al., 1996). Significant rock varnish and desert pavements are present on the Qvof1 surface, which is suggestive of long-term stability and supports an assumption of zero surface erosion and long-term surface stability (Matmon et al., 2009). The presence of desert pavements and rock varnish, however, does not ensure stability of individual boulders over the lifespan of the surface as formation can occur on timescales shorter than 50 ka, during which boulders can be eroded and rock varnish can develop on fresh surfaces (Amit et al., 1993; McFadden et al., 2000). Processes such as salt shattering of gravel and larger clasts (Amit et al., 1993) or abrasive aeolian erosional processes (Lancaster, 1984) can act to reduce TCN concentration from boulder surfaces. For the weighted mean age for the Qvof1 surface at $\sim 266 \pm 100$ ka, boulder erosion over this timescale is plausible, if not
probable. For this reason, we treat the age derived from the Qvof1 surface as minima. We cannot rule out the possibility of inheritance of $^{10}\text{Be}$ as a source of significant scatter seen in the surface exposure ages because the mechanism of sediment and boulder transport is via flash flooding and debris flows is an intrinsically episodic process. Significant Be inheritance is a common problem for dating of alluvial fan surfaces (Anderson et al., 1996; Gosse and Phillips, 2001). Field observations within the Mecca Hills indicate that boulders are present in river sediment and the low catchment-wide rates erosion rates relative to the global mean (Fig. 5, Table 4; see erosion rate discussion) suggest that there is significant possibility for inherited and pre-depositional creation of Be during transport from source to sink.

The $^{10}\text{Be}$ TCN depth profile for the Qvof1 surface provides Bayesian most probable age of $280 \pm 24.2$ ka, $16.24 \pm 5.38 \times 10^4$ atoms g$^{-1}$ for inheritance, and an erosion rate of $0.5 \pm 0.1$ m Ma$^{-1}$ (Table 3). We assumed minimal surface erosion and chose to constrain the simulation erosion rate value between 0.0-1.0 m Ma$^{-1}$. Age and inheritance was left unconstrained and most probable results determined by the profile simulator. The weighted mean surface exposure age for surface Qvof1 is in agreement with the depth profile results. The Bayesian most probable result for inheritance corresponds to an age inheritance of $\sim24-26$ ka based on the local production rate. However, adding the inheritance years to the surface age uncertainty does not completely explain the large scatter in the ages obtained from surface boulders. It is possible that if the true age of the Qvof1 surface is $\sim280 \pm 24$ ka, then the strong outlier MH-7 at $431 \pm 42$ ka (Table 2) may be indicative of a recycling of prior alluvial fan material with significant $^{10}\text{Be}$ inheritance. Samples MH-10 and MH-11 mark the lower bound of the age scatter likely deviate from the depth profile results due to boulder erosion and removal of $^{10}\text{Be}$. 

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**Qvof2 Discussion**

The range of $^{10}$Be boulder exposure ages obtained for the Qvof2 surface is large, ranging from 66.4 ± 6.0 to 124.9 ± 11.3 ka (Table 2). The NKDE plot for the Qvof2 surface displays a bimodal curve with the primary peak at ~ 70 ka and the secondary peak at ~118 ka. As with the Qvof1 surface, the presence of this distribution is problematic as which peak is most representative of true surface age is not immediately apparent. The Qvof2 surface ages passes the MSWD test and produces a weighted mean of 69.5 ± 3.5 ka only after the removal of samples MH-43, -46, -49, -50, -51. The samples removed from the first MSWD test pass a second MSWD test with the removal of sample MH-46, producing a weighted mean age of ~105 ± 11 ka. The remaining surface samples form a third grouping that passes the MSWD test with an age of 29.5 ± 1.3 ka, however these samples are spatially distal from each other. The Qvof2 surface is morphologically continuous (Fig. 2). Depth profile results from the Qvof2 surface near Box Canyon as mapped by Patt (2000) produce a significantly younger Bayesian most probable age of 17.4 ± 6.1 ka and inheritance value of 8.5 ± 0.6 x $10^4$ atoms g$^{-1}$ based on a minimal erosion rate assumption. As with surface Qvof1, the Depth Profile simulation followed the common parameters listed previously and constrained the erosion rate to between 0.0 and 1.0 m Ma$^{-1}$ and we allowed the program to optimize surface exposure age and inheritance. The modeled inheritance value approximates an inherited age of 18 ± 2 ka based on the time-dependent exposure age model (Lal 1991; Stone 2000; Balco et al 2008). Our depth profile precision and results may be hindered by the low number of samples as only four out of five samples were successfully measured via AMS.
The bimodal distribution of ages suggests that the alluvial surface mapped as QvoF2 formed over multiple episodes of alluvial fan formation during climate fluctuations in marine oxygen isotope stage (MIS) 5 (Fig. 6). The eventual abandonment of the surface must have occurred after the last episode of boulder deposition at 67.2 ± 5.3 ka. However, this assumes that no boulder deposition had occurred afterward and the surviving boulders on the surface are representative of all depositional episodes. We must note that weathered boulders on the surface were avoided to avert obtaining boulder age minima; however this has the potential to introduce a bias that excluded other possible depositional episodes. The depth profile simulation results contradict the surface exposure age data significantly and indicate that an underlying assumption may be incorrect. Whereas the surface exposure ages derived from boulders immediately above the depth profile sampling location indicate an age of ~60-70 ka, this contrasts with the depth profile derived surface exposure age of 17.4 ± 6.1 ka. Two possible scenarios may have created this disparity: 1) our assumption of minimal surface erosion is incorrect and the depth profile underestimates the true surface age; or 2) boulders on the QvoF2 surface near Box Canyon contain significant $^{10}$Be inheritance creating apparently older surface exposure ages. The QvoF2 surface present near Box Canyon displays significant rock varnish on boulders and weak desert pavement formation. Significantly more relief is present on the QvoF2 surface than on the older surface QvoF1 where our minimal erosion rate assumption is stronger. Boulder $^{10}$Be inheritance is difficult to define. The modeled inheritance value from the depth profile simulation of 18 ± 2 ka suggests that the necessary inheritance to create an apparent surface exposure age of 60-70 ka is much greater. This may be probable considering the slower rate in which boulders travel through geomorphic systems in contrast to the sand size fraction from which the depth profile
was simulated. However, a quantitative conclusion may be elusive.

Another possible scenario also exists in that the mapped Qvof2 surface near Box Canyon does not correlate with the mapped Qvof2 surface in the northwestern Mecca Hills and is instead an uplifted section of the underlying Ocotillo fanglomerate with remnants of previously overlying and now eroded Qvof2. In this scenario, the depth profile results would express a young surface exposure age and the surface boulders, having persisted since initial deposition as the now eroded Qvof2, would preserve a greater apparent surface exposure age. Whereas this ad-hoc scenario is possible, it may be impossible to test owing to the lack of available evidence of a prior Qvof2 surface. Further complicating this issue is the lack of a distinct contact between the Ocotillo fanglomerate and the Qvof2 surface as both alluvial fans are composed of the same lithology and no clear horizon between units is apparent. We conclude that the surface of Qvof2 most likely has an age of $67.2 \pm 5.3$ ka as indicated by the boulder surface exposure ages and that the apparently young age produced from the depth profile simulation is an artifact created from a highly eroded surface.

Qyf1 Discussion

The Qyf1 surface shows the tightest distribution of surface exposure ages ranging from $6.0 \pm 2.2$ ka to $14.6 \pm 2.4$ ka (Table 2; Fig. 6). The NKDE plot for the Qyf1 surface has one distinct peak at $\sim 8$ ka with a slight positive skew owing to the distribution of sample MH-19 (Fig. 6). Surface Qyf1 passes the MSWD test with the removal of sample MH-19 and produces a weighted mean surface exposure age of $8.2 \pm 2.1$ ka. This is consistent with geomorphic field observations that
suggest this is a young surface due to the lack of rock varnish and no desert pavement formation. Depth profile simulations were constrained using the common parameters listed prior and subject to a constraint of assumed minimal erosion while age and inheritance were optimized by the program. The simulation produced a Bayesian most probable age of $2.6^{+5.6}_{-1.3}$ ka and an inheritance value of $3.0^{+0.8}_{-1.0} \times 10^4$ atoms g$^{-1}$ SiO$_2$. The modeled inheritance values correspond to an inherited age of $6.5 \pm 1.9$ ka calculated from the CRONUS calculator (Balco et al., 2008). This indicates that the $^{10}$Be inheritance is dominating the signal from the depth profile.

The single peak in the NKDE plot for the Qyf1 surface illustrates the consistency of the boulder surface exposure ages relative to the Qvof1 and Qvof2 surfaces. The MSWD test is easily satisfied with the removal of sample MH-19, which we interpret as containing higher $^{10}$Be inheritance than the other sampled boulders. For younger geomorphic surfaces, $^{10}$Be inheritance is of greater importance in age considerations (Owen et al., 2011). The inheritance and age determination produced by the depth profile simulation however, demonstrate that the boulder surface exposure ages are indistinguishable within 1 $\sigma$ error from those produced entirely from inheritance (Tables 2 and 3). Unlike the Qvof1 and Qvof2 surface, the Qyf1 surface is located on an alluvial fan whose feeder catchment is composed completely of the Palm Spring and Mecca Formations. The feeder catchment therefore does not accrete boulders derived directly from original bedrock such as gneiss / granitic boulders from the little San Bernardino Mountains or greenschist from the Orocopia Mountain but rather sources them from within the Palm Spring and Mecca Formations (Diblee, 1954; Sylvester and Smith, 1976; Boley et al., 1997). The boulders are present at various levels in these formations so it is intractable to determine the exact source within the catchment. The burial time of the boulders within the formations may
have been long enough to allow all inherited $^{10}$Be to decay. These “reset” boulders are then brought to the surface and transported to the alluvial fan largely simultaneously each gaining a similar amount of $^{10}$Be inheritance. When the modeled inherited $^{10}$Be values are subtracted from the $^{10}$Be values of surface boulders, the weighted mean surface exposure age is $2.4 \pm 3.1$ ka consistent with depth profile model findings, although these samples do not pass the MSWD test.

We conclude that the most likely age for the Qyf1 surface is $8.2 \pm 2.1$ ka based on the surface exposure ages derived from boulders passing the MSWD test and that the age produced from the depth profile is suspect on account of the high Be inheritance.

**Boulder Inheritance**

Beryllium-10 ages derived from surface boulders in the active channel deposits, Qac, illustrate the complex nature of $^{10}$Be inheritance in the Mecca Hills (Table 2). The large range of ages may suggest that individual boulders undergo a complex exposure and transport history. The Mecca Hills is composed almost entirely of sedimentary units, granitic and gneissic boulders can have two primary sources: 1) the Little San Bernadino and Orocopia Mountains to the north and east where bedrock is exposed; or 2) from within the Mecca Hills stratigraphy where boulders can be seen eroding out of coarse grained units. These two scenarios, either individual or combined, should have varying exposure histories and therefore varying levels of $^{10}$Be concentration. Since the Mecca Hills stratigraphy is younger (Rymer 1992) than the half-life of $^{10}$Be, a boulder buried and exhumed from it may still retain significant $^{10}$Be from its prior transport and deposition. The varying nature of boulder inheritance complicates our interpretation of boulder surface exposure ages and the determination of the true age of the surface. The interpretation of surface exposure
ages from terrace Qt1 and the Qyf1 surface is complicated by this as the ages are all less than the mean age for boulders in the active channel, causing conclusions to be equivocal. The 36.0 ± 3.2 ka age on sample MH-HG-10 may help explain the wide variance in ages on the Qvof1 and Qvof2 surfaces by allowing individual boulders to have differing populations of $^{10}$Be concentrations rather than a single population.

**Climate Influence**

Previous work on the formation and abandonment of alluvial fan surfaces has generally focused on a climate-based mechanism for aggradation and incision (Bull, 1991; Ritter et al., 1995; Spelz et al., 2008). The generally accepted model for alluvial fan aggradation in the southwestern USA coincides with an increase in aridity during glacial to inter-glacial climate transitions (Bull, 1991, 2000; Wells et al., 1987, 1990). Contrasting with this model, other researchers have proposed that alluvial fan formation occurs during periods of increased precipitation (Harvey et al., 1999a, 1999b). Further work by Miller et al. (2010) demonstrated that alluvial fan formation may be asynchronous with the arid model for the American southwest and that alluvial fan formation correlates instead with increased sea surface temperatures and increased storm activity, which is known to be a significant driver of alluvial fan aggradation (Wells and Harvey, 1987).

Correlating episodes of alluvial fan formation in the Mecca Hills with climatic events is challenging owing to the large uncertainty associated with the dating methods. The Qyf1, Qvof1, and Qvof2 surfaces date to MIS 1, 4, and 7 respectively, however, whether these ages correlate to climatic events is uncertain owing to the large scatter of ages on individual surfaces. The Qyf1
surface is contemporaneous with multiple episodes of alluvial fan aggradation during the Holocene (Miller et al., 2010) when both surface exposure ages from boulders and age results from depth profile simulation are considered. The age for the QvoF1 surface derived from surface boulders (266 ± 100 ka) is too imprecise to ascertain a climate correlation nor does the depth profile result 280 ± 24 ka elucidate a possible triggering event. Surface QvoF2 matches a period of alluvial fan formation observed throughout the southwestern USA around 60-70 ka (see supplemental Fig. 1), but also suffers from a lack of precision, forcing ambiguous conclusions. We acknowledge that alluvial fan formation is likely a function of climate modulated sediment supply (Ritter et al., 1995), however the data currently available for the Mecca Hills does not conclude for or against these models.

Regional Correlation

We compiled 362 ¹⁰Be surface exposure ages from boulders from various studies in southwestern North America (Bierman et al., 1995; Zehfuss et al., 2001; Benn et al., 2006; Matmon et al., 2005; van der Woerd et al 2006; Delong and Arnold 2007; Duhnforth et al 2007; Frankel et al 2007a; Frankel et al., 2007b; Le et al., 2007; Lee et al., 2009; Behr et al., 2010; Kent, 2011; Blisniuk et al., 2012; Owen, personal communication) to observe if distinct depositional episodes were apparent in the dataset. The NKDE plot for compiled ¹⁰Be surface exposure ages (supplementary Fig. 1) demonstrates probability peaks at approximately 7-8 ka, 17-19 ka, 45-47 ka, 64-66 ka, and a broad peak at 160-170 ka (see supplemental material: Fig. 1). This compilation does not attempt to compensate for sampling biases such as studies collecting numerous samples on specific fan surfaces (van der Woerd, 2006; Behr et al., 2010; Owen et al.,
submitted) or geologic biases due to declining boulder preservation with time. We do not attribute these peaks to published Quaternary stratigraphies (McFadden et al., 1989; Bull, 1991; Hooke and Dorn, 1992; Wells et al., 1990; Klinger, 2001; McDonald et al., 2003) as a comprehensive look at the regional stratigraphy and correlation of dated surfaces is beyond the scope of this study. This data was collected to ascertain if the alluvial fans of the Mecca Hills have acted in synchronicity with regional depositional episodes, assuming that surface exposure ages of boulders reflect time since deposition and inheritance is minimal. If a significant deviation exists with the regional variations, it could suggest the Mecca Hills is decoupled from regional climate, tectonic uplift is the primary cause of surface abandonment, or an unrecognized bias exists in surface exposure ages from boulders in the Mecca Hills.

The Qyf1, Qvof1, and Qvof2 surfaces loosely correlate with the regional episodes of deposition. The Qyf1 surface boulder exposure age of 8.2 ± 2.1 ka is within error of the depositional period of 7-8 ka as indicated by the regional dataset. This interpretation is at odds with the results of the depth profile simulation, which produced an age at 2.6 ±5.6/1.3 ka. However, the depth profile does not demonstrate an exponential decay and may be suspect by being dominated by the beryllium inheritance of the sediment. Although somewhat unlikely, it is possible that the regional depositional episode at 7-8 ka reflects the same conditions of inheritance seen at the Qyf1 surface. The discrepancy between boulder surface exposure age, regional depositional episode, and depth profile results could reflect a simple coincidence or the age of the Qyf1 surface is 8.2 ± 2.1 ka and the depth profile age is a result of an incorrect zero-erosion assumption. The Qvof2 surface age is in good agreement with the depositional episode indicated by the NKDE peak at 64-66 ka. Older ages that produce a MSWD test passing weighted mean of
117 ± 7 ka do not seem to correlate with a regional episode of deposition. This may reflect a local period of alluvial fan formation out of synchronicity with the regional depositional episode, assuming that inheritance is minimal. The Qvof1 surface appears to be significantly older than any depositional episode as indicated by the regional dataset. While the boulder surface exposure weighted mean age of 266 ± 100 ka is within error of the regional depositional episode at 160-170 ka, although this age is from ages that do not pass the MSWD test. The Qvof1 surface depth profile age results produce an age at 280 ± 24 ka that is well outside of this range. In addition, we propose that surface exposure ages from boulders on the Qvof1 surface are among, if not, the oldest surface exposure ages currently obtained in the region. If this interpretation holds, the Qvof1 surface is potentially the oldest known alluvial surface preserved in Southern California.

**Erosion Rates**

TCN $^{10}$Be derived catchment wide erosion rates provide a unique and quantified measure of landscape evolution (Bierman and Steig, 1996; Granger et al., 1996; Bierman and Nichols, 2004) and the diffusion of gravitational potential energy throughout a geomorphic system (Cairn, 1976). The Mecca Hills demonstrates indicators of rapid landscape change since the onset of uplift since 740 ka (Rymer, 1991) such as high relief steep hillslopes, rapid incision by rivers forming slot canyons, and abandonment of geomorphic surfaces and terraces. In addition, the proximity of the Mecca Hills to the San Andreas fault zone (Sylvester and Smith, 1976) suggests that tectonic influence will have a strong effect on erosion rates (von Blanckenburg, 2005). However, the climate effect on erosion may be low due to the Mecca Hill’s location in arid southern California. Due to the Mecca Hill’s small size, we assume that climate conditions and seismicity is constant.
across the landscape. In addition, because the Mecca Hills is largely composed of the Palm Spring and Mecca Formations (Sylvester and Smith, 1976), we also assume that controls on relative erosion rate due to lithology are minimal. Furthermore, while the Mecca Hills is in a region that experiences flash flooding and localized precipitation, we assume that these processes are time-averaged over the entire catchment area and that sediment is representative of the entire catchment as opposed to individual flooding events.

The average erosion rate of 58.9 ± 10.8 m Ma⁻¹ is significantly lower than the global mean and median catchment-wide erosion rates of 218 and 54 m Ma⁻¹, respectively (Portenga and Bierman, 2011). We attribute this lower erosion rate to the arid climate of the Salton trough (Brown, 1923) consistent with the findings of Bierman et al. (2005) in the arid to semi-arid Rio Puerco basin. We must acknowledge that climate does not necessarily control erosion rates directly (Riebe et al., 2001; von Blankenburg 2005); some of the lowest erosion rates in the world were obtained by von Blanckenburg et al. (2004) in the mountains of Sri Lanka. However, erosion rates in tropical regions such as Sri Lanka act as a function of thick, protective soil profiles and vegetation, neither of which are present in the Mecca Hills which allows for the transport of sediment only during precipitation and colluvial events, and aeolian processes.

The comparison of erosion rates from the Mecca Hills with geomorphic parameters helps contribute towards the collection of global erosion rate data and the constraint of variables controlling landscape evolution. Mean catchment slope demonstrated the greatest correlation with erosion rate, consistent with Portenga and Bierman’s (2011) analysis of global erosion rates.
However, the correlation for the Mecca Hills, $R^2$ values of 0.47 suggests that the slope dependency is greater than for the global record with an $R^2$ value of 0.34 (Portenga and Bierman, 2011). We are inclined toward the exclusion of sample MH-7 as the measured current during AMS measurement was significantly low and the relative error of the $^{10}\text{Be}/^{9}\text{Be}$ ratio is 50% (Table 2). This correlation may reflect the lithologic control of the Palm Spring and Mecca Formations and/or the influence of rapid tectonic uplift. The Palm Spring and Mecca Formations are weakly indurated and easily eroded by physical action (Diblee, 1954). Slope angles therefore can easily adjust to erosion allowing a strong relationship between the two variables without the influence of another factor such as internal strength. Rapid tectonic uplift due to transpression may also allow for this close relationship by oversteepening hillslopes and river gradients and therefore increasing stream power and erosion (Bagnold, 1966; Whipple and Tucker, 1999; Sklar and Dietrich, 1998). Whereas determining if slope or erosion is the controlling variable is beyond the scope of this study, an establishment of this relationship would clarify our conclusions.

The relationship between the other geomorphic parameters is less direct. Portenga and Bierman (2011) found that catchment area was very weakly correlated with erosion rate ($R^2 = 0.003$). Our data show that for the Mecca Hills, we observe a similar lack of strong correlation although an order of magnitude greater ($R^2 = 0.02$; Fig. 8). A closer correlation for the Mecca Hills can be obtained with an $R^2$ value of 0.18 when samples from the exceptionally larger Box Canyon are excluded from the dataset. Because of this discrepancy of correlations between catchment size and erosion rate as indicated by the negative slope of the linear regression suggests that erosion rates in smaller catchments are greater on average than larger catchment in the Mecca Hills. All sampled catchment are larger than the $\sim 10^6 \text{ m}^2$ transition between dominantly hillslope process.
to fluvial processes (Wobus et al., 2006), so we do not consider the influence hillslope processes in smaller catchment. Rather, the inverse relationship seen may be a product of sampling bias, as the smaller sampled catchments are located in more tectonically active zones, as indicated by the $S_{mf}$ geomorphic index (Fig. 9c), than the samples derived from the larger Box Canyon catchment.

The relationship between mean catchment elevation and catchment wide erosion rate for catchments in the Mecca Hills is counter intuitive. There is an inverse relationship between erosion rate and mean elevation (Fig. 8). The direct consequences of this relationship suggest that catchments at higher elevations should erode slower than catchments at lower elevations, contradictory with the global dataset of Portenga and Bierman (2011). Our Mecca Hills dataset is small, thus the natural variation in the observed values may be great enough to distort the true relationship and create an apparent inverse relationship. This is supported by the low $R^2$ value (0.14) for the regression (Fig. 8). In addition, the inverse relationship observed may be a result of sampling bias generated by the catchments located at lower elevations having a greater influence of tectonic activity than the larger catchments located in the Box Canyon catchment. Catchments with greater mean elevation generally have greater gravitational potential energy and are therefore more effective at erosion (Caine, 1976). The possibility exists that catchments and sub-catchments within the Mecca Hills may have lower erosion rates due to smaller catchment areas; that is, less hydrologic flow and therefore lower stream power with which to erode the landscape. If this observed relationship is real, it may be specific to this region due to unidentified variables relating to surface hydrology. Finally, although major knickpoints in the river systems have not been identified, the difference between erosion rates at varying elevations, i.e. lower rates at higher elevations, may be suggesting that upper reaches of the drainage
network have not yet responded to a transient signal of base level fall (Schumm, 1993; Reinhardt et al., 2007).

The correlation between catchment relief and erosion rate is the weakest among our tested geomorphic parameters ($R^2$ of 0.001) and significantly lower than the global dataset regression ($R^2$ of 0.203; Fig. 9). Catchment relief should positively influence erosion rates by increasing the ability of a catchment to diffuse gravitational potential energy through the downhill transport of sediment. As sediment travels downhill, gravitational potential energy is converted to kinetic energy, which is released on impact with the river bed causing erosion (Caine, 1976). Within the Mecca Hills, this relationship is complicated by the presence of wide sediment-saturated “box canyon” channel geometry. The large volume of sediment within the channel acts to armor the bed preventing erosion (Sklar and Dietrich, 2001) potentially causing a decoupling of catchment relief and erosion rate. We must acknowledge however that our dataset is small and that significant scatter due to natural variation may obscure the true relationship. This phenomenon could be better elucidated by collecting further data on catchments within the Salton Trough, in particular, the Indio Hills to the north of the Mecca Hills may provide an acceptable analog for further data collection.

**Implications and future work**

The alluvial chronology, erosion rates, and geomorphic indices presented here contribute toward building landscape evolution models of the southern San Andreas Fault. Our alluvial chronology can be tied to other alluvial chronologies and climatic records to better identify surfaces resultant
from tectonic uplift as opposed to climate-forced river incision and abandonment. The catchment-wide erosion rates can be utilized by regional studies of the Salton trough to develop sediment budgets and transport of sedimentary material from source to sinks. Furthermore, the geomorphic indices we have calculated provide a semi-quantitative measurement of the relative effects of tectonic uplift across the Mecca Hills and may be of use to future studies of tectonic motions in the region. To build on this work, we suggest further study into three areas of focus: First, we recommend analyzing the Mecca Hills’s bedrock sedimentology to infer rates of uplift using modern tools such as paleomagnetism to constrain the timing of deformation and rotation. This would provide a rigorous tectonic context for the results presented in this paper. Second, we propose that a similar study involving the methods described here and a study of the bedrock sedimentology should be conducted in the Indio Hills to the northwest. This would allow for a comparison with the rates and timing of deformation and alluvial sedimentation along the majority of the southern San Andreas Fault though the Salton Trough. Third, a similar study on the opposite margin of the Salton Trough will provide a contrast between the geomorphology and alluvial sedimentation under a different tectonic regime and may produce interesting conclusions.

**Conclusions**

The Mecca Hills is a result of Quaternary sedimentation and tectonic deformation that has produced distinct landforms and varied catchment geometries. Beryllium-10 surface exposure geochronology has elucidated the ages of alluvial fan deposition for surfaces Qvof1 at 266 ± 100 ka, surface Qvof2 at 69.5 ± 3.5 ka and surface Qyf1 at 8.2 ± 2.1 ka. Depth profiles reveal surface
exposure ages at 280 ± 24 ka for surface Qvof1, 17.4 ± 6.1 ka for surface Qvof2, and 2.6 \( ^{+5.6/-1.3} \) ka for Qyf1. Differences in depth profile and boulder surface exposure ages derive from many variables such as erosion of surficial features, inheritance of \(^{10}\)Be and the possible recycling of older alluvial fan material which limit the utility of depth profiles on young surfaces in this environment. Average erosion rates from the Mecca Hills region are less than the global average at a mean rate of 58.9 ± 10.8 m Ma\(^{-1}\), likely reflecting the arid climate. The increasing rate of erosion with proximity towards the major zone of deformation between the San Andreas and Painted Canyon faults and the strong correlation of erosion rate with mean catchment slope indicates the influence of tectonically steepened slopes on local erosion rates. Geomorphic indices such as the SL, RVA, and \( S_{mf} \) demonstrate that the distribution of deformation within the Mecca Hills is spatially non-uniform and suggests that tectonic motion plays a strong control on the geomorphology of the Mecca Hills. Our findings will help future studies of landscape evolution of the southern San Andreas Fault and may provide constraints and a comparison towards future studies in the region.

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Figure 1: Location of the Mecca Hills in southern California showing major faults. Note presence of major tectonic structures in the surrounding landscape. Background image is a hillshade derived from a 1-arc second digital elevation model (DEM) from the U.S.G.S. National Elevation Dataset. Fault lines are sourced from the U.S.G.S. fault data repository.)
Figure 2: Geology and regional provinces of the Mecca Hills adapted from Patt (2000). Note widespread presence of Surfaces Qvof1, Qvof2, and Qyf.
Figure 3: Box model of the Mecca Hills showing major canyons and tectonic structure as described by Sylvester and Smith (1976).

Figure 4: Views of characteristic geomorphology of the Mecca Hills. Picture location given by coordinates in decimal degrees. Upper left: Surface Qvof1 displaying even surface with little to no bar and swale features. Note dark color of surface. Lower left: Boulder from surface Qvof1 representative of boulders sampled for beryllium-10 surface exposure dating. Note strong desert varnish and well developed desert pavement. Upper right: Surface Qvof2 looking northwestward from ridge north of Thermal Canyon. Surface exhibits gently sloping flat surfaces above incised broad channels. Lower right: View of Surface Qyf1 taken from incised channel looking towards sampling locations; see Figure 2b. Notice gently sloping gradient of upper surface and inset lower
Figure 5: Overview of the geomorphology of the Mecca Hills, CA including sample locations, geomorphic mapping, and erosion rate results. Insets display detailed mapping and sample-dense locations. Background image is an overlay of a hillshade image derived from a 10 meter per pixel DEM from the USGS National Elevation Dataset combined with a focal statistics raster enhancing topographic relief. Fault lines are from the USGS fault and fold database. Hillshade in image insets is derived from the B4 LiDAR dataset (Bevis et al., 2005) and aerial imagery is obtained from CalAtlas (State of California, 2013) Geomorphic mapping was done in the field in December 2012 and via remote methods on aerial imagery. Surface exposure ages are presented.
in Table 2 and cumulative probability plots in Figure 3. Depth Profile curves and results are located in Figure 7 and Table 3 respectively.

Figure 6: (A) Normal kernal density estimate or “camel plot” for $^{10}$Be surface exposure ages from boulders throughout the Mecca Hills juxtaposed with oxygen isotope ratios from the past 300 ka. Red curves represent individual boulder ages and error with assumed Gaussian distributions; black curve with white fill represents sum of individual distributions. Most probable age for individual fan surfaces indicated by labeled peaks in the black curve with white fill. Black curve with alternating gray fill is the $\delta^{18}$O ratio for the past 300 ka. Higher values of $\delta^{18}$O indicate colder glacial periods whereas lower values indicate warmer inter-glacial periods (note reversed scale). Numbers on alternating dark and light gray fill delineate marine isotope
stages as defined by Aitken and Stokes (1997). Most probable surface ages do not seem to correlate with a consistent type of climate transition. (B) Camel plot for boulder ages from surface Qyf1. The surface displays a most probable peak at around 7-8 ka consistent with field observations that suggest a young age. A slight positive skew is evident in the curve which we interpret as higher 10Be inheritance for sample MH-19 (Table 2). (C) Cumulative probability plot for boulder ages from surface Qvof2. The surface illustrates a most probable peak at around 70 ka yet significant dispersion of ages is present producing an asymmetrically trimodal distribution of ages. Older ages are spatially dispersed amongst younger ages on continuous surfaces (see Figure 2; Table 2). This distribution is interpreted as reflecting either disparity in 10Be inheritance and/or variance in boulder erosion. Age distribution does not appear to be biased by boulder lithology (Table 2). (D) Cumulative probability plot for boulder ages from surface Qvof1. Surface exposure ages produce a most probable peak around 220 ka yet the surface demonstrates an asymmetrical bimodal distribution to surface Qvof2. Most probable age is consistent with results from depth profile simulation (Figure 3). The secondary peak is interpreted as significant inheritance of 10Be among samples MH-7 and MH-9 (Table 2).
Figure 7: Beryllium-10 depth profiles for major geomorphic surfaces within the Mecca Hills. Gray curves represent profiles simulated with MATLAB code developed by Hidy et al. (2010). Red curve indicates mean profile after $> 5 \cdot 10^5$ iterations. Profile results are summarized in Table 3. Sampled locations are indicated on Figure 1. See text for parameters used in profile simulation. Red line indicates best-fit profile for beryllium data. (a) Depth profile of cosmogenic beryllium 10 concentrations from unit Qvof1; see Figure 1 for location. Note well constrained curve and approximately Gaussian distributions for age and inheritance results. Profile is interpreted as supporting near-zero erosion assumption for alluvial surface. (b) Depth profile of $^{10}\text{Be}$ concentrations from surface Qvof2 near Box Canyon; see Figure 1. (c) Depth profile of $^{10}\text{Be}$ concentrations from surface Qyf1 near Painted Canyon; see Figure 1. Note near constant concentration of $^{10}\text{Be}$ with depth. Profile was constrained with ages obtained from surface exposure ages (Figure 5; Table 2).
Figure 8: Beryllium-10 catchment wide erosion rates from catchments within the Mecca Hills compared to various environmental parameters. (a) The strongest correlation is with mean catchment slope consistent with the analysis of global erosion rates of Portenga and Bierman (2011). (b) Catchment size demonstrated an inverse relationship that is likely due to sampling bias created by sampling smaller catchments within tectonically active zones. (c) Catchment relief, taken as the difference of maximum and minimum elevation within the catchment, has the weakest correlation with erosion rate, consistent with the analysis of Portenga and Bierman (2011). (d) Mean catchment elevation also produced an inverse relationship inconsistent with the analysis of global finding of Portenga and Bierman (2011); this is likely due to sampling bias of catchments at lower elevations having a greater influence of tectonic uplift.
Figure 9a: SL Index value averages for catchments within the Mecca Hills, CA. The SL index is calculated as the product of river gradient versus distance from the drainage divide. The average SL value for each catchment was computed by extracting the main channel network from a hole-filled and smoothed USGS National Elevation Dataset DEM and performing the calculation on a pixel by pixel basis and averaging the values for a given catchment. Catchments were selected by delineating catchments draining into major trunk streams and applying a cut-off of $10^6 \text{ m}^2$ to ensure dominance of fluvial over hillslope processes. This assumes major trunk streams act as
local base level due to very high sediment loads, gentle gradients, and wide channel geometry. SL index values are greater in regions of higher relief toward the southwestern edge of the Mecca Hills and taper off toward the fringes of the hills. This pattern is interpreted as demonstrating greater tectonic activity in regions of higher index values.

Figure 9b: Ratio of catchment volume to area (RVA) values for catchments within the Mecca Hills. RVA is calculated by computing the catchment volume from a catchment DEM and dividing this value by the catchment’s 2-D planimetric area (Frankel and Pazzagila 2006). The
RVA are chosen over the commonly utilized valley width to height ratio (Bull and McFadden 1979) because it eliminates the subjectivity of choosing a measurement location and acts as a first-order approximation of the width/height ratio (Frankel and Pazzagila 2006).

Figure 9c: Mountain front sinuosity values for the Mecca Hills and nearby mountain ranges. Mountain front sinuosity is calculated by measuring the distance of the slope break between piedmont and hillslopes and dividing this value by the straight line distance; Values closer to 1 indicate more tectonically active ranges in terms of uplift (Bull and McFadden 1979). Values collected and derived from Patt (2000). The Mecca Hills demonstrates a notably lower value (1.11) than nearby mountain ranges (1.38-1.67) suggesting that the Mecca Hills is significantly more tectonically active and uplifting at a faster rate.
### Table 1: Geomorphic Surface Descriptions and ages for Surfaces in the Mecca Hills, CA

<table>
<thead>
<tr>
<th>Surface Name</th>
<th>Age Range (ka)</th>
<th>Weighted Mean Surface Age (ka)</th>
<th>Depth Profile Age (ka)</th>
<th>Marine Isotope Stage (MIS)</th>
<th>Mean Sampled Elevation (m a.s.l.)</th>
<th>Description of Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qvo1</td>
<td>200 - 475</td>
<td>206 ± 100</td>
<td>280 ± 24</td>
<td>MIS 8</td>
<td>552</td>
<td>This is the highest surface in the alluvial stratigraphy and is found dominantly in the northeastern side of the Mecca Hills. It demonstrates an extremely well developed desert pavement with little bar and swale morphology. Polymictic granite and metamorphic sand to cobble lithology with infrequent boulders. Significant carbonate development and vents are present. Vegetation density is very low and displays greater diversity than other surfaces in the Mecca Hills.</td>
</tr>
<tr>
<td>Qvo2</td>
<td>11 - 160</td>
<td>67.2 ± 5.3</td>
<td>17.4 ± 6.1</td>
<td>MIS 4 / 5</td>
<td>110</td>
<td>This surface is the most prominent surface in the Northwestern Mecca Hills north of Thermal Canion (Fig 2). Desert pavement development is weaker than Qvo1 yet boulders at the surface have significant desert varnish and are weathered. Remnant bar and swale features are present. Carbonate soil development is present but thinner than Qvo1. Vegetation density is low and less diverse than Qvo1.</td>
</tr>
<tr>
<td>Qv1</td>
<td>3.8 - 17</td>
<td>8.2 ± 2.0</td>
<td>2.6 ± 5.55</td>
<td>MIS 1</td>
<td>81</td>
<td>This is the most recent episode of alluvial fan deposition in the Mecca Hills. Little to no desert pavement or varnish on boulders. Boulders are not weathered and intact and frequent on surfaces. Lithology is identical to other alluvial units. Sand to cobble clasts size. Bar and swale features present. Vegetation is sparse and not diverse.</td>
</tr>
<tr>
<td>Qff</td>
<td>5.1 - 20</td>
<td>9.0 ± 4.8</td>
<td>-</td>
<td>MIS 1</td>
<td>166</td>
<td>Identical to Qv1, yet located as terraces in canyons. Lithology varies between granite/gneiss and schist dominated end members depending on location.</td>
</tr>
<tr>
<td>Qcc</td>
<td>5.1 - 40</td>
<td>8.4 ± 16</td>
<td>-</td>
<td>MIS 1</td>
<td>57</td>
<td>Active channel deposits that are reactivated on occurrence of flash flooding. Imbricated boulders and cobbles present. Vegetation is denser and more diverse relative to other surfaces. Lithology is a mix of granite, gneiss, and rarely hornblende. Beryllium concentrations assumed to be entirely inheritance.</td>
</tr>
</tbody>
</table>

### Table 2: Geomorphic Surface Descriptions and ages

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Geomorphic Stage</th>
<th>Rock Type</th>
<th>Lithology</th>
<th>Elevation (m)</th>
<th>Thickness (mm)</th>
<th>Dendritic Erosion</th>
<th>Alluvial Terraces</th>
<th>Incised Valleys</th>
<th>Time Deposition (ka)</th>
<th>Time Induration (ka)</th>
<th>Deposit (mm)</th>
<th>Lithification Factor</th>
<th>Time Induration Factor</th>
<th>Time Deposition Factor</th>
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<tbody>
<tr>
<td>1</td>
<td>Qv1</td>
<td>Granite</td>
<td>Gravel</td>
<td>1200</td>
<td>50</td>
<td>100</td>
<td>80</td>
<td>20</td>
<td>100</td>
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<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Qv2</td>
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<td>Sedimentary</td>
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<td>100</td>
<td>80</td>
<td>20</td>
<td>100</td>
<td>50</td>
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<td>100</td>
<td>50</td>
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</tr>
<tr>
<td>4</td>
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<td>Gneiss</td>
<td>Gneiss</td>
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<td>50</td>
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<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2 Footnotes:**
1 All ages calculated using the CRONUS online calculator version 2.2 (Balco et al. 2008; http://hess.esswashington.edu).

2 Corrected for blanks run concurrent with sample measurement.

3 Samples MH-7 through MH-51 measured at Lawerence Livermore National Laboratory, all others at PRIME lab, Purdue university.

4 Sampled uppermost surface of boulder

5 No correction for topographic shielding necessary (horizon < 20°)

6 Uncertainties reported to 1σ confidence level
Table 3: Surface Ages and Depth Profile Results\textsuperscript{1,2}

<table>
<thead>
<tr>
<th>Surface Name</th>
<th>Age \textsuperscript{(ka)}</th>
<th>Inheritance (10^9 \text{ atoms g}^{-1})</th>
<th>Erosion Rate (\text{cm ka}^{-1})</th>
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<tr>
<td>Qvof1</td>
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<tr>
<td>mean</td>
<td>280.3</td>
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<td>0.05</td>
</tr>
<tr>
<td>median</td>
<td>279.2</td>
<td>15.7</td>
<td>0.05</td>
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<tr>
<td>mode</td>
<td>280.1</td>
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<td>min (\chi^2)</td>
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<td>maximum</td>
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<td>Qvif1</td>
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<td>median</td>
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<tr>
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<td>min (\chi^2)</td>
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<td>minimum</td>
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<td>3.01</td>
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<td>0.55</td>
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</table>

Table 3 Footnotes:

1 \(^{10}\)Be data for depth profile simulation included in supplemental Table 2; all samples run at Lawrence Livermore National Laboratory.

2 Parameters for each depth profile simulation described and justified in text.

3 Although erosion rate is reported, these values subject to an assumed constraint of near zero (see methods) and cannot be used to describe erosion rate.
Table 4: 10Be Catchment-wide Erosion Rate Results

<table>
<thead>
<tr>
<th>Name</th>
<th>Drainage System</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Concentration (10^3 atoms/g SmI2)</th>
<th>Erosion Rate</th>
<th>Basin Width (m)</th>
<th>Erosion Rate</th>
<th>Applicable age range (ka)</th>
<th>Mean Basin Slope</th>
<th>Mean Basin Relief (m)</th>
<th>Mean Basin Size (km^2)</th>
<th>Mean Basin Elevation (m.a.s.l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MH-HG-3</td>
<td>Box Canyon</td>
<td>-115.98059</td>
<td>33.65757</td>
<td>162.4</td>
<td>6.0</td>
<td>256</td>
<td>3.8</td>
<td>19.1</td>
<td>10.9</td>
<td>1130</td>
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<tr>
<td>MH-HG-6</td>
<td>Box Canyon</td>
<td>-115.98059</td>
<td>33.65760</td>
<td>146.5</td>
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<td>287</td>
<td>3.8</td>
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<td>MH-HG-7</td>
<td>Box Canyon</td>
<td>-115.98053</td>
<td>33.65750</td>
<td>478.8</td>
<td>6.0</td>
<td>892</td>
<td>19.6</td>
<td>5.7</td>
<td>11.6</td>
<td>1336</td>
<td>491.7</td>
<td>719.9</td>
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<td>MH-HG-15</td>
<td>NW Mecca Hills</td>
<td>-115.99063</td>
<td>33.67416</td>
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<td>5.5</td>
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<td>MH-HG-24</td>
<td>NW Mecca Hills</td>
<td>-116.02037</td>
<td>33.60076</td>
<td>144.6</td>
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<td>3.2</td>
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<td>MH-HG-28</td>
<td>Painted Canyon</td>
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<td>33.50882</td>
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<td>356</td>
<td>19.3</td>
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<td>753</td>
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<td>MH-HG-34</td>
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<td>532</td>
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<td>MH-HG-ER3</td>
<td>Hidden Sping</td>
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<td>33.55815</td>
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<td>14.0</td>
<td>12.8</td>
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</table>

Table 4 Footnotes:

1. 10Be measurements made at PRIME lab, Purdue University. See supplemental data table 2 for standards used and AMS results.

2. 10Be production rates and topographic shielding calculated using MATLAB v. (2009) following the methods of Dortch et al 2011


4. Catchment parameters determined using ArcGIS 10.1 Student Version and USGS NED DEMs.
Supplemental Figure 1: NKDE plot for all published Beryllium-10 surface exposure ages on boulders in the southwestern USA.

Supplemental Figure 2 (not shown): Complied photographs of sampled boulders and locations within the Mecca Hills, CA.