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TITLE

Climate-driven unsteady denudation and sediment flux in a high-relief unglaciated catchment-fan using ^{26}Al and ^{10}Be: Panamint Valley, California

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KEYWORDS

Sediment Routing System, Catchment-fan, Signal Propagation, Paleodenudation, Climate, Cosmogenic Radionuclides

HIGHLIGHTS

- ^{26}Al/^{10}Be Burial ages/paleodenudation rates measured in early to middle Pleistocene alluvium
- Pleistocene paleodenudation averaged ~30 – 50% higher than modern ^{10}Be denudation rates
- Maximum variability of +50/-33% from mean paleodenudation rate in unglaciated catchment-fan
- 100 kyr Milankovitch periods may drive observable variability in CRN concentrations
- Limitations of ^{26}Al/^{10}Be method applied to alluvial fan stratigraphy are discussed

ABSTRACT

Environmental changes within erosional catchments of sediment routing systems are predicted to modulate sediment transfer dynamics. However, empirical and numerical models that predict such phenomena are difficult to test in natural systems over multi-millennial timescales. Tectonic boundary conditions and climate history in the Panamint Range, California, are relatively well-constrained by existing low-temperature thermochronology and regional multi-proxy paleoclimate studies, respectively. Catchment-fan systems present there minimize sediment storage and recycling, offering an excellent natural laboratory to test models of climate-sedimentary dynamics. We used stratigraphic characterization and cosmogenic radionuclides (CRNs; ^{26}Al & ^{10}Be) in the Pleasant Canyon complex (PCC), a linked catchment-fan system, to examine the effects of Pleistocene high-magnitude, high-frequency climate change on CRN-derived denudation rates and sediment flux in a high-relief, unglaciated catchment-fan system. Calculated ^{26}Al/^{10}Be burial ages from 13 samples collected in an ~180 m thick outcropping stratigraphic succession range from ca. 1.55 ± 0.22 Ma in basal strata, to ca. 0.36 ± 0.18 – 0.52 ± 0.20 Ma within stratigraphically highest portions of the fan. The mean long-term CRN-derived paleodenudation rate, 36 ± 8 mm/kyr (1σ), is higher than the modern rate of 24 ± 0.6 mm/kyr from Pleasant Canyon, and paleodenudation rates during the middle Pleistocene display some high-frequency variability in the high end (up to 54 ± 10 mm/kyr). The highest CRN-derived denudation rates are associated with stratigraphic evidence for increased precipitation during glacial-pluvial events after the middle Pleistocene transition (post ca. 0.75 Ma), suggesting 100 kyr Milankovitch periodicity could drive the observed variability. We investigated the potential for non-equilibrium sedimentary processes, *i.e.* increased landslides or sediment storage/recycling, to influence apparent paleodenudation rates; end-member mixing models suggest that a mixture of >50% low-CRN-concentration sediment from

landslides is required to produce the largest observed increase in paleodenudation rate. The overall pattern of CRN-derived burial ages, paleodenudation rates, and stratigraphic facies suggests Milankovitch timescale climate transitions drive variability in catchment denudation rates and sediment flux, or alternatively that climate transitions affect sedimentary process regimes that result in measurable variability of CRN concentrations in unglaciated catchment-fan systems.

1.0 INTRODUCTION

Sediment routing systems consist of an erosional zone, a fluvial transfer zone, and a depositional basin (Allen, 2008). The creation and preservation of stratigraphy within a sediment routing system is the sum of complex processes including up-system environmental changes in the erosion zone, sediment storage and recycling in the erosion and/or fluvial transfer zones, and changes in accommodation and intrinsic system dynamics in depositional basins (Paola et al., 1992). Some geoscientists have conceptualized sediment production, transport, storage, and remobilization dynamics along sediment routing systems in terms of environmental signal propagation (Castelltort and Van Den Driessche, 2003; Romans et al., 2016). In this framework, sediment flux is the carrier of environmental change signals. Inverting sediment flux from stratigraphy is thus complicated by issues including signal to noise ratio, signal delay, signal attenuation, or signal 'shredding', and combinations of these phenomena may preclude preservation or inversion of up-system environmental change from depositional products (Jerolmack and Paola, 2010; Romans et al., 2016). Given this context, *a priori* assumptions of minimal signal delay, attenuation, or shredding are required to explore effects of up-system drivers on magnitude and variability of signals of erosion-deposition dynamics. A steep catchment-fan system with a continuously subsiding depositional segment represents an ideal natural laboratory for the investigation of sedimentary signal propagation because: (1) it may react rapidly to changes in boundary conditions, (2) it likely experiences minimal signal delay or attenuation because it lacks, or has a very short transfer zone, and (3) rapidly subsiding alluvial basins contain relatively complete records of past surface dynamics (Straub and Esposito, 2013). Catchment-fan systems have previously been used to explore effects of environmental change on catchment erosion, sediment flux, and sediment caliber exiting catchments (Fig. 1) (Allen and Densmore, 2000; Densmore et al., 2007; Armitage et al., 2011). In such a framework, changes in erosion and sediment flux from catchment to fan are direct signals of environmental change in a catchment. A fundamental question then is what are the magnitudes of signals emitted from the erosive source of a natural catchment-fan system? And a related question is by how much do such magnitudes vary through time? Placing constraints on denudation rate variability — a proxy for sediment supply at a catchment outlet — through time, in a single sediment routing system, allows for the examination of signals of environmental change.

Predicting catchment response to environmental change, specifically climatic transitions, on a global to individual catchment basis is challenging, because with several exceptions there is a lack of empirical data sets that constrain high-resolution and long-term (10^{3-4} yr and 10^6 yr, respectively) records of changes in catchment-scale erosion or sediment flux (Granger and Schaller, 2014; Puchol et al., 2016; Oskin et al., 2017). Researchers have addressed this topic by measuring CRNs in alluvial and lacustrine stratigraphy to derive a time series of paleodenudation rates (Balco and Stone, 2005; Granger and Schaller, 2014), by utilizing volumetric estimates of basin fill (Covault et al., 2011), or by analyzing provenance of dated sedimentary deposits spanning climatic transitions (Mason et al., 2017). Results indicate many glaciated sediment routing systems have responded to changing climatic boundary conditions within resolution of the various chronometers (Stock et al., 2005; Glotzbach et al., 2013; Marshall et al., 2015; Gulick et al., 2015; Mason et al., 2017), whereas other records from glaciated and unglaciated systems show a complex response, or a lack of any measurable change in denudation rate or fluxes to basins across major climate transitions (Granger et al., 2001; Oskin et al., 2017). For instance, in the Tibetan Plateau, ^{10}Be-derived denudation rates across the Plio-Pleistocene transition show a complex, asynchronous, or weak transient response to onset of glaciation (Puchol et al., 2016). In the unglaciated Peninsular Ranges of southern California, ^{10}Be-derived paleodenudation rates across the Plio-Pleistocene transition (ca. 4 – 1 Ma) remained constant (Oskin et al., 2017). However, in the unglaciated Northern Kenya Rift erosion/deposition rates saw a significant transient increase during the African Humid Period, between ca. 5 – 15 ka, (Garcin et al., 2017), and tectonically quiescent, unglaciated sediment routing systems along the Texas Gulf Coast responded to interglacial warm periods with increased CRN-derived denudation rates (Hidy et. al., 2014). Yet in the Pacific Northwest, periglacial conditions during the last glacial maximum increased CRN-derived denudation rates relative to the Holocene (Marshall et al., 2015). These results highlight the complexity in natural system response to changing climate, complicate interpretations of sedimentary records of environmental change, and prediction of system response to future global climate change.

Numerical simulations of linked catchment-fan systems represent a tool to bridge the gap between modern and geologic-timescale empirical studies, and may be used to explore effects of up-system forcings on depositional products. Simulations typically impose changes in catchment or orogen-scale boundary conditions — often precipitation and fault-slip rate (Fig. 1) — and measure various model outputs including channel incision rate, catchment denudation, sediment flux at catchment outlets, and spatial distribution of grain-size variations in the depositional segment (Allen and Densmore, 2000; Armitage et al., 2011). Such studies predict distinct timescales of system response and equilibrium for various forcings, with reaction timescales to perturbations in precipitation occurring over ~$10^{3\text{-}4}$ yrs, and reaction timescales to tectonic perturbations occurring over $10^{5\text{-}6}$ yrs (Fig. 1) (Allen, 2008; Armitage et al., 2011). Crucially, models that modulate precipitation rates mimicking Milankovitch-timescale climate change result in concomitant modulation of catchment denudation rates and sediment fluxes (Allen and Densmore, 2000), and CRN concentrations may respond to changes in erosion rates over multi-millennial timescales (Fig. 1c). To test the predictions of numerical models in natural systems, two fundamental conditions must be met: (1) tectonic and paleoclimatic boundary conditions should be relatively well constrained, and (2) the system must preserve a stratigraphic record of changes in denudation rates, sediment flux, or depositional volumes through time.

In this paper, we place new constraints on CRN-derived signals of denudation rate variability over multi-millennial timescales in a steep, unglaciated, catchment-fan system within an uplifted normal fault block in Panamint Valley, California. This configuration is common to much of the American Great Basin, Basin and Range of the United States and Mexico, and elsewhere globally, yet is underrepresented in existing literature. We present new data and interpretations from 13 CRN samples collected throughout a 180-m thick succession of outcropping Pleistocene alluvial-lacustrine strata, and from two samples of modern sediment collected at feeder catchment outlets. This empirical record of CRN-derived denudation rate and sediment supply, as stored in the depositional segment of a linked catchment-fan, represents a test of conceptual, numerical, and empirically derived predictions for the effects of multi-millennial timescale climate change on catchment-erosion and fan-deposition dynamics.

2.0 BACKGROUND

2.1 Pleasant Canyon Complex Source-to-Sink Parameters

The Panamint Range and Valley are located in eastern California, west of Death Valley and east of the Argus and Slate Ranges (Fig. 2). The Pleasant Canyon complex (PCC) lies at the terminus of a high-relief catchment (~2350 meters) that drains 32.8 km^2 of the central Panamint Range. Figure 3 displays catchment parameters including elevation, surface slope, geology and hypsometry for Pleasant Canyon. The bedrock lithologies of Pleasant Canyon are primarily quartz-bearing Proterozoic-aged metamorphic, igneous, and sedimentary units, with the exception of restricted exposures of the Sentinel Peak member of the Noonday Dolomite (Fig. 3c) (Albee et al., 1981). The contact between World Beater Gneiss and Proterozoic sedimentary units in the upper reaches of Pleasant Canyon (Figure 3c) corresponds to a decrease in slope associated with minor Pleistocene to Holocene alluvial deposits (Albee et al., 1981).

The exhumed depositional segment of the PCC is positioned at the mouth of Pleasant Canyon (Figs. 2 and 3) and is composed of ~180 m of mixed alluvial and lacustrine deposits of Pleistocene age (Smith, 1976; Vogel et al., 2002). Stratigraphic surfaces in the PCC were once active alluvial fan, subaqueous lake bed, or playa floor environments. Deposits aggraded during progressive burial via tectonic subsidence, followed by Pleistocene exhumation and inversion along a series of high-angle normal faults known as the Panamint Valley fault zone (Fig. 2) (Cichanski, 2000; Vogel et al. 2002). The timing of localized high-angle faulting and inversion of PCC deposits is constrained only by the unknown age of the youngest abandoned alluvial fan surfaces. Small headward eroding gullies have formed since exhumation, and now afford excellent 3-D exposures of PCC stratigraphy.

2.2 Late Cenozoic Tectonic History

The tectonic history of the Panamint Mountains is a first-order control on the pace of catchment denudation and sediment flux to linked alluvial fans (Allen and Densmore, 2000). The Panamint Mountains (Fig. 2) are located within the eastern California-Walker Lane shear zone, a region of diffuse dextral plate boundary deformation east of the San Andreas Fault. Panamint Valley is defined by active structures displaying complex Plio-Quaternary deformation patterns; eastern Panamint Valley is bound by the low-angle Panamint-Emigrant detachment system exposed along, or at low elevation within, the Panamint rangefront (Fig. 2). Active deformation is potentially mainly accommodated by a second set of high-angle oblique dextral faults, the Panamint Valley fault zone, which has cut and displaced Pleistocene to Holocene alluvium exposed along eastern Panamint Valley and the western Panamint rangefront (Fig. 2; Cichanski, 2000). The western Panamint Valley is structurally bound by the dextral-oblique Ash Hill fault system near the eastern foot of the Argus Range (Fig. 2) (Densmore and Anderson, 1997).

Early tectonic exhumation and uplift of the Panamint Mountains may have initiated along a single west-dipping, west-side-down, master detachment fault—the Panamint-Emigrant detachment fault (Fig. 2)—starting close to ca. 12 Ma (Bidgoli et al., 2015). Low-temperature thermochronometry (zircon U-Th/He) from the central Panamint Range shows exhumation-related cooling initiated after ca. 12 Ma, while lower temperature thermochronometers (apatite U-Th/He) cluster at ca. 4 Ma, and support rapid Pliocene cooling and tectonic exhumation of the Panamint Range, potentially associated with the initiation of the dextral oblique Panamint Valley fault zone (Bidgoli et al., 2015). Sediment accumulation within the Nova Basin in northeast Panamint Valley occurred between ca. 4.4 – 3 Ma, consistent with Pliocene tectonic rejuvenation (Fig. 2) (Snyder and Hodges, 2000).

Pleistocene to recent rates of dip-slip motion for the Panamint Valley fault zone near Ballarat are ~0.35 – 1 mm/yr (Fig. 2), and were derived using detrital zircon maximum depositional ages from basal stratigraphy of the PCC (Vogel et al., 2002). Dextral deformation rates along the Panamint Valley fault zone are debated, but are thought to be between 1 – 4 mm/yr (Smith, 1976; Oswald and Wesnousky, 2002). Given available information, early to middle Pleistocene catchment denudation rates should reflect equilibrium with respect to uplift patterns of the central Panamint Range since ca. 3 – 4 Ma (Fig. 1) (Allen and Densmore, 2000; Densmore et al., 2007; Armitage et al., 2011).

2.3 Pleistocene Climate History

Panamint Valley is an arid to semi-arid endorheic basin located in a major rain shadow east of the Sierra Nevada Range. Precipitation is scarce at low elevations in Panamint Valley, but increases with elevation in a semi-logarithmic manner in the Panamint Range (Jayko, 2005). The Wildrose Ranger station (1250 m asl) in the northern Panamint Range receives an average of 19 cm of precipitation annually (Jayko, 2005). No long-term record of precipitation exists for Pleasant Canyon, but the mean elevation of ~1700 m asl likely results in >25 – 35 cm of mean annual precipitation. Observations of modern sedimentation events in Death and Panamint Valley indicate catchment hillslopes and fluvial channels transmit material to alluvial fans during low-frequency, high-magnitude storm events. Thus, long-term trends in major storm frequency may influence sediment transfer from catchment to fan.

Pleistocene climate in the Great Basin was on average wetter and colder than the late Holocene interglacial (See inset map from Fig. 2; Oster et al., 2015). Pluvial lakes filled Panamint Valley multiple times during the Pleistocene (Smith, 1976) via increased local precipitation and runoff from the paleo Owens River system (Jannik et al., 1991; Phillips, 2008). Continental paleoclimate records including pollen, hydrological restorations of pluvial lakes, oxygen isotope data, and mass-balance models of Pleistocene Sierra Nevada glaciers agree that temperatures during the last glacial maximum were ~5 – 6°C colder, and precipitation was up to 2x greater than during the late Holocene (D'Arcy et al., 2016, and references therein). Mid-glacial climate conditions typify most of the Pleistocene, and were 2 – 3°C colder with precipitation rates ~1.5x those of modern conditions (D'Arcy et al., 2016). D'Arcy et al. (2016) found that Late Pleistocene climatic forcing, specifically increased precipitation, resulted in measurable differences in patterns of down-system fining of alluvial sediments on Death Valley fans, corresponding to an ~20% increase in Pleistocene catchment-fan sediment flux.

2.4 Previous Regional Paleodenudation Studies

The ages of alluvial fans in the Death Valley area have been used to understand rates of tectonic deformation and effects of climate on alluvial fan morphology (Frankel et al., 2007). Unfortunately, few employed catchment-wide paleodenudation rate techniques. Frankel et al. (2007) dated faulted alluvial fans in northern Death Valley using ^{36}Cl depth profiles, and used inherited concentrations to derive paleodenudation rates of ~40 and ~80 mm/kyr for two catchment-fan systems along the western Grapevine Mountains during the last mid-glacial (ca. 70 ± 10 ka).

Alluvial fan volumetric estimates and rough age constraints were used to quantify time-averaged denudation rates for catchments along the western Panamint Range; results suggest denudation rates between ~40 – 230 mm/kyr. Jayko (2005) used these results to suggest higher precipitation may lead to higher sediment flux in the western Panamint Range. We note that differential slip rates along the range-bounding faults would play a fundamental role in controlling relief and slope, both of which may correlate positively to higher denudation rates. A time series of denudation rates from a single high-relief, unglaciated catchment within the Great Basin represents a crucial missing component to understanding variability of erosion-deposition dynamics across glacial-interglacial climate transitions.

3.0 METHODS

3.1 Sedimentary Lithofacies & Stratigraphic Architecture

We characterized the stratigraphy of the PCC using measured lithostratigraphic sections, and high-resolution photopanoramas for inaccessible outcrops. For our two measured sections (Fig. 2b), stratigraphy and sedimentology were characterized at the cm to decimeter scale. We recorded dominant grain size, bed thickness, sedimentary structures, sorting, particle roundness, clast vs. matrix support, and lateral continuity of beds, and constructed lithofacies and lithofacies associations that were used to interpret depositional environments (See Supplementary material S2).

3.2 Field Sampling, Laboratory Preparation, and Measurement of Cosmogenic $^{26}Al/^{10}Be$

We took advantage of the linked nature of the Pleasant Canyon catchment-fan system by collecting quartz-rich sediment in a vertical succession from Pleistocene alluvium derived directly from Pleasant Canyon. Samples taken vertically through a stratigraphic succession represent a record of catchment denudation rates through time (*e.g.* Balco and Stone, 2005). All samples were located within, or stratigraphically correlated to our measured sections (locations depicted in Fig. 2b).

Our sampling strategy was designed to minimize effects of modern exposure to cosmic rays (similar to that of Puchol et al., 2017; Oskin et al., 2017). We collected sediment from well-shielded vertical or overhanging canyon walls, mostly within narrow canyons. In each case, sediment was excavated from a horizontal depth of at least 50 cm into outcrops, parallel to bedding. We sieved sediment in the field and collected the medium sand-sized fraction (250 – 500 µm). A total of 15 samples were collected during this study; 13 samples were collected from outcrops, and 2 samples were collected from modern wash sediment at catchment outlets. Our goal was to quantify both catchment-averaged paleodenudation in Pleasant Canyon through time, and to quantify the modern catchment-averaged denudation rate.

Samples of Pleistocene and modern sediment underwent standard physical separation and chemical purification procedures at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab). Samples were washed and wet sieved to remove fine particles, then underwent a technique of froth-floatation to separate quartz from feldspar. Samples underwent magnetic separation and were then treated with heavy liquids to isolate quartz. Purified quartz was then leached in dilute HF-HNO_3 baths in an ultrasonic tank to remove the meteoric CRN components. All samples of pure quartz were screened using inductively coupled plasma optical emission spectrometry (ICP-OES). Samples of pure quartz were spiked with ^{27}Al or ^{9}Be carrier of known concentration, and dissolved using concentrated HF/HNO_3. Samples were then filtered through cation and anion exchange columns, then Al and Be hydroxides were dried and converted to oxides, and loaded into targets to be measured using accelerator mass spectrometry (AMS) at the PRIME Lab. AMS results were corrected using blank concentrations following standard PRIME Lab procedures (See "Supplementary AMS Data" file for complete chemistry blank and uncorrected sample measurements).

3.3 Cosmogenic $^{26}Al/^{10}Be$ Burial Dating and Paleodenudation Calculations

Quartz sediment eroded from a catchment and mixed in a fluvial system retains a concentration of CRNs (^{26}Al and ^{10}Be) inversely proportional to the spatially averaged denudation rate within that catchment (Lal, 1991; Bierman and Steig, 1996; Granger and Muzikar, 2001). Consequently, rapidly eroding landscapes result in low concentrations of CRNs in fluvial sediment, while the opposite is true for slowly eroding landscapes. Sediment in catchment-fan systems is evacuated and rapidly deposited on the fan surface, and assuming the pre-burial concentration of CRN found in sediment is due to steady vertical advection during erosion, the concentration ($N_{Al,Be}$ in atoms/g SiO_2) is simply a function of the erosion rate (E) in cm/yr:

$$(1)\ N_{Al}\ (0) = \frac{A_0}{\frac{1}{\tau_{Al}} + \frac{E}{L_0}} + \frac{A_1}{\frac{1}{\tau_{Al}} + \frac{E}{L_1}} + \frac{A_2}{\frac{1}{\tau_{Al}} + \frac{E}{L_2}} + \frac{A_3}{\frac{1}{\tau_{Al}} + \frac{E}{L_3}}$$

$$(2)\ N_{Be}\ (0) = \frac{B_0}{\frac{1}{\tau_{Be}} + \frac{E}{L_0}} + \frac{B_1}{\frac{1}{\tau_{Be}} + \frac{E}{L_1}} + \frac{B_2}{\frac{1}{\tau_{Be}} + \frac{E}{L_2}} + \frac{B_3}{\frac{1}{\tau_{Be}} + \frac{E}{L_3}}$$

Where A_j and B_j are coefficients, with values of $A_0 = 28.5$, $A_1 = 0.72$. $A_2 = 0.16$, $A_3 = 0.19$, $B_0 = 4$, $B_1 = 0.09$, $B_2 = 0.02$, and $B_3 = 0.02$, and in units of atoms/yr/g SiO_2, (Granger and Muzikar, 2001; Borchers et al., 2016). L_j represents an attenuation length scale for CRN production reactions; L_0 refers to the attenuation length for spallogenic reactions, L_1 and L_2 are attenuation lengths for negative muon capture, and L_3 is the attenuation length for fast muon capture. We assign values of $L_0 = 160/\ \rho$, $L_1 = 738/\ \rho$, $L_2 = 2688/\ \rho$, and $L_3 = 4360/\ \rho$, where ρ represents rock density covering a sample in g/cm^3 (Granger and Muzikar, 2001). Density of overlying mass in the catchment during erosion is assumed to be 2.6 g/cm^3, and the bulk density of sediment in the PCC is assumed to be 2.2 g/cm^3, and τ_{Al} and τ_{Be} represent the radioactive mean lives for ^{26}Al and ^{10}Be (1.02x10^6 and 1.93x10^6 yrs, respectively; Norris et al., 1983; Chmeleff et al., 2010).

Buried sediment derived from a steadily eroding source retains a concentration of CRNs that evolves through time as a function of the pre-burial concentration (itself a function of erosion rate), and the time since burial (Granger and Muzikar, 2001):

$$(3)\ N_{Al}(t) = N_{Al}(0)\exp\left(\frac{-t}{\tau_{Al}}\right) + P_{Al}(d)\tau_{Al}[1 - \exp\left(\frac{-t}{\tau_{Al}}\right)]$$

$$(4)\ N_{Be}(t) = N_{Be}(0)\exp\left(\frac{-t}{\tau_{Be}}\right) + P_{Be}(d)\tau_{Be}[1 - \exp\left(\frac{-t}{\tau_{Be}}\right)]$$

Where $N_{Al,Be}$ is the number of atoms/g SiO_2, t is time in years, $P_{Al,Be}$ are production rates in atoms/yr/g SiO_2, and d is sample depth in cm. In equations three and four, the first term describes post-burial radioactive decay, and the second term describes post-burial production of CRNs. At depths greater than several 10s of m, the right-hand term may be considered negligible, but post-burial production in shallowly buried sediment may be significant (Granger and Muzikar, 2001). Lacustrine environments such as pluvial lakes provide extra post-depositional shielding to sediment from cosmic rays, yet we elected to use an equation with terms that describe muonogenic post-burial CRN production:

$$(5)\ P_{Al}(d) = A_0\exp\left(\frac{-d}{L_0}\right) + A_1\exp\left(\frac{-d}{L_1}\right) + A_2\exp\left(\frac{-d}{L_2}\right) + A_3\ \exp\left(\frac{-d}{L_3}\right)$$

$$(6)\ P_{Be}(d) = B_0 \exp\left(\frac{-d}{L_0}\right) + B_1 \exp\left(\frac{-d}{L_1}\right) + B_2 \exp\left(\frac{-d}{L_2}\right) + B_3 \exp\left(\frac{-d}{L_3}\right)$$

where *A* and *B* are mechanisms of CRN production as given in equations one and two. Equations one through six combine through substitution to form a system of two equations and two unknowns, time (t) and erosion rate (E), and using measured CRN concentrations ($N_{Al,Be}$) and the depth of each sample (d), we may solve for both t and E. To recover t and E, we forward model pre-burial concentrations of CRNs, and use a least-squares optimization to determine a best-fit burial age and denudation rate for each measured pair of CRN concentrations (after Craddock et al., 2010). We used published sea-level high latitude reference production rates for ^{26}Al and ^{10}Be of 28.5 and 4 atoms/g SiO_2/yr, respectively (Borchers et al., 2016), and scaled them to the catchment average production rates using latitude and catchment hypsometry to correct for altitude and shielding by the horizon, resulting in catchment average production rates for ^{26}Al and ^{10}Be of 102 and 14.3 atoms/yr/g SiO_2, respectively (Stone, 2000; and code described in Dortch et al., 2011).

3.4 Assumptions Associated with Burial Age and Paleodenudation Rate Calculations

To calculate the ^{26}Al/^{10}Be burial age and paleodenudation rate from sediment in the PCC we assumed the sampled bed was instantaneously buried to the modern depth below the fan surface (~500 m asl). In reality, deposits aggraded by accumulation on the alluvial-fan surface and rapid tectonically controlled subsidence of the hanging wall. A conservative estimate for the average aggradation rate in the PCC is at least ~100 – 400 m/Ma (Vogel et al., 2002). Craddock et al. (2010) calculated burial ages and denudation rates using an instantaneous emplacement model, and again using a depth-dependent model; they found calculating burial ages and denudation rates using the instantaneous emplacement model only resulted in significant bias when aggradation rates were very low, on the order of 10 m/Ma, which is an order of magnitude lower than our lowest estimate of aggradation rate.

We assumed a uniform distribution of quartz-bearing lithology in the catchment, and we made no corrections for recent exposure to cosmic rays during exhumation, because (1) we have no way to constrain the timing and rate of headward erosion in the PCC, except that incision occurred after deposition of the youngest strata, and (2) we feel the measures taken during sampling, as outlined in section 3.2, ensure samples were relatively well-shielded from modern exposure. Reported errors for burial ages and denudation rates represent analytical uncertainties and decay rate related uncertainties (See Table 1).

4.0 RESULTS

4.1 Depositional Lithofacies Associations of the Pleasant Canyon Complex

We used data from measured lithostratigraphic sections to construct depositional lithofacies and lithofacies associations for stratigraphic units in the PCC (after Blair and Mcpherson, 2008). Example lithofacies and lithofacies associations are pictured in Figure 4, and the large-scale stacking patterns of facies associations are presented in Figure 5 (See Supplementary material S2 for complete description).

Lithofacies of the PCC fall under one of two broad groups of depositional environments, those deposited in or modified by subaqueous lacustrine environments during pluvial intervals termed the Lacustrine Lithofacies Association, or those deposited on a subaerial alluvial fan surface termed the Alluvial Lithofacies Association (after Blair and McPherson, 2008). In addition, we note the occurrence of both Lacustrine and Alluvial Lithofacies in close vertical association, which we call a Mixed Lithofacies Association.

4.1.1 Lacustrine (and Mixed) Lithofacies Association

The Lacustrine Lithofacies Association (Fig. 4c – l) is defined by laterally continuous grey- to white-colored, finely laminated to featureless beds of clay, silt, and sand. In Section One, several meters of rhythmically bedded sandy turbidites are preserved (Fig. 4h). Characteristic lithofacies that define the Lacustrine (and Mixed) Lithofacies Association include Lithofacies F: Fine silt to clay (Fig. 4c – 4i), Lithofacies Gcr: rounded, clast-supported gravel conglomerate (not pictured), and Lithofacies Sc: horizontally laminated and contorted sand beds (Fig. 4h).

The 'mixed' aspect of this lithofacies association refers to lithofacies (Fig. 4a, b, & l) that are interpreted as distinct environments of deposition, alluvial and lacustrine, which are stacked in close vertical succession, thus representing a mixed association. Where fine-grained units interpreted as lacustrine (F, Sl) are interbedded with sands (Sl, Sg), and coarse-grained gravel conglomerates (Gc, Gm), we interpret a shallow or ephemeral lake with rapidly fluctuating water level or environment of deposition (examples pictured in Figure 4a, 4b, and in the upper 1/3 of Figure 4k, and 4i).

4.1.2 Alluvial Lithofacies Association

Alluvial fan facies are ubiquitous within the PCC, and are like those described in numerous publications (*e.g.* Blair and McPherson, 2008). In the PCC, these facies are composed primarily of cobble to boulder conglomerates interbedded with thin (cm) to thick (m) clean to muddy sand beds of varying but typically low lateral continuity (Fig. 4m, n). Characteristic lithofacies that define the Alluvial Lithofacies Association include Lithofacies Gm: matrix-supported gravel conglomerate (Fig. 4m, n), Lithofacies Gc: clast-supported gravel conglomerate (Fig. 4m), Lithofacies Sg: Granule-pebble rich sand (Fig. 4a), Lithofacies Sh: horizontally laminated or featureless sand (Fig. 4a, d, h).

4.2 Stratigraphic Architecture and Depositional Evolution of the PCC

Here we use our scheme of lithofacies associations, and documented large-scale stratigraphic architecture to describe the overall depositional history of the PCC (Fig. 5). Basal deposits of the PCC indicate early deposition was dominated by coarse grained, muddy debris flows, most likely on an alluvial fan surface, separated by laterally discontinuous and patchy lacustrine-influenced conglomerate (minor lacustrine lithofacies; Gcr, Gc), as evidenced by clast rounding, open framework, and relatively coarse matrix content.

Stratigraphically above the basal alluvial-fan dominated component of the PCC, the sedimentological record shows a significant episode of system flooding, lake deepening, and backstepping of coarse-grained lithofacies (positioned at ~115 – 120 m above base of Section Two, and ~19 – 30 m above base of Section One; see Fig. 2c for locations of measured sections). The Lacustrine Lithofacies Association at this interval (lithofacies F, and Sl) signals the greatest relative water depth, and likely a major full glacial-pluvial climate event. Preservation of sandy sediment gravity flows and meters of finely laminated silt to clay beds attest to deeper lake conditions during this phase of PCC evolution.

Overlying the Lacustrine Lithofacies Association, we document a transition from dominantly fine-grained deposits to thin sands, granule to pebbly sands, and muddy alluvial sediments that prograde across fine grained facies, and grade laterally in the dip direction into lacustrine facies. The mixed association of both alluvial and lacustrine lithofacies (Sl, Sg) grades vertically into coarsening upward bundles of sand, pebble, and cobble to boulder conglomerate (Sl, Sg, Gm, Gc). This evolution is likely in response to changes in base level associated with lake desiccation.

We used the prominent lacustrine unit in the upper portion of the outcrop transect (Fig.5) to correlate the two measured sections and to create a composite stratigraphic section for the PCC. We note syndepositional normal faulting in the south part of the PCC, and subtle depositional geometry of the paleo fan may explain the overall thickening, and lower stratigraphic position of the lacustrine unit in Section One (See Supplementary Fig. 2.2).

4.3 CRN-derived Stratigraphic Ages and Paleodenudation Rates

Table 1 shows results of blank corrected AMS measurements, $^{26}Al/^{10}Be$ burial ages, and paleodenudation rates for samples from modern catchment outlets and the PCC. Figure 6 shows the global $\delta^{18}O$ curve (Lisiecki and Raymo, 2005) plotted with a synthesis of our stratigraphic and CRN-derived data sets, including a composite stratigraphic section with sample locations, interpreted lithofacies associations, CRN-derived burial ages, and CRN-derived paleodenudation rates plotted against composite stratigraphic thickness.

The results of burial dating in the PCC yield a depositional age model that supports previous interpretations for the age of basal stratigraphy of at least ca. 0.9 Ma (~20 m above the playa floor; Vogel et al., 2002). However, our results indicate the PCC was an active alluvial fan environment up to 0.6 Myr earlier than previously thought (Fig. 6). A basal burial age of ca. 1.55 ± 0.22 Ma (PAN15), and a stratigraphically higher sample age of 1.16 ± 0.25 Ma (PAN09) obey stratigraphic superposition, and samples generally become younger up-section (Fig. 6d). Within the composite stratigraphic section, the highest $^{26}Al/^{10}Be$ burial ages are ca. 0.36 ± 0.16 Ma

(PAN04) and 0.52 ± 0.20 Ma (PAN05; see Table 1 & Fig. 6a), and constrain the timing of fan abandonment.

Middle Pleistocene sediment samples from the PCC yield paleodenudation rates of similar magnitude to estimates made by others in Death and Panamint Valley (Frankel et al., 2007; Jayko, 2005). Paleodenudation rates vary from 28 ± 4 mm/kyr (PAN01) up to 54 ± 10 mm/kyr (PAN13), with a long term mean denudation rate for the PCC of 36 ± 8 mm/kyr (1σ for all PCC CRN-derived paleodenudation rates; see Table 1). Modern sediment from Pleasant Canyon and Middle Park Canyon outlets yields lower denudation rates of 24 ± 1 (PAN10) and 28 ± 2 mm/kyr (PAN12), respectively, averaged over ca. 21 – 25 kyr timescales.

The highest measured paleodenudation rate, 54 mm/kyr, represents a >2x increase (125%) over the modern, and lowest rate of 24 mm/kyr for Pleasant Canyon. Individual paleodenudation rates have uncertainties that do not overlap (Fig. 6), and while only 2/15 samples (13%) have errors that fall outside the mean paleodenudation rate envelope, we note the highest and lowest CRN-derived denudation rates vary by +50%/-33% from the long-term mean rate. In the remaining sections, we focus on interpretation of these results, then discuss limitations to the methods, and finally explore potential alternative drivers of CRN-derived denudation rate and sediment flux variability in catchment-fan systems.

5.0 DISCUSSION

5.1 Climate-driven Variability in Catchment-fan System Response

Our primary objective was to explore how climate transitions affect the magnitudes and temporal variability of CRN-derived signals of catchment denudation and sediment flux in a natural unglaciated system. Paleodenudation rates in the PCC were not constant, though many rates were similar in magnitude for much of >1 Myr interval. Modern denudation rates from Pleasant and Middle Park Canyons (24 and 28 mm/kyr, respectively) are systematically lower than all but one paleodenudation rate from the PCC (see Table 1), suggesting differences in sediment transport rates or process regimes between Pleistocene and Holocene epochs. These results are consistent with independent findings based on physical sedimentology of alluvial fans in Death Valley (D'Arcy et al., 2016). Prolonged extreme aridity represents the most likely driver for the observed decrease in CRN-derived denudation rates measured in modern samples.

Taken at face value, CRN-derived paleodenudation rates preserved in alluvial fan stratigraphy have varied by a factor of ~2x. A pattern of relatively steady paleodenudation rates juxtaposed with significant variability in the high end, as measured in the PCC, is similar to the pattern of imposed erosion rates vs. resulting CRN-derived erosion rates simulated in Figure 1c. This qualitative comparison between a predicted pattern of climate-driven actual erosion vs. CRN-derived erosion (Fig. 1c) and our empirical record of CRN-derived denudation rate variability (Fig. 6e), and documented stratigraphic evidence for major environmental changes in Panamint Valley (Figs. 5 & 6), suggests that glacial-interglacial climate transitions have an observable effect on CRN-derived denudation rates and sediment flux in unglaciated catchment-fan systems.

We observe variability in depositional environments and CRN-derived paleodenudation rates in sediments deposited after the middle Pleistocene transition. Though we cannot rule out CRN-derived denudation rate variability during the early Pleistocene, as preserved in the sparsely sampled lower portion of the PCC, we may compare our record to other CRN-derived paleodenudation records measured across climate transitions in unglaciated catchments. Climate cooling and increased variability across the Plio-Pleistocene transition did not affect CRN-derived paleodenudation rates in southern California or Kentucky, USA (Oskin et al., 2017; Granger et al., 2001). However post-middle-Pleistocene CRN-derived paleodenudation rates from Fisher Valley, Utah, between ca. 0.6 – 0.7 Ma, varied by as much as 2x, and are up to 2x higher than modern rates (Balco and Stone, 2005). Periglacial processes in the Pacific Northwest United States lead to increased CRN-derived denudation rates during the last glacial maximum compared to the Holocene (Marshall et al., 2015), and interglacial climates increased CRN-derived denudation rates via enhanced chemical weathering in unglaciated catchments on the Texas Gulf Coast (Hidy et al., 2014). Others have documented major changes in sedimentary processes regimes across multi-millennial timescale climate transitions that produced measurable variability in CRN concentrations (*e.g.* Garcin, et al., 2017).

Thus two tentative and related hypotheses may be drawn that explain observations from the PCC and from published literature: (1) 100 kyr Milankovitch periods are more efficient than 41 kyr periods at modulating sediment flux, and thus CRN concentrations in unglaciated systems, and (2) that variability in CRN-derived denudation rates is potentially the result of changes in process regimes, rather than steady state erosion rates, across climate transitions. These hypotheses make testable predictions and represent opportunities for future research related to climate-surface dynamics.

5.2 Limitations to Interpretation of CRN-derived Signals from Alluvial Fan Stratigraphy

Changes in measured CRN-derived denudation and sediment supply apparent in our record allude to catchment response to climate change. However, we acknowledge that several limitations of the CRN methodology pose challenges to assessing the true magnitude and variability of paleodenudation/sediment flux signals emitted from Pleasant Canyon. First, we note that alluvial fans may experience allogenic or autogenic driven erosion-deposition processes, introducing potential stratigraphic incompleteness and/or preferential stratal preservation (Armitage et al., 2011; D'Arcy et al., 2016; Straub and Esposito, 2013). A second challenge relates to theoretical constraints on the CRN technique. True denudation rates may only be measured using CRNs where steady state between catchment erosion and CRN flux has been reached (Bierman and Steig, 1996). In the context of Milankovitch climate forcing, a catchment's CRN export may never equilibrate to the true denudation rate/sediment flux, especially during punctuated climate events (Fig. 1c). As a result, CRN-derived denudation signals extracted from alluvial stratigraphy may be out of phase and dampened compared to actual denudation/sediment flux. Last, it is plausible that the resolution of sampling for this study does not capture other periods of high or low paleodenudation/sediment supply that were recorded in alluvial stratigraphy (as in the lower portion of the PCC, *e.g.* Fig. 6).

Potential stratigraphic incompleteness, long CRN lag times, and sample resolution limit definitive interpretations of our data set. However, normal-fault bound, rapidly subsiding alluvial basins likely represent the most complete archives of past continental surface dynamics (Straub and Esposito, 2013), highlighting the value of these data. Furthermore, long CRN lag times may suggest that our highest CRN-derived rates actually represent minimum estimates for true denudation rates. In other words, it is likely that catchment-fans experience buffering or dampening of the CRN-derived signal of climate-forced sediment flux (as in Fig. 1c). We propose that future studies utilizing valuable alluvial fan records should consider potential stratigraphic completeness and sample resolution as first order controls on robust data interpretation.

5.3 Unsteady Catchment Processes and Denudation Signal vs. Noise

It remains challenging to relate changes in apparent sediment transfer to specific external forcings, even in well-constrained natural systems (*e.g.* Balco and Stone, 2005). Here, we consider the potential for noise in the record, which we define as variability driven by up-system non-equilibrium processes, *e.g.* complex sediment storage and remobilization or mass wasting in the catchment. Consider two end-member scenarios: (1) thin (several m thick) and relatively old (>15 – 20 kyr since bedrock denudation) deposits stored within the upper catchment acquire a large post-erosion CRN concentration, and when remobilized, become mixed with sediment of average concentration, resulting in depressed apparent denudation rates, and (2) localized mass wasting within the catchment supplies sediment with relatively low CRN concentrations, which when mixed with sediment of average CRN concentration, results in an increase of apparent paleodenudation rate. We prescribed plausible CRN concentrations to sediment from each scenario — stored sediment or landslide-derived sediment — and applied a binary end-member mixing model to estimate the relative contribution from each source necessary to drive variability equal to the highest and lowest CRN-derived denudation rates from the PCC (See Supplementary material S3 for complete explanation).

Figure 7 shows a conceptual illustration of processes that could impart noise in the paleodenudation record, as well as the results of mixing high- and low-CRN concentration sediment with average CRN concentration sediment. This analysis suggests that our lowest denudation rate (24 mm/kyr) requires ~48% of sediment to be derived from a high-concentration, recycled deposit, whereas the highest calculated paleodenudation rate (54 mm/kyr), requires ~56% of sediment to be derived from a low-concentration source, presumably representing landslide-derived material.

We observe no evidence in the upper catchment of significant fluvial incision and terrace development that might be expected for $>10^4$ yr old deposits. Thus mixing of significant amounts of old stored sediment (at least 48%) may be unlikely. In the case of the second scenario, mixing of large proportions (~56%) of mass-wasting derived sediment is difficult to evaluate; the high-relief and short length-scale of the system may suggest paleodenudation variability in the high end could be driven by episodic mass wasting. Similar proportions (~50%) of landslide-derived sediment were deduced from ^{10}Be concentrations found in some fluvial systems after widespread coseismic landslides associated with the 2008 Wenchuan earthquake (West et al., 2014). Yet another plausible scenario is that wetter, colder Pleistocene climates lead to enhanced rates of mass wasting in the PCC (*e.g.* Marshall et al., 2015; D'Arcy et al., 2016). Detailed quantitative sedimentological analyses could potentially help resolve these outstanding hypotheses. Still, our analysis of catchment-fan sediment transfer through time and end-member sediment mixing models represent a novel perspective on the role of climate transitions in modulating sedimentary process regimes and catchment-fan sediment transfer.

6.0 CONCLUSIONS

We measured cosmogenic radionuclides (CRNs; ^{26}Al and ^{10}Be; n = 13 samples) vertically through a succession of outcropping Pleistocene alluvium, and in modern sediment (n = 2 samples) from a linked catchment-fan system to examine the effects of climate change on magnitude and temporal variability of CRN-derived denudation rates and source-to-sink sediment transfer. Full glacial climates in the Panamint Valley region were ~5 – 6 °C colder, and the area experienced ~50 – 100% more precipitation relative to the Holocene (D'Arcy et al., 2016, and references therein), conditions that resulted in major pluvial lake formation in Panamint Valley as deduced from lacustrine strata preserved in the Pleasant Canyon Complex (PCC). Many of the resultant paleodenudation measurements from the PCC are similar in magnitude over the period of interest (ca. 1.5 Ma through ca. 0.3 – 0.6 Ma), with a mean rate of 36 ± 8 mm/kyr (1σ). However, paleodenudation and modern denudation rates do display maximum variability of +50%/-33%, respectively, from the mean long-term denudation rate. Modern CRN-derived denudation in Pleasant Canyon (24 ± 1 mm/kyr) is systematically lower than all Pleistocene paleodenudation rates, suggesting climate plays a fundamental control on sedimentary process regimes in catchment-fan systems. Simulated erosion-CRN concentration lag times suggest that the highest measured CRN-derived paleodenudation rates (49 – 54 mm/kyr) from the PCC may represent minimum estimates of true catchment paleodenudation. We explored other potential drivers of denudation variability, specifically sediment recycling and sediment derived from localized landslides in the catchment. An end-member mixing model suggests a proportion >50% of low-CRN-concentration landslide-derived sediment is required to mix with average concentration sediment to produce the highest denudation rates in our record. Sample age resolution prevents us from delineating specific relationships between paleodenudation magnitude and specific Milankovitch cycles — still, our paleodenudation record within a framework of documented lithofacies associations preserved in the PCC depositional segment suggests the highest CRN-derived paleodenudation rates occur in association with climatic transitions, *i.e.,* glacial-interglacial cycles. CRN-derived paleodenudation rates are highest and most variable in samples deposited after the middle Pleistocene transition — the change from 41 to 100 kyr periods — suggesting that 100 kyr periodicity in climate forcing may result in significant changes in sedimentary process rates and regimes within this, and other high-relief unglaciated catchment-fan systems globally.

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APPENDICIES

Supplementary material related to this article may be found online at…

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FIGURE CAPTIONS

Figure 1: Modeled changes in sediment flux (q_s per unit width) and erosion rate across two timescales (Myr and kyr), resulting from perturbations in climatic or tectonic boundary conditions in a catchment-fan system bounded by a range-front normal fault, and simulated imposed erosion rate plotted with resultant CRN-derived erosion rate. Time progresses from left to right in all plots. **a**: q_s response to stepwise increase (+100%, black line) or decrease (-50%, gray line) in precipitation rate. **b**: q_s response to stepwise increase (+100%, black line) or decrease (-50%, gray line) in fault slip rate. Dashed vertical red line indicates timing of change in forcing in parts a and b. Modified from Densmore et al. (2007). **c**: Simulated response of cosmogenic radionuclide (CRN) derived erosion rates to a change in actual (imposed) erosion

rate. The duration of the simulation is similar to that of middle to late Pleistocene Milankovitch periods of 100 kyrs. Green solid line represents user defined erosion rate, and blue dashed line represents the model output, or CRN-derived erosion rate through time. ^{10}Be production rate for simulation as described in main text and code described in Garcin et al. (2017).

Figure 2: Study area shaded relief map, regional paleoclimatic reconstruction, and photopanorama of the Pleasant Canyon Complex (PCC). **a**: Topography, and active faults of the Panamint/Death Valley area. Pleasant Canyon catchment-fan system highlighted in red dashed lines. Extents of Pleistocene pluvial lakes of the Owens River system highlighted in dashed blue lines, and blue arrows denote pluvial lake flow directions into and out of Panamint Valley (Reheis et al., 2014). **b**: Last glacial maximum paleoclimatic reconstruction showing precipitation change for the western United States after Oster et al. (2015). **c**: Photopanorama of the PCC with locations of measured sections (Photo credit: Ron Schott). AHFZ = Ash Hill fault zone, Mid. Park = Middle Park Canyon, PEDF = Panamint Emigrant detachment fault, PVFZ = Panamint Valley fault zone. Fault data from U.S. Geological Survey Quaternary fault database. 1 arc second elevation data from the U.S. Geological Survey.

Figure 3: Pleasant Canyon catchment metrics. **a**: digital elevation model. **b**: Surface slope map. **c**: Areal distribution of lithology in the catchment. All units are quartz bearing except for the Sentinel Peak dolomite and probably the basalt/amphibolite unit (after Albee et al., 1981). **d:** Pleasant Canyon catchment hypsometry. Left y-axis represents total catchment area within each

bin, x-axis represents elevation of catchment increasing from left to right (100 equal bins, each 22.7 m), and right y-axis is the cumulative catchment area. 1 arc second elevation data from U.S. Geological Survey.

Figure 4: Lithofacies of the Pleasant Canyon complex**. a**, **b**: Horizontally laminated and low-angle cross-stratified sand and granule- to pebble-rich beds (lithofacies Sl, Sg) that compose a gradational transition in lithofacies from Lacustrine Lithofacies Association to Alluvial Lithofacies Association. Note thick gravel debris flow capping units in **b** (lithofacies Gc, Gm). **c** – **l**: dominantly fine-grained silt and clay (lithofacies F, Sl, Sg) that composes the Lacustrine Lithofacies Association. **c**: Pebble-granule-rich sand lithofacies (Sg). **d**: Laminated sand lithofacies (Sl). **e**, **f**: Fine-grained and pebble-granule rich lithofacies (Sf, Sg, and F), with small burrows or root-traces. **g**: interbedded fine-grained and granule-rich lithofacies (F, Sg). **h**: Sandy turbidites with contorted bedding (Sl). **i**: Laminated to cross-laminated sand with weakly developed paleosol (Sl). **j**: fine grained lacustrine lithofacies (F) with possible varves. **k**: Thick exposure (note person for scale) of fine-grained lithofacies (F, Sl) composing the Lacustrine Lithofacies Association in section one. **l**: Interbedded fine-grained and gravel lithofacies (F, Gm, Gc) that compose the Lacustrine (and Mixed) Lithofacies Association in Section Two. **m**, **n**: Interbedded clast- and matrix-supported debris flow gravels with lenticular to laterally continuous sands (lithofacies Gc, Gm, Sl, Sf) typical of the Alluvial Lithofacies Association.

Figure 5: Photomosaics and large-scale lithofacies associations and stratigraphic architecture of the Pleasant Canyon Complex (PCC). **a:** Uninterpreted photomosaic of the southwest PCC. **b**: interpreted photomosaic from part a, with colored lithofacies associations. **c**: Uninterpreted photomosaic of the northwest PCC with the ghost town of Ballarat in the foreground. **d**: Interpreted panel from part c illustrating subtle inclined geometries of progradational foresets within alluvial-lacustrine lithofacies. Lacustrine units pinch-out or grade into mixed or alluvial lithofacies associations up dip.

Figure 6a: Overview of the Pleasant Canyon complex (PCC) with schematic locations of measured lithostratigraphic sections and cosmogenic radionuclide (CRN) samples. **6b** – **e**: Pleistocene paleoclimate, PCC composite stratigraphic framework, burial ages, and paleodenudation rates since ca. 1.5 Ma. **b**: Global oxygen isotope curve of Lisiecki and Raymo, (2005), with known pluvial lake events in Panamint Valley shaded blue (after Jannick et al., 1991). **c**: Composite stratigraphic section with interpreted lithofacies associations and CRN sample numbers and positions. Blue shaded boxes indicate stratigraphic position of Lacustrine Lithofacies Associations. **d**: CRN-derived burial ages vs. composite stratigraphic height, **e**: CRN-derived paleodenudation rates vs. composite stratigraphic height beginning at ca. 1500 kyr. Dashed vertical lines are mean and standard deviation (1σ) of all paleodenudation rates. Modern catchment denudation rates are plotted at 5 meters height and shown with red circles. Individual sample error bars represent the average of upper and lower bounds (1σ) on burial age-erosion rate calculations (after Craddock et al., 2010). Refer to text and Supplementary Materials for explanation of composite stratigraphic framework.

Figure 7: Conceptual model and binary mixing model results. 7a: catchment-fan system with low CRN-concentration (red) landslide derived material, and high CRN-concentration (blue) stored/recycled material. 7b: Curves represent synthetic ^{10}Be-derived denudation rates associated with a given mixture of either low CRN-concentration landslide-derived sediment (red curve), or high CRN-concentration stored/recycled sediment (blue curve), with ‘average’ concentration sediment that experienced a mean erosion rate of ~36 mm/kyr.

Table 1: Corrected AMS results, ^{26}Al and ^{10}Be burial ages and denudation rates for samples from the Pleasant Canyon Complex and modern catchment outlets, Panamint Range and Valley, USA

Sample location information						AMS Results (blank corrected)				Burial ages and denudation rates			
sample ID	lat.	lon.	elevation (m asl)	depth (cm)	location	^{26}Al (a/g SiO_2)	*error	^{10}Be (a/g SiO_2)	error	$^{26}Al/^{10}Be$ burial age (yr)	† error (yr)	denudation rate (mm/kyr)	error (mm/kyr)
PAN01	36.02861	-117.21487	430	7000	PCC	1309759	43805	252927	6311	705,000	155,000	28	4
PAN02	36.0293	-117.21377	466	3400	PCC	1564624	55644	263806	9493	425,000	176,000	31	5
PAN03	36.0293	-117.21377	466	3400	PCC	1564426	77465	262072	7548	410,000	192,000	31	5
PAN04	36.02942	-117.21354	476	2400	PCC	1103834	40630	177904	5627	359,000	175,000	49	7
PAN05	36.0295	-117.21344	481	1900	PCC	1214501	48460	209390	6973	518,000	200,000	39	6
PAN06	36.02905	-117.21461	435	6500	PCC	1258579	64415	218528	7525	486,000	205,000	36	6
PAN07	36.03671	-117.21848	482	1800	PCC	1600021	59776	256047	6211	326,000	158,000	34	4
PAN08	36.03579	-117.21942	452	4800	PCC	1046392	51235	195296	5617	654,000	199,000	37	6
PAN09	36.03536	-117.22203	366	13400	PCC	671949	33194	160023	7205	1,164,000	252,000	34	6
PAN10	36.04724	-117.21092	412	…	Modern Pleasant Canyon	2225616	77950	362733	8772	…	…	24	0.6
PAN11	36.03868	-117.2192	482	1800	PCC	1341444	57291	245223	11679	645,000	248,000	31	6
PAN12	36.02749	-117.21577	390	…	Modern Middle Park	1637336	65025	287452	16818	…	…	28	1.6
PAN13	36.03493	-117.21848	448	5200	PCC	755308	29065	137675	6190	618,000	211,000	54	10
PAN14	36.02861	-117.21487	430	7000	PCC	1210537	60013	215151	8287	536,000	212,000	36	7
PAN15	36.04103	-117.22286	336	16400	PCC	471472	20247	134163	4084	1,549,000	223,000	34	5

*AMS measurement errors based on one standard deviation of analytical uncertainties

†Burial ages/denudation rate errors include analytical uncertainty and decay rate uncertainties for $^{26}Al/^{10}Be$ (Norris et al., 1983; Chmeleff et al., 2010).

SUPPLEMENTARY MATERIALS

Supplementary Text S1.0, S2.0, S3.0, References

Supplementary Figures S1, S2.1, S2.2, S3

Supplementary Data File "Supplementary AMS Data"

S1.0 CLAST PROVENANCE OF THE PLEASANT CANYON COMPLEX

Sediments preserved in deposits of the PCC were mainly derived from the Pleasant Canyon catchment, as indicated by the position of the deposit at the canyon mouth, the progradation direction of the PCC, a closed drainage in the upper portions of Middle Park catchment, and sediment provenance (clast compositions) in measured sections. Pleasant Canyon contains a unique geologic unit known as the World Beater complex, a foliated gneiss with well-developed augen porphyroblasts (Albee et al., 1981). The World Beater is not present in the Middle Park catchment; thus, the presence of World Beater clasts supports a model where sediment preserved in the PCC was derived largely from the Pleasant Canyon. We conducted reconnaissance-level field work to survey for the presence of this unique lithology in our measured lithostratigraphic sections; clasts of World Beater were ubiquitous at all levels of strata in outcrop, and in float along canyon floors, (Supplementary Figure 1). We are confident that sediment in the PCC was derived from Pleasant Canyon, and that the use of a catchment average production rate derived from the hypsometry of Pleasant Canyon is justified. We note Middle Park catchment probably contributed minor amounts of sediment to the PCC, but the small difference in catchment hypsometry only affects the production of CRNs to a minor degree (~1 atom/g SiO_2/yr) and thus we elect to use one catchment production rate for all rate and age calculations for samples from outcrop in the PCC.

S2.0 DEPOSITIONAL LITHOFACIES OF THE PLEASANT CANYON COMPLEX

We used data from measured lithostratigraphic sections to construct depositional lithofacies and lithofacies associations for units in the PCC (after Miall, 1985; Blair and Mcpherson, 2008; Blair and McPherson, 2009). The following sections describe lithofacies associations and their interpreted lithofacies components. Example lithofacies and lithofacies associations are pictured in Figure 4, and the large-scale stacking patterns of lithofacies associations are presented in Figure 5.

S2.1 Alluvial Lithofacies Association

Alluvial fan lithofacies are ubiquitous within the PCC, and are similar to those described in previous publications (*e.g.* Blair and McPherson, 2009). In the PCC these lithofacies are composed primarily of cobble to boulder conglomerates interbedded with thin clean to muddy sand beds of varying lateral continuity (Figure 4m, n).

Lithofacies Gm: matrix supported gravel conglomerate

Lithofacies Gm is found throughout the PCC in continuous to laterally discontinuous beds of 10 cm to >1-3 m thickness. Gm matrix is brown to greyish green, sand- to silt-sized grains, with pebble- to cobble- to boulder-sized angular to subangular clasts. Lithofacies Gm usually lacks internal structure, but may contain faint stratification. Lithofacies Gm is interpreted to be the product of pseudoplastic, unconfined to channelized mud-supported debris flows.

Lithofacies Gc: clast supported gravel conglomerate

Lithofacies Gc is found throughout the PCC, and is often laterally continuous to discontinuous over 1s to 10s of meters, can be <10 cm to >3 m in thickness, is composed of angular and subangular pebble to boulders, with interstitial sand- and silt-sized grains. Clasts may be imbricated with evidence for bedload traction structures and faint stratification. Matrix in Gc is typically fine to coarse sand with little mud present. Lithofacies Gc is interpreted to be water-lain debris flow deposits, reworked debris-flow material, or sieve deposits. Gc is pictured in Figure 4m.

Lithofacies Sg: Granule-pebble rich sand

Lithofacies Sg occurs in the transition from fine-grained units to conglomerate alluvium in Section One in the south PCC. Granule- to pebble-rich coarse to medium sand in beds 10 cm – >1 m thick are faintly laminated or contain low-angle cross stratification. Traction structures indicate a water-lain origin, either subaerial or subaqueous deposition, while the association of these lithofacies to fine-grained lithofacies (discussed below) indicates a possible shallow lacustrine origin. Facies Sg is pictured in Figure 4a.

Lithofacies Sh: horizontally laminated or structureless sand

Lithofacies Sh is found throughout the PCC in laterally continuous to discontinuous beds ranging from 1 cm up to 3 m thickness. Laminations of very fine to medium-upper sand may be graded, or display load structures and deformation along bed contacts. Faintly bedded to structureless sand may exist in association with laminated beds. Lithofacies Sh is interpreted to represent unconfined sheetwash deposits in distal alluvial environment, possible waning stage subaerial dilute sediment flows. Lithofacies Sh is pictured in Figure 4a, d, and h.

S2.2 Lacustrine (and Mixed) Lithofacies Association

The Lacustrine Lithofacies Association is defined by finely laminated to featureless beds of fine silt to clay, and in section one, several meters of rhythmically bedded sandy turbidites. Lithofacies Sh, F, and Sg are the most common facies in the Lacustrine Lithofacies Association, and are pictured in Figure 4d – j.

Mixed lithofacies are present in both Alluvial and Lacustrine Lithofacies Associations, thus the term Mixed Lithofacies does not refer to a specific depositional environment, but rather an association of two mixed environments of deposition, stacked in vertical succession. Where fine-grained units interpreted as lacustrine (F, Sl) are interbedded with sands (Sl, Sg), and coarse-grained gravel conglomerates (Gc, Gm), we interpret a shallow or ephemeral lake with rapidly fluctuating environment of deposition. Examples of the Mixed Lithofacies are pictured in Figure 4a, 4b, and in the upper 1/3 of Figure 4k, and 4i.

Lithofacies F: Fine silt to clay

Lithofacies F crops out in laterally-continuous (100s m to km) deposits across the PCC, specifically in Section Two at ~115 – 119 m, and in Section One at ~19 – 28 m above the base of sections. Lithofacies F contains $CaCO_3$ and reacts to HCl, is white or greyish green or yellow in color, and composed of very fine sand, silt and clay-sized grains. sparse disarticulated ostracod or gastropod(?) fossils are observed in thin section. Bedforms include mm to cm scale horizontal, wavy, and crinkly lamination, minor ripple cross laminations, and reddish siderite filled root traces or burrows. Lithofacies F is commonly interbedded with Gm, and grades into Sf, Sl, and Gc, Gm up section. Lithofacies F is interpreted to represent a shallow to deep lacustrine environment. The complexity of preserved bedforms and dominant grain size argues against deposition in a fluvial or alluvial environment. Lithofacies F might best be termed a lacustrine marl.

Lithofacies Sc: horizontally laminated and contorted sand beds

Subaqueous sandy turbidity currents, stacked in sets of normally graded beds displaying contorted laminae, or dewatering structures. Sandy turbidites are subaqueous deposits interpreted to represent relatively deep lacustrine depositional environments. Lithofacies Sc is pictured in Figure 4h.

Lithofacies Gcr: rounded clast supported gravel conglomerate

Lithofacies Gcr is found at only one location, in the base of Section One (southern PCC; Figure 5). Gcr has the same sedimentary characteristics as Gc, with the notable difference of abundant subrounded to rounded pebble to cobble clasts and little matrix or when present loose coarse-grained sand and granule matrix. We interpret facies Gcr as wave reworked beach gravel deposits. Modern gravels near catchment outlets are typically angular with little rounding of clasts.

S3.0 SUPPLEMENTARY TEXT FOR MIXING MODEL

S3.1 Mixing model

We used a simple two-component (binary) mixing model to estimate proportions of various sediment sources necessary to drive observed CRN-derived paleodenudation variability. The CRN concentration (^{10}Be) in a binary mixture is dependent upon the starting concentration of end members ($C_{A, B}$) and the proportions of each end member present in a mixture (f_A):

$$(Eq. S1)\ C_m = C_A f_A + C_B(1 - f_A)$$

where C_m is the concentration of the binary mixture. We specified end-member concentrations (explained below), mixed end members, and used the resulting ^{10}Be concentration of mixed sediment, and the standard steady state catchment denudation equation (See Fig. 1 in Granger and Schaller, 2014) to calculate a denudation rate associated with each calculated mixed value of C_m. Supplementary Figure 3 shows the sensitivity of calculated denudation rate to prescribed end member concentrations. Lower CRN concentrations represent landslide-derived sources, and higher CRN concentrations represent stored sediment sources.

S3.2 Justification for end member CRN concentrations used in mixing model

The CRN-concentrations used in our mixture model were prescribed based on several factors: (1) the value assigned to the 'average' sediment fraction is based on the mean paleodenudation rate of the catchment, *i.e.* 36 mm/kyr, which corresponds to ~2.5×10^5 atoms $^{10}Be/g\ SiO_2$, (2) the value of the 'stored sediment' end member is twice the average concentration (5×10^5 atom/g SiO_2), and was estimated using a beginning 'average' concentration for a theoretical deposit, and assuming exposure for ~15 kyr near the surface at elevations of ~1800 – 2000 m asl, where production rates range, but are approximately 16 atoms $^{10}Be/g\ SiO_2$/yr (we do not consider decay of ^{10}Be to be important at this timescale), and finally, (3) for the mass wasting-derived CRN concentration, we assumed relatively shallow mass failures (~1 – 3 m depths) that may entrain other material such as pre-existing regolith and bedrock, and we assigned this end member a value of 1x10^5 a/g SiO_2. We acknowledge concentrations of mass wasting derived sediment may be extremely variable and dependent on the depth of detachment (Yanites et al., 2009). We also acknowledge that the resultant proportions of stored or mass wasting derived sediment necessary to drive denudation variability are dependent upon the prescribed CRN concentrations. Supplementary Figure S3 shows the sensitivity of ^{10}Be-derived denudation rates associated with a range of end-member concentrations, and highlights the necessity for mixing of significant proportions (>35 – 45%) of any modeled end member sources with average concentration sediment to drive the magnitude of variability observed in the PCC.

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Supplementary Figure Captions

Supplementary Figure S1: Clasts of augen gneiss (World Beater complex) unique to the Pleasant Canyon catchment are found throughout measured sections of the Pleasant Canyon complex, in float and *in situ* within outcrops. **a**, **b**: Well-formed feldspar augen porphyroblasts in clasts of World Beater found in float in section 1. **c**, **d**: Examples of World Beater clasts found in outcrop in section 1.

Supplementary Figure S2.1: Correlations of lithostratigraphic measured sections and cosmogenic radionuclide (CRN) sample location within the Pleasant Canyon complex (PCC). **a**: Photomosaic of outcrops of the PCC with CRN sample locations marked with red filled circles and associated text with sample numbers. White arrows denote samples taken from catchment outlets and modern CRN-derived denudation rates. **b**: Simplified lithostratigraphic sections one and two from the PCC with CRN results placed within stratigraphy.

Supplementary Figure S2.2: **a**: Syndepositional normal fault (~NW-SE striking) in north wall of Middle Park Canyon, approximately 200 m south of Section One. **b**: close up of three to five meters of throw on a steep normal fault (shown as dashed red line), down toward the basin in part S2.2a. Subsidence via active normal faulting in part explains the expanded lacustrine strata in the southern Pleasant Canyon complex.

Supplementary Figure S3: Sensitivity of calculated denudation rates to prescribed end member CRN concentrations and relative mixing proportions. Red curves show proportion of low-CRN concentration mass-wasting derived sediment of various concentrations required to produce highest denudation rate. Blue curves show proportion of high-CRN concentration stored/recycled sediment of various concentrations required to produce lowest denudation rate. Bold curves represent values used in the main text. Horizontal grey dashed lines are the measured maximum (54 mm/kyr) and minimum (24 mm/kyr) denudation rates for the Pleasant Canyon complex.

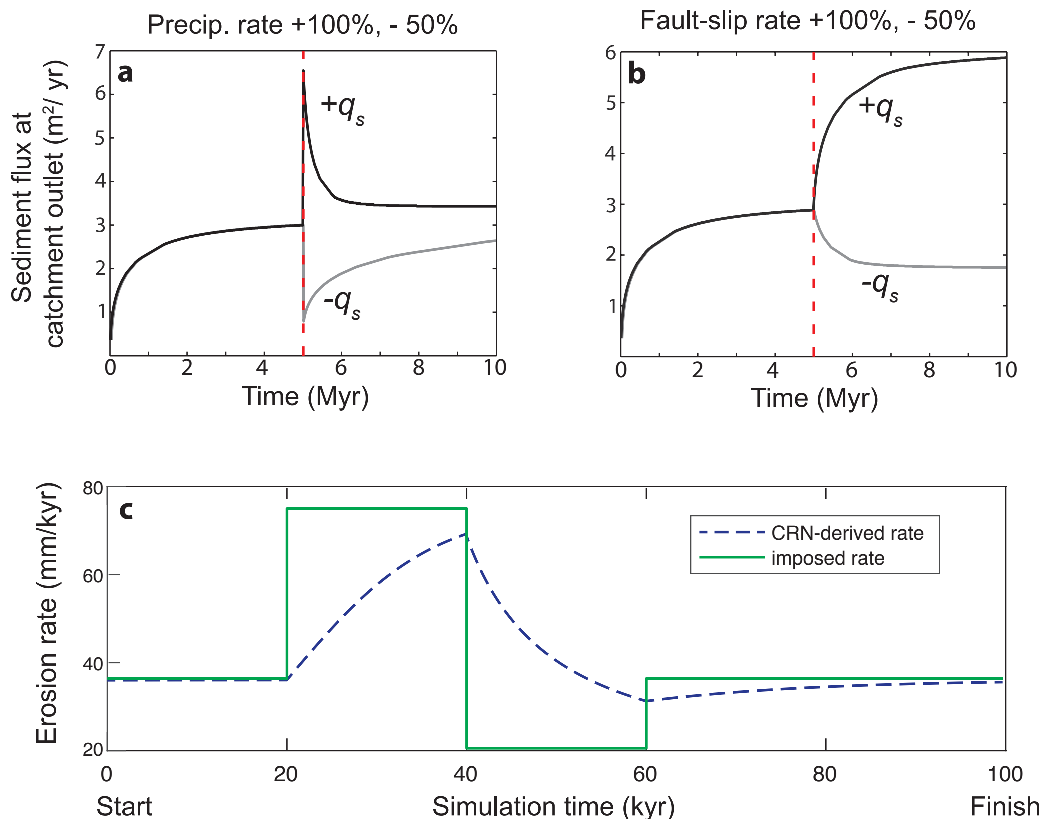

Precip. rate +100%, - 50%
a
Sediment flux at catchment outlet (m²/ yr)
+q_s
-q_s
Time (Myr)
Fault-slip rate +100%, - 50%
b
+q_s
-q_s
Time (Myr)
c
Erosion rate (mm/kyr)
CRN-derived rate
imposed rate
Start
Simulation time (kyr)
Finish

Figure 1

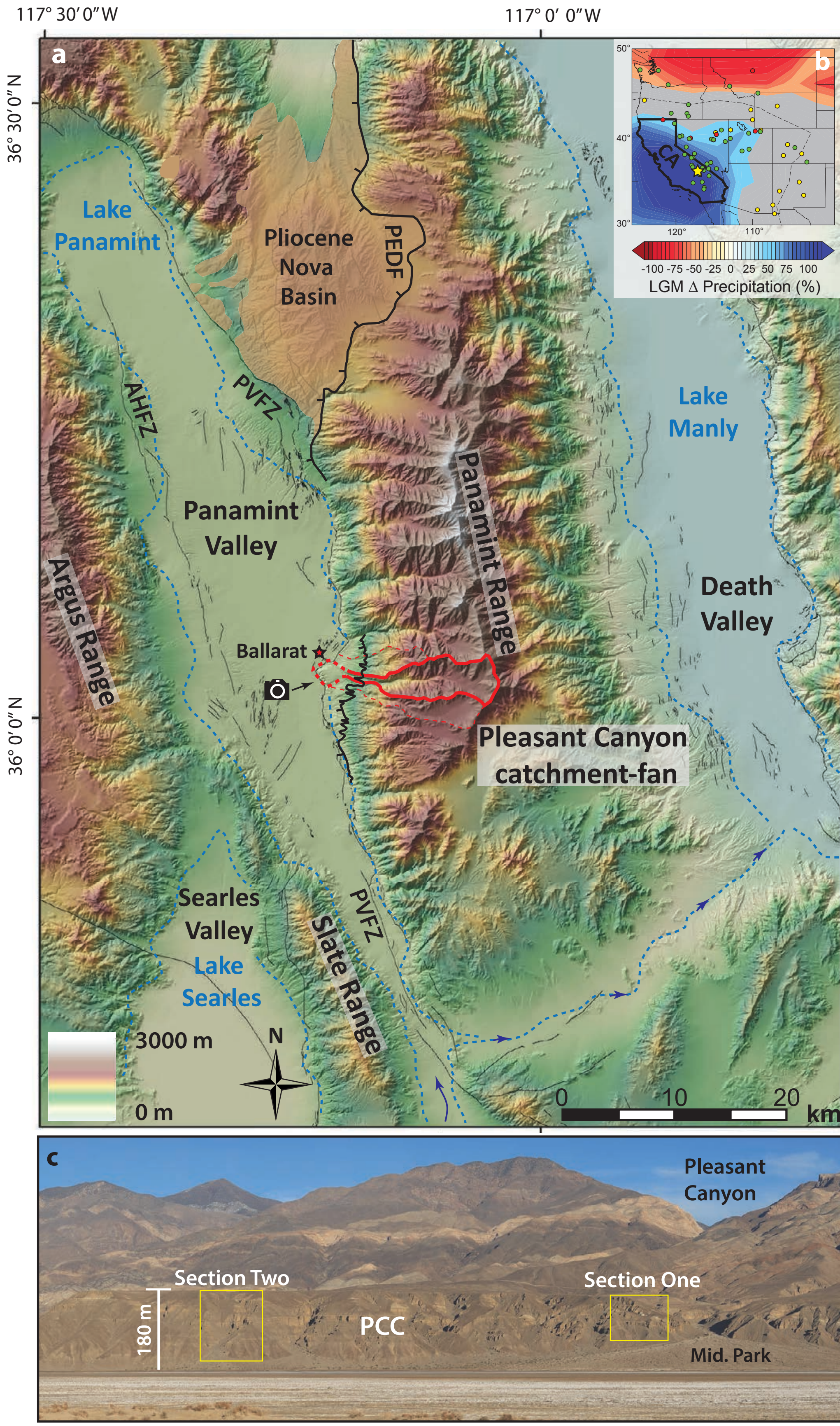

117° 30′ 0″ W
117° 0′ 0″ W
36° 30′ 0″ N
36° 0′ 0″ N
a
b
Lake Panamint
Pliocene Nova Basin
PEDF
PVFZ
AHFZ
Panamint Valley
Argus Range
Panamint Range
Lake Manly
Death Valley
Ballarat
Pleasant Canyon catchment-fan
Searles Valley
Lake Searles
Slate Range
PVFZ
3000 m
0 m
N
0
10
20
km
CA
-100 -75 -50 -25 0 25 50 75 100
LGM Δ Precipitation (%)
c
Pleasant Canyon
Section Two
Section One
PCC
180 m
Mid. Park

Figure 2

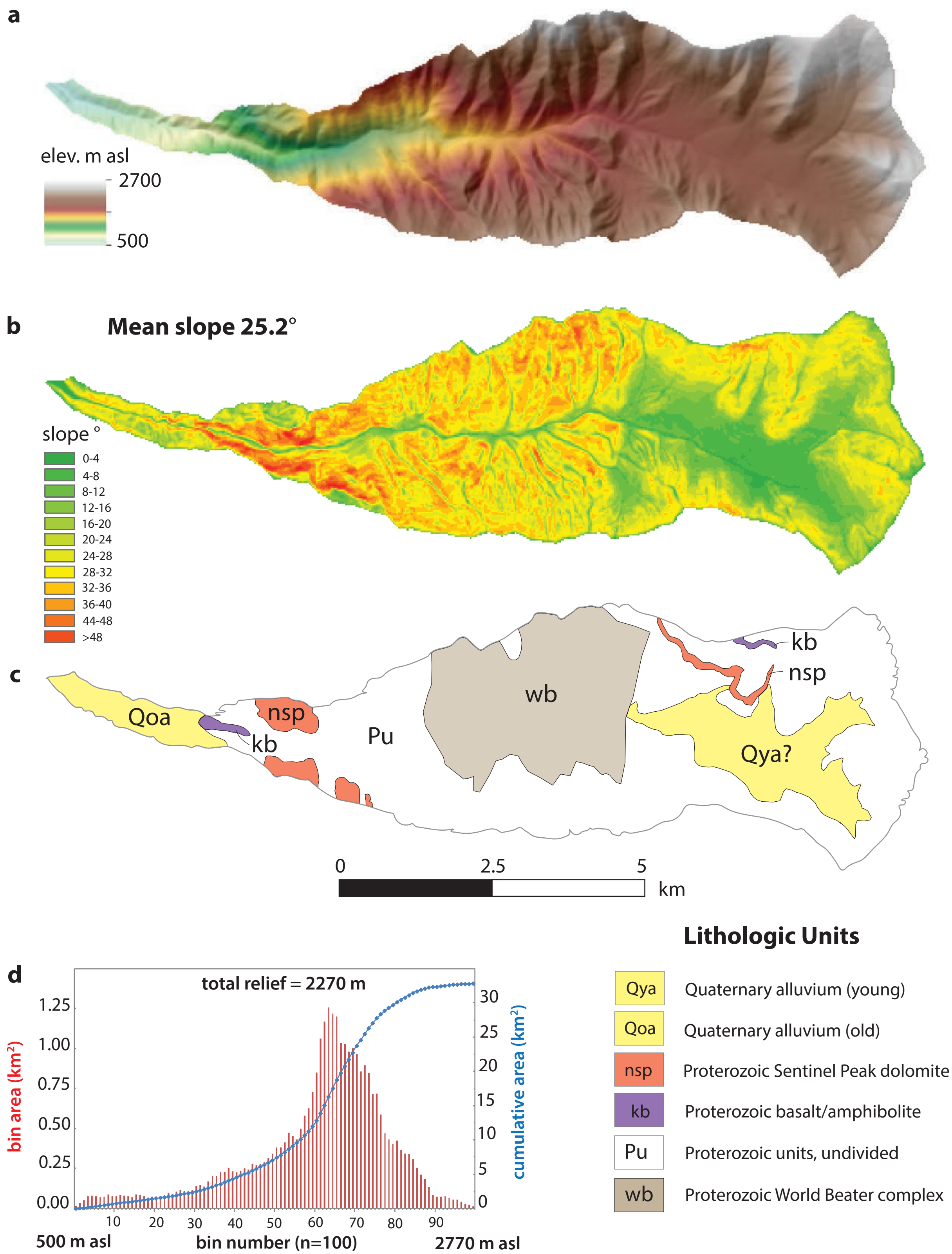

a
elev. m asl
2700
500
b
Mean slope 25.2°
slope °
0-4
4-8
8-12
12-16
16-20
20-24
24-28
28-32
32-36
36-40
44-48
>48
c
Qoa
kb
nsp
Pu
wb
kb
nsp
Qya?
0
2.5
5
km
Lithologic Units
Qya
Quaternary alluvium (young)
Qoa
Quaternary alluvium (old)
nsp
Proterozoic Sentinel Peak dolomite
kb
Proterozoic basalt/amphibolite
Pu
Proterozoic units, undivided
wb
Proterozoic World Beater complex
d
total relief = 2270 m
bin area (km²)
cumulative area (km²)
500 m asl
bin number (n=100)
2770 m asl

Figure 3

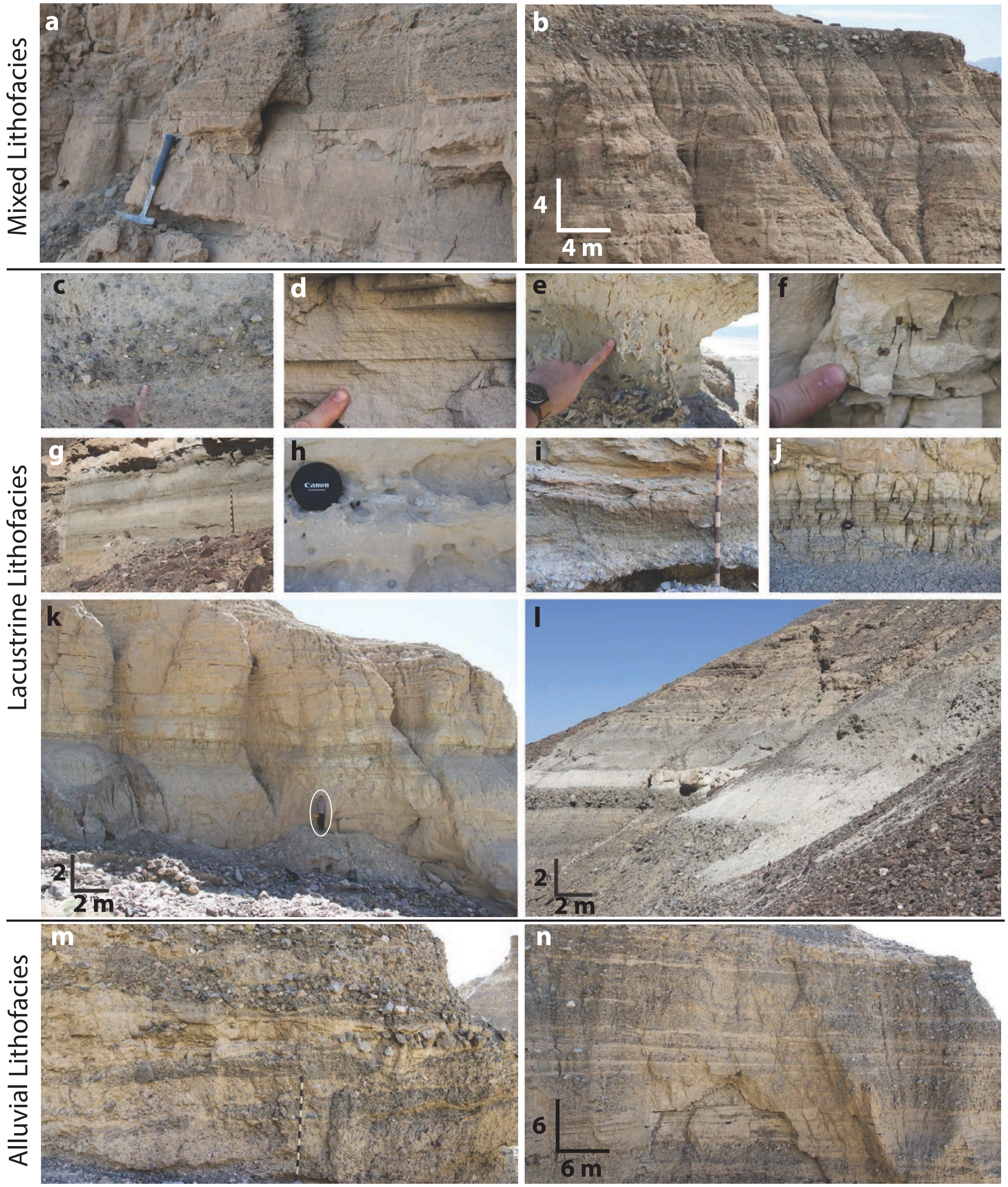

Mixed Lithofacies
Lacustrine Lithofacies
Alluvial Lithofacies
a
b
c
d
e
f
g
h
i
j
k
l
m
n
4
4 m
2
2 m
2
2 m
6
6 m
Canon

Figure 4

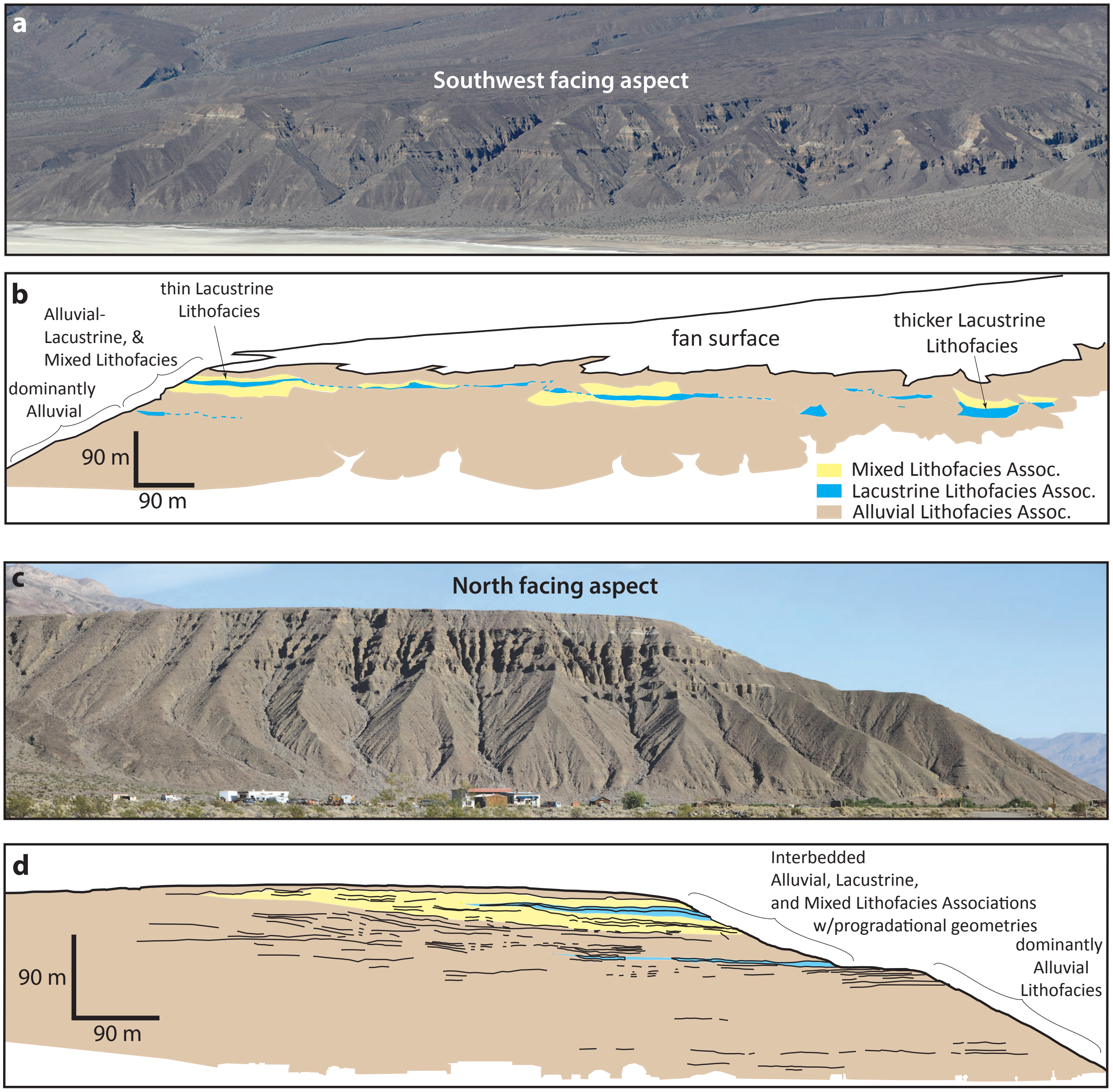

a
Southwest facing aspect
b
thin Lacustrine Lithofacies
Alluvial-Lacustrine, & Mixed Lithofacies
dominantly Alluvial
fan surface
thicker Lacustrine Lithofacies
90 m
90 m
Mixed Lithofacies Assoc.
Lacustrine Lithofacies Assoc.
Alluvial Lithofacies Assoc.
c
North facing aspect
d
Interbedded Alluvial, Lacustrine, and Mixed Lithofacies Associations w/progradational geometries
dominantly Alluvial Lithofacies
90 m
90 m

Figure 5

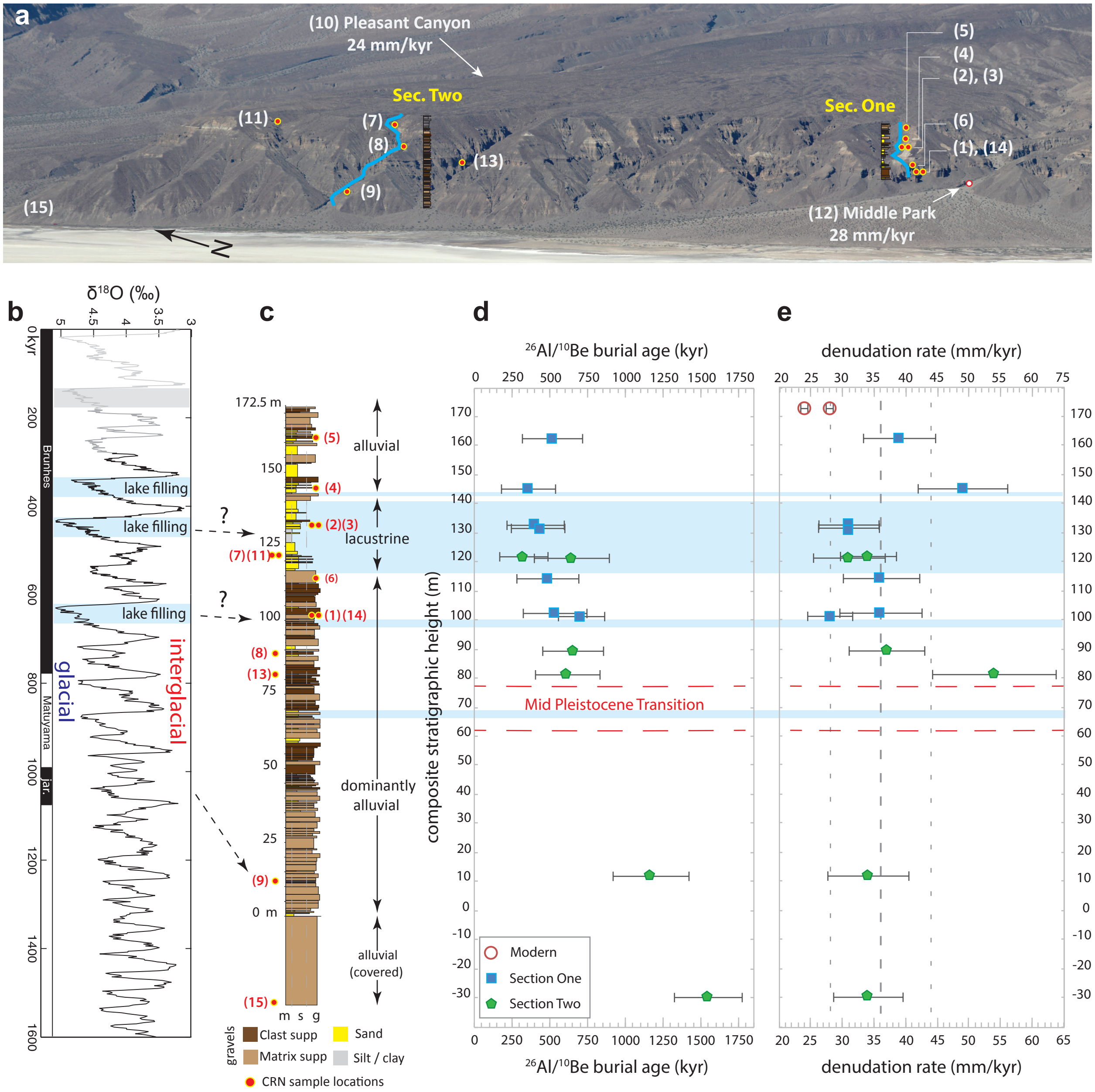

a
(10) Pleasant Canyon
24 mm/kyr
Sec. Two
Sec. One
(5)
(4)
(2), (3)
(6)
(1), (14)
(11)
(7)
(8)
(9)
(13)
(15)
(12) Middle Park
28 mm/kyr
N
b
δ18O (‰)
lake filling
lake filling
lake filling
interglacial
glacial
Brunhes
Matuyama
Jar.
c
172.5 m
alluvial
lacustrine
dominantly alluvial
alluvial (covered)
Clast supp
Matrix supp
Sand
Silt / clay
gravels
CRN sample locations
d
26Al/10Be burial age (kyr)
composite stratigraphic height (m)
Mid Pleistocene Transition
Modern
Section One
Section Two
e
denudation rate (mm/kyr)

Figure 6

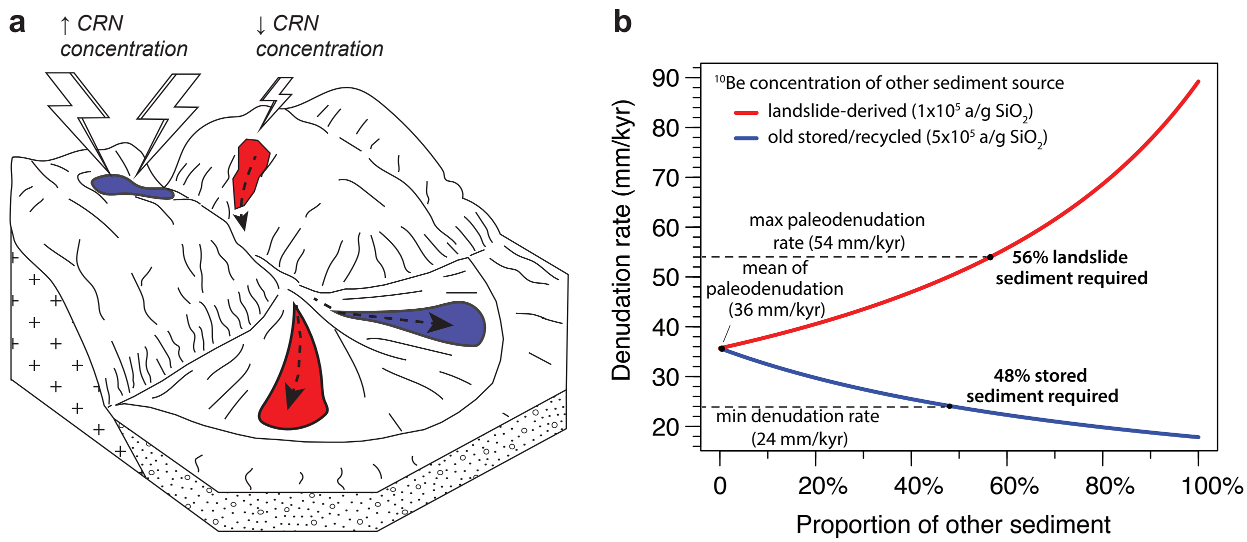
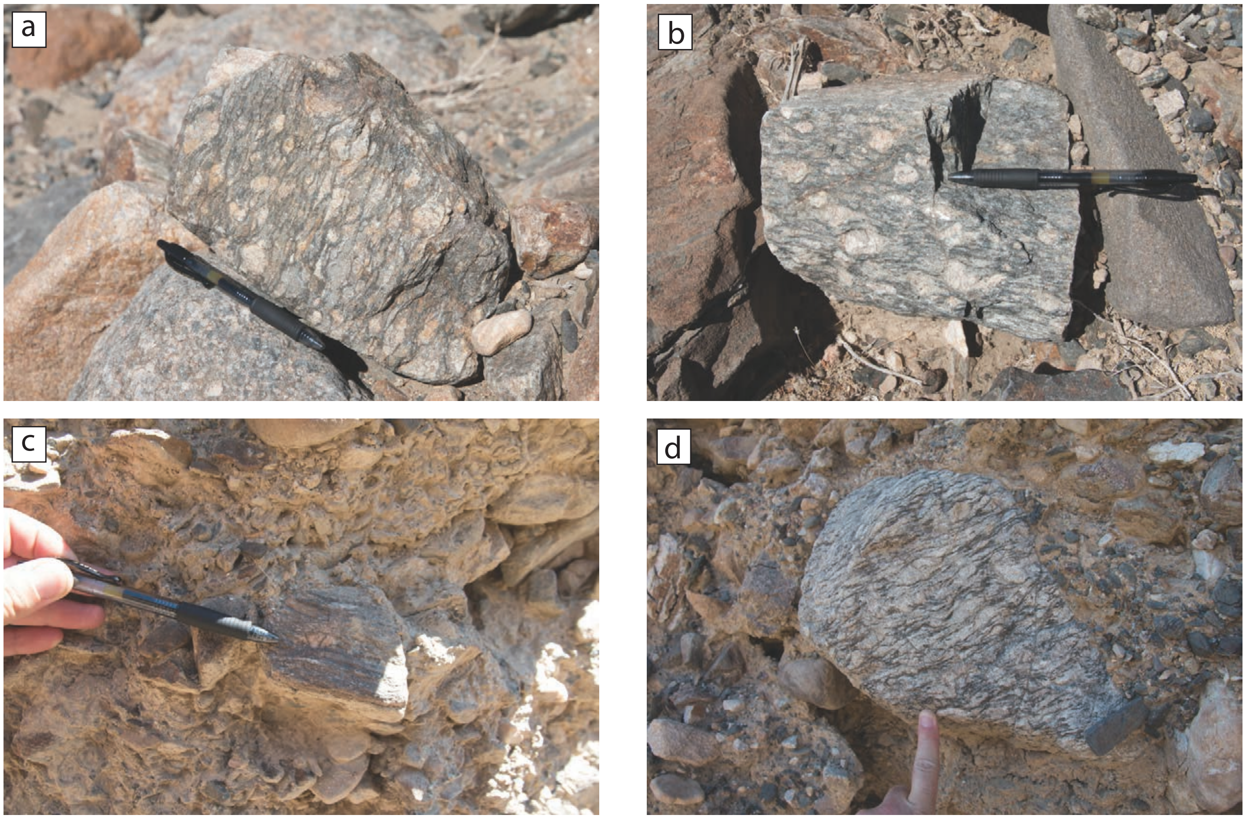
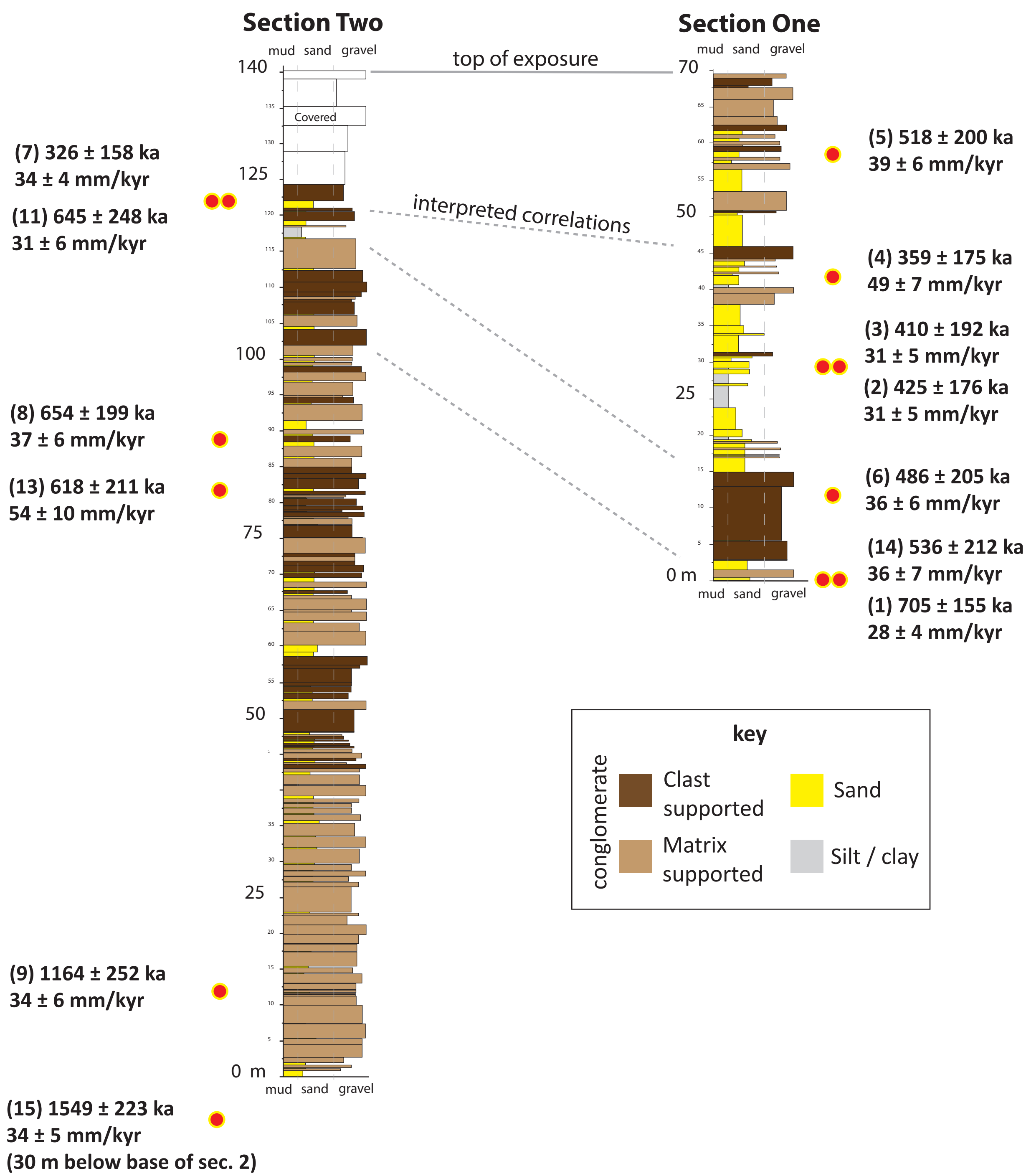

a
↑ CRN concentration
↓ CRN concentration
b
^{10}Be concentration of other sediment source
landslide-derived (1x10^5 a/g SiO$_2$)
old stored/recycled (5x10^5 a/g SiO$_2$)
max paleodenudation rate (54 mm/kyr)
mean of paleodenudation (36 mm/kyr)
56% landslide sediment required
48% stored sediment required
min denudation rate (24 mm/kyr)
Denudation rate (mm/kyr)
Proportion of other sediment
90
80
70
60
50
40
30
20
0
20%
40%
60%
80%
100%

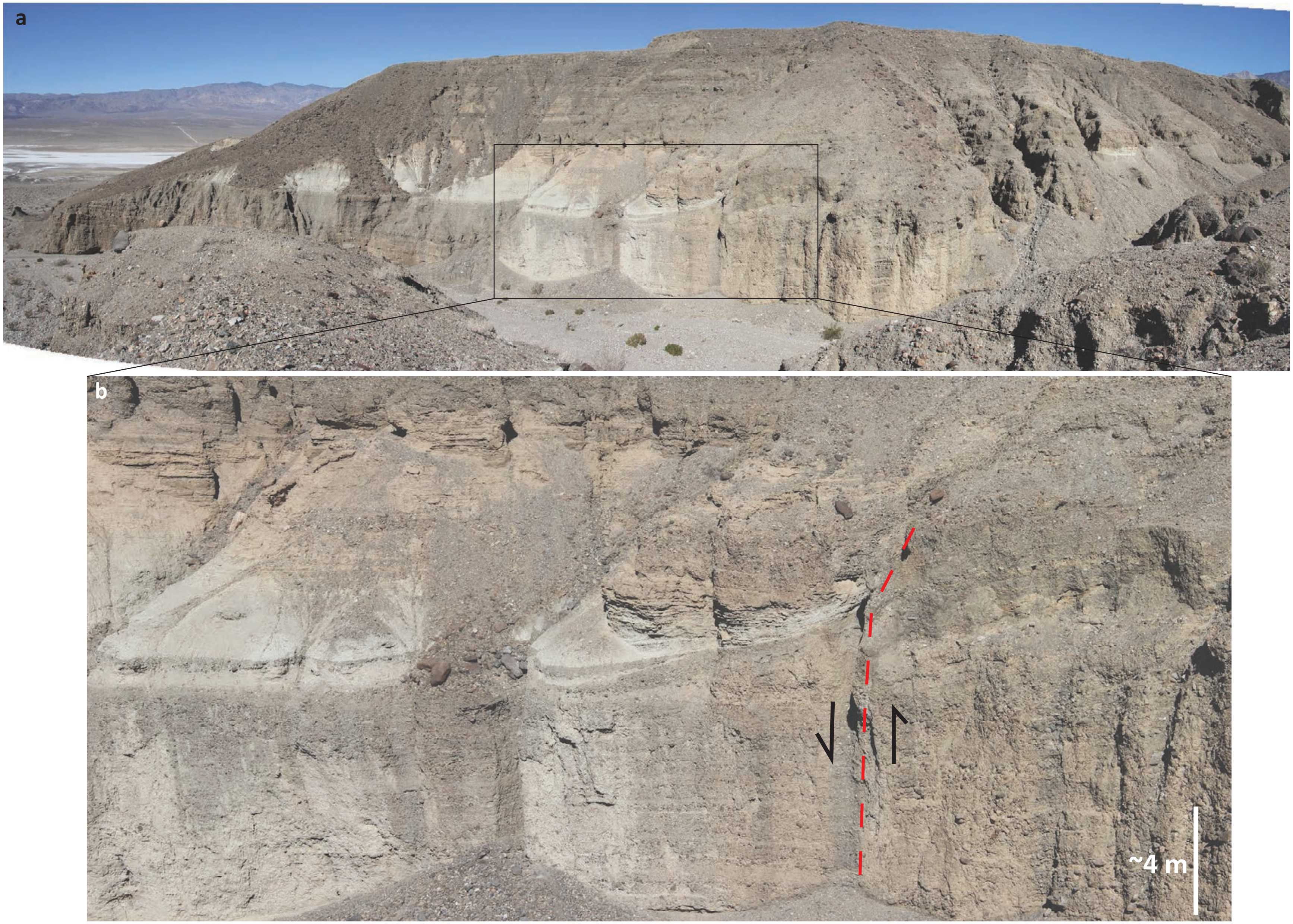
Figure 7



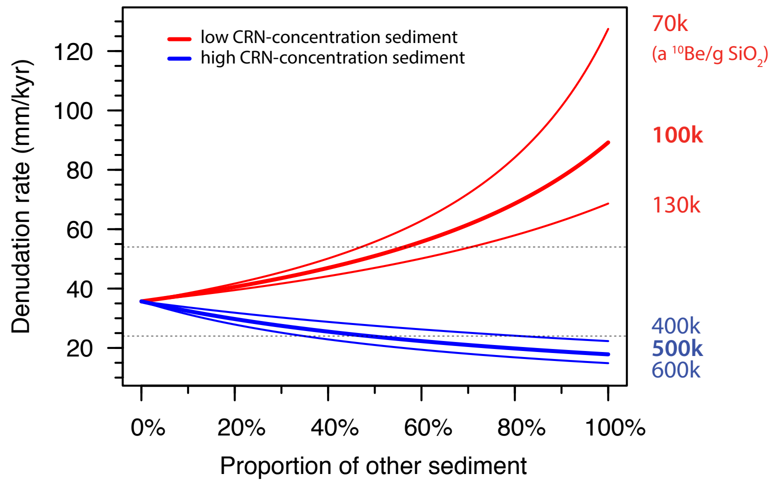
Suppl. Figure S1



Suppl. Figure S2.1



Suppl. Figure S2.2



Suppl. Figure S3