Measuring alluvial fan sensitivity to past climate changes using a self-similarity approach to grain size fining, Death Valley, California

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Abstract

The effects of climate change on eroding landscapes and the terrestrial sedimentary record are poorly understood. Using mountain catchment-alluvial fan systems as simple analogues for larger landscapes, a wide range of theoretical studies, numerical models and physical experiments have hypothesised that a change in precipitation rate could leave a characteristic signal in alluvial fan sediment flux, grain size, and down-system fining rate. However, this hypothesis remains largely untested in real landscapes. In this study, we measure grain size fining rates from apex to toe on two alluvial fan systems in northern Death Valley, California, which each have well-exposed modern and ~ 70 ka surfaces, and where the long-term tectonic boundary conditions can be constrained. Between them, these surfaces capture a well-constrained temporal gradient in climate. We adapt a grain size fining model, based on self-similarity and selective deposition, for application to these alluvial fans. We integrate this model with cosmogenic nuclide constraints on catchment erosion rates, and observed grain size fining data from two catchment-fan systems, to estimate the change in sediment flux from canyon to alluvial fan that occurred between mid-glacial and modern interglacial conditions. In a fan system with negligible sediment recycling, a ~30% decrease in precipitation rate led to a ~20% decrease in sediment flux and a clear increase in the down-fan rate of fining, supporting existing landscape evolution models. Consequently, this study shows that small mountain catchments and their alluvial fan stratigraphy can be highly sensitive to orbital climate changes over < 10⁵ year timescales. However, in the second fan system we observe that this sensitivity is completely lost when sediment is remobilised and recycled over a time period longer than the duration of the climatic perturbation. Our analyses offer a new approach to quantitatively reconstructing the effects of past climate changes on sedimentation, using simple grain size data measured in the field.

1. Introduction

The terrestrial stratigraphic record is widely recognised as a valuable archive of information about past environmental change, including the history of major controls on sedimentation such as climate, tectonics and erosion (Molnar & England, 1990; Heller and Paola, 1992; Paola et al., 1992a; Blum & Törnqvist, 2000; Allen, 2008a). Changes in sediment volumes and characteristics delivered to basins, driven by temporal and spatial variations in these boundary conditions, are therefore translated into sedimentary deposits with varying degrees of preservation (Humphrey and Heller, 1995; Castelltort and Van Den Driessche, 2003; Jerolmack and Paola, 2010; Duller et al., 2010; Whittaker et al., 2010; Simpson and Castelltort, 2012; Foreman, 2014). While qualitative descriptions of sedimentary facies produced as result of these drivers are a mainstay of sedimentary research (Bull, 1991; Blair and McPherson, 1992; Blair 1999; Harvey et al., 1999; Castelltort et al., 2011; Huyghe et al., 2012; Nagel et al., 2013; Ballato and Strecker, 2014), in principle it should be possible to decode aspects of this physical record quantitatively for past environmental change (Robinson and Slingerland, 1998, Allen, 2008a). Alongside geomorphological analyses (DiBiase and Whipple, 2011; Whittaker, 2012; Champagnac et al., 2012; 2014; D'Arcy & Whittaker, 2014; Herman et al., 2014; Salcher et al., 2014), the ability to quantitatively invert terrestrial sediment characteristics as a function of past climate would, (i) enable us to constrain the magnitudes, timescales and impacts of past environmental change on the Earth's surface (Romans et al., 2009; Duller et al., 2012, Allen et al., 2013; Foreman, 2014); (ii) allow us to determine how sensitive eroding landscapes are to past climate, particularly when compared with tectonic drivers (Bull, 1991; Armitage et al., 2013; Allen et al., 2013; Michael et al., 2013; Ballato and Strecker, 2014; Schildgen et al., 2016); and (iii) give new insights into the erosional-depositional response of landscapes to future climate changes over a range of timescales and magnitudes (Pepin et al., 2010; Armitage et al., 2011; 2013; Simpson and Castelltort, 2012).

However, in practice it is difficult to extract past climatic information from the stratigraphy produced by real eroding landscapes. This is partly due to the potential for signal shredding and interference by self-organised criticality, autogenic processes, and chaotic behaviour within sediment routing systems themselves (Hallet, 1990; Humphrey and Heller, 1995; Clarke et al., 2010; Jerolmack and Paola, 2010). Such effects may mean that climate changes are not translated into a 'clean' sediment flux signal at a catchment outlet (Simpson and Castelltort, 2012; Armitage et al., 2013; Forzoni et al., 2014); indeed these signals may be highly damped and thus landscape response times to perturbation may be long (Castelltort and Van Den Driessche, 2003; Allen, 2008b; Jerolmack and Paola, 2010, Whittaker and Boulton, 2012). The sedimentary record is also fundamentally a selectively-sampled record of past surface fluxes over a depositional basin, with varying preservability (Fedele and Paola,

2007; Schumer and Jerolmack, 2009; Whittaker et al., 2010; Allen et al., 2013), so sediments may best record past environmental change only where accumulation rates are high. Finally, different drivers of the surface process system, such as tectonics and climate, may produce similar stratigraphic responses. For instance the progradation of coarse wedges of gravel into a basin may be marker of a changing tectonic boundary conditions (e.g., Jones et al., 2004; Allen and Heller, 2011; Whittaker et al., 2010; Parsons et al., 2012), but may equally represent changes in rainfall or storminess (e.g., Duller et al., 2012; Armitage et al., 2013; Foreman, 2014). While diagnostic differences between these competing scenarios have been suggested from theoretical considerations (Allen and Heller, 2011; Armitage et al., 2011), applying these to real stratigraphic examples over long spatial scales where exposure is incomplete remains a significant challenge.

One solution to these issues is to collect field data that measure the sensitivities of sediment routing systems to climate changes in carefully-selected locations where boundary conditions are well-constrained and where some of the above problems can be eliminated or controlled. Coupled mountain catchments and alluvial fans are good systems to study for three main reasons (Bull, 1964; Hooke, 1968; Whipple and Traylor, 1996; Allen and Hovius, 1998); firstly, while their catchment processes include a range of sediment transfer functions (from hillslope sediment sources to the sediment flux at the fan apex), their geometry is both simple and tractable (Allen and Densmore, 2000; Armitage et al., 2011). Secondly, alluvial fans are often volumetrically-closed landforms with high sedimentation rates, comprising terraces of different ages that can be easily dated using exposure techniques (c.f., D'Arcy et al., 2015). Finally, small sediment-routing systems are likely to capture the effects of climatic or tectonic changes with greater sensitivity. They are likely to have shorter response times than large catchments (Castelltort and Van Den Driessche, 2003; McPhillips et al., 2013) and they may be less affected by the signal shredding and damping issues mentioned above (Allen, 2008b; Armitage et al., 2013).

Field studies have described a number of examples of alluvial fans aggrading during periods of enhanced precipitation and incising during subsequent drier conditions when sediment supply is depleted, for example in the south-western United States (Bull, 1991; McDonald et al., 2003; Spelz et al., 2008; Miller et al., 2010; Antinao & McDonald, 2013) and in Peru (Steffen et al., 2009, 2010; Bekaddour et al., 2014). In these cases, alluvial fans have responded to climate changes during the last glacial-interglacial cycle and hence the implied catchment response time is on the order of 10^3 - 10^4 years. Similarly, McPhillips et al. (2013) demonstrated that erosion rates and sediment fluxes in catchments along the western Peruvian Andes were greater during stormier parts of the Pleistocene with greater effective runoff, compared to the Holocene. Recent studies have also pointed to the role of rapid climate

changes in modulating the architecture and grain size of terrestrial sedimentary deposits. Waters et al. (2010) sampled grain size from late Pleistocene stream-flow dominated alluvial fan deposits in Cyprus, and found that coarser gravel was clearly deposited during periods of wetter climate. Further back in time, the deposition of coarse, prograding conglomerates in Colorado, Wyoming, and the Pyrenees has been attributed to abrupt ($\sim 10^4$ to 10^5 year) warming during the Palaeocene-Eocene Thermal Maximum (Foreman et al., 2012; Allen et al., 2013; Foreman, 2014). These studies generally agree that wetter climates promote greater sediment fluxes and coarser grain sizes, although uncertainties remain about the relative importance of storms compared to average precipitation (Miller et al., 2010; Antinao and McDonald, 2013), the role of vegetation in modulating sediment flux (Harvey et al., 1999; Pelletier, 2014), and autogenic processes (Paola et al., 2009; Clarke et al., 2010). It is important to note that some case studies show pulses of alluvial fan sedimentation during periods of arid climate, for example in the Mediterranean and Nevada (Harvey et al., 1999; Harvey, 2005). These uncertainties highlight the need for more case studies about alluvial fan dynamics and how rainfall rates translate into effective runoff rates. Nonetheless, in terms of their three-dimensional architecture it appears that alluvial fans are sensitive in at least some locations to high-amplitude climate changes over 10^3 to 10^5 year orbital timescales.

Numerical models and physical experiments also agree that alluvial fans might record climate changes in their stratal architecture and grain size distributions (e.g., Paola et al., 1992a; Allen and Densmore, 2000; Morehead et al., 2001; Densmore et al., 2007; Armitage et al., 2011; Rohais et al., 2012; Allen et al., 2013). In general, these models predict that doubling average precipitation rate would approximately double the sediment flux exported to an alluvial fan and trigger significant progradation of a coarse-grained deposit. A halving of precipitation rate causes the inverse response and is recorded by sediment fining, and in each case the climate change is preserved as a transient signal in fan stratigraphy. In these models, precipitation rate changes of 50 to 100 % typically generate measureable changes in the gravel fraction grain size exported to the fan. Consequently, climate changes of a similar magnitude to glacial-interglacial cycles may be expected to produce a macroscopic (> 10 mm amplitude) grain size signal locked into the sedimentary record and easily detected in the field (e.g., Allen and Densmore, 2000; Armitage et al., 2011; Allen et al., 2013). Likewise, physical analogue experiments also show that changing precipitation rate has a clear effect on landscape erosion and form (Bonnet and Crave, 2003), and that doubling precipitation rate causes increased sediment flux to an alluvial fan and a temporary spike of coarse sediment deposited (Rohais et al., 2012). These studies establish the clear hypothesis that climate changes should be recorded by both the sediment flux and grain size delivered to alluvial fan systems.

In this paper, we test this hypothesis explicitly using a combination of field measurements and numerical modelling of grain size fining (section 2). We examine two alluvial fan systems in northern Death Valley, California, which each have well-exposed and well-dated mid-glacial (~ 70 ka) and modern depositional units (Frankel et al., 2007a). Between the deposition of these fan surfaces, Death Valley experienced substantial climate changes associated with the last glacial-interglacial cycle (Phillips, 2008). We integrate a self-similarity approach to grain size analysis based on selective deposition with field observations and existing cosmogenic nuclide estimates of catchment-wide erosion rates, to quantitatively explore how past climate change and sediment recycling affected fan architecture and grain size in these simple sediment routing systems.

2. Grain size fining and the self-similarity model

Compared to a climatic signal being recorded by incision-aggradation sequences or catchment geomorphology, attempting to invert climate variables from sedimentary grain size brings several analytical advantages. Grain size can be measured easily in the field (even in very old deposits), and has an accessibility and preservation potential much greater than the three-dimensional architecture of an alluvial fan. It is known to record key information about sediment sources and transport (Whittaker et al., 2007; Duller et al., 2012; Attal et al., 2015) and boundary conditions such as tectonics and climate (e.g. Robinson and Slingerland, 1998; Whittaker et al., 2007, 2010; Allen and Heller, 2011; Waters et al., 2010; Foreman et al., 2012; Allen et al., 2013; Foreman, 2014; Allen et al., 2015). Additionally, grain size data can easily be represented as a quantitative time series that can be compared to tectonic or climatic proxies (Whittaker et al., 2011; Parsons et al., 2012; Michael et al., 2013).

Recently, a number of studies have shown that careful measurements of grain size and fining rates along discrete stratigraphic time-lines can be used to quantitatively decode stratigraphy for driving variables such as tectonically-driven subsidence or sediment flux (c.f., Paola and Martin, 2012). Focusing on ~ 40 Ma old Eocene alluvial fans in the Pobla Basin of the Spanish Pyrenees, Duller et al. (2010) were able to demonstrate that an increasing grain size fining rate along two time-lines in the basin fill related to a period of enhanced subsidence, driven by increased displacement on the basin-bounding thrust. Similarly, Whittaker et al. (2011) quantitatively related changes in grain size fining rate in upper Eocene and Oligocene stratigraphy of the south-central unit of the Spanish Pyrenees to tectonically-mediated variations in sediment supply and accommodation. Similar insights have also been gained from changes to grain size fining rate within the Sis conglomerate (Parsons et al., 2012). Recently, down-system changes in sediment calibre within a mass-balance framework have

been shown to reflect both the volume and grain size distribution supplied to the sediment routing system feeding the upper Cretaceous Castlegate sandstone in the western interior basin of the US (Hampson et al., 2014), and the mid-Eocene Escanilla Formation in north-eastern Spain (Michael et al., 2013; 2014).

Duller et al. (2010) and Whittaker et al. (2011) were able to invert stratigraphic grain size trends explicitly for tectonic subsidence and sediment supply variations using a self-similarity model for grain size fining, which was proposed in its current form by Fedele and Paola (2007). The modelling approach is described in detail by Fedele and Paola so only a brief account is given here. The existing model is a two-dimensional solution based on empirical observations that indicate the grain size distributions of stream flow-dominated deposits are self-similar. For gravel grain sizes, this means that the mean, $\bar{D}$, and standard deviation, σ , of surface and subsurface sediment both decrease at the same rate downstream (c.f., Paola et al., 1992b; Paola and Seal, 1995; Toro-Escobar et al., 1996; Duller et al., 2010; Whittaker et al., 2011). A similarity variable, ξ , for gravels can thus be defined as:

$$\xi = \frac{D - \bar{D}}{\sigma} \quad [1]$$

where D is a given grain size, and $\bar{D}$ and σ are the local mean and standard deviation of the gravel sediments at any down-system distance, x . If self-similar, the shape of the gravel grain size distribution at any position along the length of the depositional system is the same when scaled by the similarity variable, ξ . Exploiting this self-similarity, the modelling approach of Fedele and Paola (2007) uses a version of a fractional Exner sediment mass balance (c.f., Toro-Escobar et al., 1996) to account for particle transfer between the transporting system and deposited stratigraphy, and to describe the extraction of sediment along the length of the depositional system. The rate of change of a grain size fraction in the deposit, f , as a function of dimensionless distance down-system, x^* , can therefore be expressed as:

$$\frac{df}{dx^*} = f \left[R^* \left(1 - \frac{1}{J} \right) \right] - \frac{1}{J} \frac{dJ}{dx^*} \quad [2]$$

where J is a relative mobility function ($J = p/f$, where p is the fraction of a given sediment size in the transport system), and R^* represents the spatial distribution of deposition downstream, which can be expressed in two-dimensional form as:

208

$$209 \quad R^*(x^*) = (1 - \lambda_p) L \frac{r^*(x^*)}{Q_S(x^*)} \quad [3]$$

210

211 where λ_p is sediment porosity; L is the total length of the sediment routing system in
 212 downstream direction x ; $r^*(x^*)$ is the spatial distribution of tectonic subsidence; and $Q_S(x^*)$
 213 is the sediment flux at any down-system distance. Numerical modelling suggests that the form
 214 of J is also approximately self-similar (Fedele and Paola, 2007; Duller et al., 2010), so this
 215 means that down-system sediment extraction can be collapsed via J . Moreover, both f and J
 216 can therefore be expressed as functions of ξ . It is important to stress that the spatial distribution
 217 of deposition, R^* , represents the relative distribution of sediment mass down-system, due to
 218 selective extraction into stratigraphy. It can therefore be determined directly from stratigraphic
 219 data (c.f., Whittaker et al., 2011). To find deposit grain size for any value of $R^*(x^*)$, a
 220 dimensionless distance transformation $y^*(x^*)$ is used, which integrates the downstream
 221 distribution of sediment mass R^* as a function of dimensionless down-system distance:

222

$$223 \quad y^*(x^*) = \int_0^{x^*} R^*(x^*) dx^* \quad [4]$$

224

225 The mean grain size of gravel, $\bar{D}$, at any down-system distance can be expressed as an
 226 exponential function of y^* and it is therefore explicitly linked to R^* (Fedele and Paola, 2007):

227

$$228 \quad \bar{D}(x^*) = \bar{D}_0 + \sigma_0 \frac{C_2}{C_1} (e^{-C_1 y^*} - 1) \quad [5]$$

229

230 In this case, $\bar{D}_0$ and σ_0 represent the mean and standard deviation of the size distribution of
 231 the sediment supply at the initial point of deposition, and C_1 and C_2 are constants that express
 232 the relative partitioning of the variability in gravel supply arising from systematic down-system
 233 change in mean grain size (C_2) compared to the at-site variation (C_1) (Fedele and Paola, 2007;
 234 Whittaker et al., 2011). This ratio can be approximated by measuring the coefficient of variation
 235 of the grain size distribution in the supply:

236

$$237 \quad C_v = \frac{\sigma(x^*)}{\bar{D}(x^*)} = \frac{C_1}{C_2} \quad [6]$$

239 Values of constant C_1 used in previous studies lie between 0.5 and 0.8 (e.g. Duller et al.,
 240 2010), and numerical models suggest that $0.5 < C_1 < 0.9$ (c.f. Fedele and Paola, 2007). The
 241 coefficient of variation, C_v , for gravels is easy to measure from field data, and has been
 242 observed to lie between 0.7 and 1.0 (e.g. Fedele and Paola, 2007; Duller et al., 2010,
 243 Whittaker et al., 2010, Michael et al., 2013). Consequently, C_2 can also be calculated.

244 The sensitivity of this model to changing sediment flux and subsidence rate has been explored
 245 in previous studies (Duller et al., 2010; Parsons et al., 2012), and a key implication of equations
 246 3, 4 and 5 is that a larger sediment flux, relative to an unchanged rate of accommodation
 247 generation, would generate a slow grain size fining rate down-system, resulting in
 248 progradation and a coarsening of grain size at a particular down-system point in cross-section.
 249 For a system of fixed depositional length, this would result in increased sediment bypass, e.g.,
 250 to an axial river system. A decrease in sediment flux would generate a fast rate of grain size
 251 fining, relative retrogradation, a decrease in cross-sectional grain size at a particular point
 252 down-system, and reduced sediment bypass at the end of a system of fixed length.

253 This approach provides a clear opportunity to derive quantitative information about sediment
 254 fluxes and tectonic subsidence rate directly from grain size data. Advantageously, the model
 255 requires knowledge of only a small number of parameters (c.f., Whittaker et al., 2011): (i) the
 256 length of the depositional system, L ; (ii) the rate and spatial distribution of subsidence, $r * (x *$
 257 $);$ (iii) an estimate of sediment flux to the fan, Q_{s0} ; and (iv) knowledge of the input grain size
 258 distribution ($\bar{D}_0$ and σ_0). Limitations of the model include that assumption that grain size
 259 distributions are indeed self-similar and that fining is driven by selective extraction.
 260 Additionally, it is assumed that there are no down-system point sources of sediment with very
 261 different grain size. Here, we apply the self-similar grain size fining model to two alluvial fans
 262 in northern Death Valley that are well-suited to this type of analysis. They have well-exposed
 263 surfaces on which grain size fining can be measured all the way from fan apex to toe, and
 264 existing cosmogenic nuclide constraints on catchment-wide erosion rates allow us to break
 265 the coupled ratio between sediment flux and extraction in Eq. 3.

266

267 3. Study Area

268 3.1. Geomorphology and Tectonics

269 We examine two neighbouring catchment-fan systems along the eastern margin of northern
 270 Death Valley, eastern California (Fig. 1), which drain the Grapevine Mountains directly below
 271 Grapevine peak. These are the Backthrust canyon and Moonlight canyon systems, which have

similar geomorphology and total drainage areas of 46.2 km² and 36.7 km², respectively. The canyons drain south-westwards into the northern Death Valley extensional basin (the Mesquite flat), constructing ~ 6 km long coalesced alluvial fans mantling the western range front. These fans are shown in Fig. 1a, which is a contrast-enhanced LandSat 8 false colour composite (bands 642-RGB) in which modern deposits appear bright blue and older incised terraces appear red-brown. Both fans are toe-cut by the axial Death Valley wash.

Faulting in this area is dominated by extension, but this is distributed into two fault systems. The Northern Death Valley Fault Zone (NDVFZ) dissects the alluvial fan terraces (Fig. 1a) and has a small scarp visible in the field. This is a dextral strike-slip fault with a horizontal geologic slip rate of ~ 4.5 mm yr⁻¹ measured at this location (Frankel et al., 2007a). The Grapevine Fault Zone (GFZ) is a south-west-dipping normal fault system (Mabey, 1963; Reynolds, 1969; Niemi, 2012) located about 3 km north-east of the NDFVZ (Fig. 1a). The GFZ is the range-bounding fault system responsible for some of the relative subsidence/uplift between the alluvial fans and the catchments, however its age, throw, and throw rate are not fully constrained (Niemi, 2002). Nonetheless, the northern Death Valley basin contains deposits several kilometres thick, estimated using gravity data (Blakely et al., 1999), and as such the GFZ was evidently a major frontal fault system with substantial throw from the Pliocene onwards (Niemi, 2002). The GFZ is likely to be active, and Machette et al. (2002) estimate that it has a low slip rate of ~ 0.2 mm yr⁻¹. Additional subsidence is due to regional extension along a NNW-SSE axis (Reynolds, 1969; Klinger, 2001; Hammond et al., 2012), which is responsible for the complex placement of a strike slip fault near the frontal normal fault. Hammond et al. (2012) present detailed vertical motion constraints from interferometric synthetic aperture radar (InSAR) that reveal the average subsidence rate in central and northern Death Valley is ~ 0.5 mm yr⁻¹. We exploit these constraints as a starting point in our analyses, but our approach offers a new opportunity to refine estimates of both the rate and spatial variation of subsidence beneath our target alluvial fans, and we explore this as a topic of interest later.

The Backthrust and Moonlight canyon catchments have equivalent outcrop patterns of bedrock lithologies (Fig. 1b), which we have broadly classified into three groups: volcanics, carbonates, and conglomerates. Niemi (2012) provides a detailed geological map and full lithological descriptions. The majority of the catchments are eroding carbonates from the Bonanza King and Carrara formations, composed of Cambrian (and minor Ordovician-Devonian) limestones and dolostones with some siltstones and shales (Niemi, 2012). These carbonate hillslopes also have the steepest slopes (Fig. 1c), and provide the majority of sediment to the channels. The headwaters of the catchments have gentler slope distributions and are underlain by Miocene volcanics, comprising rhyolitic lavas, tuffs, and ash flows (Niemi,

2012; Fig. 1c). The lowermost parts of the catchments have extended basin-wards through partially consolidated conglomerates, likely of Pliocene age, that form local topographic relief (Niemi, 2012). Although sediment supply to the alluvial fans integrates these different sources, more than 80 % of the fan gravels are derived from carbonates, owing to the large extent and steep hillslopes of the carbonate bedrock.

The Backthrust and Moonlight canyon alluvial fans are dominated by channelized gravel deposits on two distinct depositional surfaces: modern deposits, and older raised surfaces mapped as Q2c in previous stratigraphic frameworks (Bull, 1991; Klinger, 2001; 2002; Frankel et al., 2007a; Niemi, 2012). Representative photographs of the alluvial fan surfaces are shown in Fig. 2. Photographs 2a and 2b are taken near the apices of both fans, looking upstream towards the catchments. The modern gravel surfaces (foreground) and raised Q2c terraces (marked by yellow triangles) are clearly visible. The modern surface is incising on both fans, but the magnitude of this incision is significantly greater on the Moonlight canyon fan. At the apex of the Backthrust canyon fan, the modern surface has only incised a few metres into Q2c, whereas on the Moonlight canyon fan this incision averages 40 m, with the Q2c surface forming a paved terrace at the top of a heavily dissected cliff, which provides a cross-section exposure of older alluvial fan conglomerates onto which Q2c aggraded. In this fan, the Q2c terrace is landsliding into the modern depositional surface, so there is clearly a significant recycling of material via steep scree cones and large blocks, visible on the right of Fig. 2b. Figure 3 shows the longitudinal profiles of the fan surfaces studied. The solid lines represent the modern surfaces and the dashed lines represent the Q2c terraces. From apex to toe, the Q2c surfaces have greater slopes than the modern surfaces, reflecting this recent incision. This difference is larger on the Moonlight canyon fan (4.3 ° on the Q2c surface, 3.8 ° on the modern surface), compared to the Backthrust canyon fan (with a difference in slope of only 0.1 °), reflecting the enhanced down-cutting observed on the Moonlight canyon fan. We therefore select these two fan systems as comparable examples where one (Moonlight canyon fan) has experienced substantial incision and recycling, and the other (Backthrust canyon fan) has not. We return to this comparison later.

Figures 2c and 2d show representative outcrop-scale photographs of the modern and Q2c surfaces as exposed on the Moonlight canyon fan near its apex. The modern surface is predominantly composed of carbonate gravels, pebbles and cobbles distributed by small channels with subtle topographic relief < 1 m. These channels are active during flash floods triggered by infrequent storms, reflecting the arid modern climate of Death Valley. Frankel et al. (2007a) documented debris flow deposits on the alluvial fans; we observed primarily channel deposition resulting from flash floods, and did not sample any boulder-rich levees that could be attributed to debris flows. Figure 2e shows a typical image of the modern deposits

used for characterising the grain size distribution (see Methods). The majority of the clasts are partially-rounded white/grey limestone and dolostone gravels and pebbles. The Q2c surface (Fig. 2d) has lost its original depositional relief due to desert pavement formation, and is composed of equivalent sediment to the modern deposits (Fig. 2f), only heavily oxidised and varnished, giving the terraces a rust-red colour and making them easy to distinguish. As is typical of desert pavements, the clasts are arranged in an interlocking pattern (Goudie, 2013).

Frankel et al. (2007a) dated the Q2c surface on both fans to 70 (+22 / -20) ka using ^{10}Be cosmogenic nuclide measurements. They analysed 16 samples in total, and we have reproduced their exposure age probability distributions here in Fig. 4. We note that Frankel et al. (2007a) used different names for the alluvial fans that do not correspond to the names of the parent canyons (Niemi, 2002; 2012). We have updated the fan names in this study, according to the map of Niemi (2012). As such, the Backthrust canyon fan is the 'Big Dip' fan of Frankel et al. (2007a) and the Moonlight canyon fan is the 'Red Wall' fan of Frankel et al. (2007a). This clarification is necessary because Red Wall canyon is actually the next canyon ~ 7 km south-east of Moonlight canyon. Figures 4a and b show the probability distributions for age estimates on each fan separately, with clear peaks centred at ~ 70 ka. The Moonlight canyon fan data include two inherited clasts, dating to ~ 120 ka and ~ 220 ka, presumably recycled from older aggraded units that were later remobilised. The presence of an inherited signal on this fan may be significant given that it also shows more evidence for incisional recycling of earlier deposits today, compared to the Backthrust canyon fan (Fig. 4a and b).

Frankel et al. (2007a) also combined the samples from each fan deposit, reproduced here as Fig. 4c, to calculate their final Q2c age estimate. It is reasonable to assume that the two Q2c surfaces were deposited co-synchronously, given the widespread occurrence of fan terraces dating to ~ 70 ka in Death Valley, e.g., the Indian creek fan (Frankel et al., 2007b), the Perry Aiken creek fan (Ganev et al., 2010), and the Hanaupah canyon fan (Machette et al., 2008). The uncertainty on the exposure ages spans from 50 ka to 92 ka, and we have highlighted this period of activity on the benthic Pacific $\delta^{18}\text{O}$ stack of Lisiecki and Raymo (2009) for comparison in Fig. 4d. Some of this variation in age will reflect a true range in the timescales of deposition of the Q2c surfaces, and it is also clear from Fig. 2 that sediment is being transported diffusively down-fan in braided channels that form a distributary network. The ^{10}Be data from Frankel et al. (2007a) and these field observations highlight a key advantage of studying these systems: the formation of these terraces integrates over a ~ 10^4 year depositional timespan and many transport events, thus avoiding anomalous climate fluctuations over sub-millennial timescales and making them suitable for characterising the mid-glacial climate state. As well as providing ^{10}Be exposure dates for the Q2c surface, Frankel et al. (2007a) also used two ^{36}Cl depth profiles to estimate the Q2c source area

erosion rate for the Moonlight canyon system. They obtained values of $46 \pm 9 \text{ mm ka}^{-1}$ and $83 \pm 10 \text{ mm ka}^{-1}$, giving an overall average erosion rate of $\sim 65 \pm 20 \text{ mm ka}^{-1}$ for this catchment at $\sim 70 \text{ ka}$.

3.2. Modern and Past Climate

Today, Death Valley has an arid desert climate, and records between 1911 and 2015 give a mean annual precipitation rate of 57 mm yr^{-1} and a mean temperature of $25 \text{ }^{\circ}\text{C}$ (Western Regional Climate Center, 2015). The valley occupies a powerful rain shadow created by the Sierra Nevada and White-Inyo mountain ranges to the west, and the entire catchment-fan systems are virtually un-vegetated apart from sparse desert scrub (Fig. 2). However, the south-western United States was cooler and wetter during the last glacial period, and Death Valley contained a large pluvial lake called Lake Manly (Blackwelder, 1933; Ku et al., 1998; Lowenstein et al., 1999). A variety of terrestrial palaeoclimate proxies from the region have constrained the Last Glacial Maximum (LGM) as between 5 and $6 \text{ }^{\circ}\text{C}$ colder, and 2 times wetter overall, than the present day. These include pollen records (Thompson et al., 1999), hydrological restorations of pluvial lakes (Menking et al., 2004), oxygen isotope data (Quade et al., 2003), and mass-balance models of former Sierra Nevada glaciers (Kessler et al., 2006). Given that Q2c deposition occurred during a benthic Pacific $\delta^{18}\text{O}$ value of ~ 4.0 to $4.5 \text{ }_{\text{‰}}$, halfway between the modern and LGM values of ~ 3.5 and $5.0 \text{ }_{\text{‰}}$, respectively (Fig. 3d; Lisiecki and Raymo, 2009), we assume that the Q2c climate excursion was half the LGM excursion, i.e., a temperature depression of 2 to $3 \text{ }^{\circ}\text{C}$ and an overall increase in precipitation of ~ 1.5 times, relative to present conditions. This is a reasonable assessment of the mid-glacial period at $\sim 70 \text{ ka}$ in the south-western United States. There are a number of other palaeoclimate records that support this interpretation, and we briefly summarise them here.

Well-dated pollen records are reliable indicators of past changes in moisture availability. For example *Juniperus* (juniper) pollen abundance has been shown to correlate well with orbital climate changes (Woolfenden, 2003). In Owens Valley—very close to our study area and also in the Sierra Nevada rain shadow—*Juniperus* pollen abundance is $\sim 25 \%$ at the timing of Q2c deposition, lying between end-member values for the LGM ($\sim 50 \%$) and the early Holocene ($\sim 10 \%$) (Woolfenden, 2003). This is observed in other assemblages in the south-western United States, for example warm-arid taxa have an intermediate abundance of 10 - 15% around 70 ka , compared to $\sim 20 \%$ today and 5 - 10% at the LGM (Jiménez-Moreno et al., 2007, 2010). Records using *Quercus* (oak), *Pinus* (pine), *Alnus* (alder), forest assemblages, herbs and shrubs, and other warm-arid assemblages all show intermediate conditions around 70 ka lying between interglacial and LGM end-member states (Adam et al., 1981; Whitlock

and Bartlein, 1997; Heusser, 1998, 2000; Jiménez-Moreno et al., 2007, 2010; Lyle et al., 2012).

Other proxies and archives give similar signals. Reconstructions of the groundwater table from calcite precipitation in the Amargosa Desert (very close to Death Valley) indicate that it was elevated by 5-6 m above modern from 50-100 ka, compared to 9 m above modern at the LGM, declining to 4 m above modern at the start of the Holocene and then current values today (Szabo et al., 1994). From the same area, the Devil's Hole $\delta^{18}\text{O}$ record shows an intermediate value of 14 ‰ at ~ 70 ka (compared to 13.5 ‰ at the LGM and 14.5 ‰ today), and this signal is highly correlated with moisture sources (Winograd et al., 2006; Oster et al., 2014). The rock flour content of several Owens Lake cores, which is an archive of glacial activity, shows a minor peak of ~ 50 % abundance centred on 70 ka, compared to ~ 70 % at the LGM and minimum values of ~ 20 % (Bischoff and Cummins, 2001; Benn et al., 2006). The CaCO_3 and Sr contents of lake cores also record past precipitation rates, occurring in lacustrine deposits as indicators of closed lake conditions due to low rainfall rates (Bischoff et al., 1997). In core OL-92, Bischoff et al. (1997) report intermediate CaCO_3 values of 10-15 % from 60-80 ka, compared to 5 % at the LGM and ~ 30 % at the start of the Holocene. Similarly, they report a Sr concentration of 250-300 ppm from 60-80 ka compared to < 100 ppm at the LGM and up to 1000 ppm at the start of the Holocene (Bischoff et al., 1997).

Interpreting records from pluvial lakes is complex because of transient overflow events between neighbouring valleys. For example raised shorelines in Panamint Valley indicate an overflow event from the Owens Valley-Searles Lake system between ~60-75 ka, which is a general indicator of wetter conditions, and at some points the system overflowed from Panamint Valley to Death Valley as well (Li et al., 2004; Machette et al., 2008; Phillips, 2008). Cores from Lake Manly deposits in the Badwater area of Death Valley show mudflat and salt pan deposits that do not indicate a wet period around 70 ka (Li et al., 1996, 1997; Lowenstein et al., 1999), however this is not conclusive evidence of climate because runoff from the Sierra Nevada may have stopped overflowing to Death Valley after ~ 130 ka (cf., Machette et al., 2008), thereby dramatically reducing the drainage area supplying the lake and resulting in a change in lacustrine facies regardless of the rainfall rate. Ku et al. (1998) identify a raised shoreline in Death Valley dating to around 80 ka despite mudflat deposits in lacustrine cores, and recognised the difficulty in reconciling these for information about local rainfall rate. Machette et al. (2008) suggest a shallow lake in Death Valley ~ 70 ka, but allude to the complexities of interpreting pluvial lake records in this area. Indeed, inverting lacustrine facies for palaeo-rainfall rates is not trivial, and when done accurately must also account for temperature change, evapotranspiration rates, groundwater flux, modulating factors like soil and vegetation, solar radiation, humidity and wind speed in addition to the significant drainage

reorganisations that have taken place (Menking et al., 2004). Furthermore, recent ^{36}Cl and U-series chronologies for pluvial lakes in Nevada very near to Death Valley suggest highstands at 10-25 ka (LGM) and 50-95 ka (mid-glacial), and it has been suggested that some local lacustrine chronologies may need to be re-evaluated (Kurth et al., 2011).

Nonetheless, the evidence for some overflow from the Owens Valley system (Li et al., 2004; Phillips, 2008), but a lack of very deep conditions in Lake Manly (Ku et al., 1998), offers general support for the interpretation of intermediate ~ 70 ka palaeo-rainfall rates lying between the LGM and modern end-member states, based on evidence from pollen, isotope, rock flour, carbonate and strontium archives/proxies, as well as pluvial lake, groundwater table and glacier modelling work described above.

4. Methods

i. Grain size sampling

The alluvial fan surfaces were sampled from the fan apices (at the Grapevine fault zone) to their toes (intersecting the axial Death Valley wash) at intervals of approximately 300 m (Fig. 1a). We used scaled, high-resolution photographs of channel deposits (e.g., Fig. 2e and f) to reconstruct the grain size distributions of the > 1 mm size fraction by Wolman point counting (Wolman, 1954). A range of studies have demonstrated that the grain size distribution of the gravel fraction can be characterised effectively using Wolman point counting of high-resolution photographs, and that this approach is equivalent to Wolman point counting in the field (Cowie et al., 2008; Duller et al., 2010; Whittaker et al., 2010; Michael et al., 2013; Litwin Miller et al., 2014). At each locality, a minimum of 6 photographs were taken of channel gravel deposits, to ensure representative coverage of the channel surface. We note that the channels on the fan surfaces braid and interact, forming a wide distribution surface (Fig. 2a to c), so it is not possible to follow one single channel from apex to toe. As such, our grain size measurements sample a variety of discrete sediment paths down the alluvial fans, making them representative of many individual flow events. Using all photographs taken at each site, the maximum diameters of 100 randomly-selected clasts were measured and compiled into a cumulative grain size distribution curve, from which the mean diameter, $\bar{D}$, and the standard deviation, σ , were calculated. These were then used to characterise the grain size fining rate from apex to toe. In Appendix 1, we evaluate the uncertainty associated with this method of characterising grain size distribution, and demonstrate that averaging 100 clasts is sufficient to obtain a mean grain size value within a precision uncertainty of $\sim 2\%$ in the majority of cases.

ii. Self-similarity analysis and model design

We apply the self-similarity equations of Fedele and Paola (2007) (see section 2) to the Backthrust and Moonlight canyon alluvial fan surfaces in a multi-step analysis, and we adapt them to predict sediment extraction and grain size fining in 3D across the fans.

The starting point is the ^{36}Cl cosmogenic nuclide estimate of catchment-wide erosion rate, ε , during the Q2c time period, provided by Frankel et al. (2007a). We use this erosion rate ($\sim 65 \text{ mm ka}^{-1}$) and the catchment areas, A , to estimate the sediment flux, Q_{S0} , exported to the alluvial fans during Q2c deposition. We combine this sediment flux, the observed Q2c grain size fining rates, the surface geometry of the alluvial fans, and the self-similarity equations of Fedele and Paola (2007), to derive the subsidence profile beneath the alluvial fans at this location. With this information, we then estimate the adjustment in sediment flux that is needed to explain the different grain size fining rate observed on the modern alluvial fan surface.

To accomplish this, we first adapt the equation for sediment extraction, $R^*(x^*)$ (Eq. 3) for application to three-dimensional alluvial fans. The volumetric extraction of sediment into stratigraphy is the multiple of the vertical subsidence profile creating accommodation and the horizontal distribution of sediment across the fan surface (Fig. 5). Therefore, we add an expression for how the fan width changes down-system into Eq. 3 such that:

$$R^*(x^*) = (1 - \lambda_p)L \frac{r^*(x^*)W^*(x^*)}{Q_s(x^*)} \quad [7]$$

where $W^*(x^*)$ represents the plan-view width of the depositional fan surface at each point x^* down the length of the fan. It is essential to make this modification when applying the equations to alluvial fan systems that distribute the input sediment flux at the fan apex, Q_{S0} , across a wide surface and many channels. This means it is impossible to know $Q_s(x^*)$ at any individual grain size sampling location without knowing the spatial distribution of sediment flux and integrated extraction upstream of that point. Furthermore, multiplying the cosmogenically-derived catchment-wide erosion rate by catchment area gives an estimate of Q_{S0} that is clearly averaged over many depositional events and a long integration time period. Over this long term, the locus of deposition will avulse across the fan surface, so it is entirely unrealistic to model the input sediment flux, Q_{S0} , as being deposited in one single two-dimensional path along the alluvial fan. Instead, the flux exported from the catchment must be distributed across

the active fan surface, and incorporating $W^*(x^*)$ into Eq. 7 acts to normalise $Q_s(x^*)$ in this way.

We calculate $Q_s(x^*)$ as the input sediment flux, Q_{s0} , minus the integrated volume of sediment deposited on the fan upstream of location x^* , which we equate to the accommodation created by the subsidence profile (i.e., we assume topographic steady-state):

$$Q_s(x^*) = Q_{s0} - \int_0^{x^*} \frac{dr^*(x^*)W^*(x^*)}{dx^*} (1 - \lambda_p) \quad [8]$$

We assume a typical subsidence profile that decays exponentially down-system away from the range-bounding normal fault zone (Fig. 5):

$$r^*(x^*) = r_0 + e^{-r_{decay}x^*} \quad [9]$$

where r_0 is the subsidence rate at the fan apex; and r_{decay} is a decay constant that describes the rate at which r^* decreases with x^* . We also use an exponential equation to describe how the alluvial fan surfaces become wider down-system, which reproduces reality well:

$$W^*(x^*) = W_0 + W_{max} \cdot (1 - e^{-W_{growth}x^*}) \quad [10]$$

Here, W_0 is the alluvial fan surface width at the fan apex; W_{max} is the maximum surface width; and W_{growth} describes the rate at which W^* increases with x^* . Note that W_{max} is not the same as the width of the alluvial fan surface at the fan toe, especially if it is dissected by an axial river system, as the shape may have continued to widen according to W_{growth} if the fan were able to prograde further.

We are able to parameterise Eq. 6 for these alluvial fans, to describe how sediment is distributed across the fan surfaces. The total widths of the modern incised fan surfaces were measured at 500 m intervals down-fan using high-resolution aerial imagery (Fig. 6a,b), and were then plotted these against the normalised down-system distance (Fig. 6c). We then simulate equation 6 using different values of the exponent W_{growth} (dashed lines), which is varied at intervals of 0.1. A low value of W_{growth} produces a narrow fan, and a high value

produces a wide fan. We find that a value of 0.5 best reproduces the observed fan surface geometry in both cases (solid line), meaning that the fan widths grow with length following an inverse square law. These lines are plotted using a W_0 of 100 m, as this is the width of both modern channel surfaces where they emerge from the canyons at the fan apices. The parameter W_{max} cannot be measured directly because the fans are toe-cut by Death Valley wash. However, it trades off with the exponent W_{growth} to determine the width of the fan at the toe, which can be measured also. We find values of W_{max} that produce the correct toe width of the modern surfaces are 7500 m for Moonlight canyon fan and 9500 m for Backthrust canyon fan. The curves in Fig. 6c are therefore plotted with a middle value of 8500 m for illustrative purposes; we emphasise that this difference has an immaterial effect on the estimated value of W_{growth} (see supporting information), and is simply required to generate the correct plan-view form of the alluvial fan surfaces. It is not possible to repeat this analysis for the Q2c terraces, which are partially buried by modern deposits (Figs 1 and 7a), so we assume that the aspect ratios of the fans can be taken to be constant over 70 ka, and this is qualitatively supported by the aerial imagery.

Together, the subsidence profile and the fan surface geometry determine the sediment extraction (Fig. 5). As such, our approach is a three-dimensional model of how sediment flux, and therefore grain size fining, varies down-fan. With the known growth in fan surface width parameterised (Eq. 10, above), we are in a position to derive the subsidence profile in our results, using equations 7 and 9, because $R * (x *)$ can be calculated from measured grain size fining rates via equations 4 and 5. Note that we obtain values of C_1 and C_2 from Eq. 6, and also an analysis of the similarity variable, ξ , described in Eq. 1. We explain this sub-section of the analysis in Appendix 2.

iii. Data processing

We analyse our data using Microsoft Excel and OriginPro v.9.1. Locality elevations (above sea level) and the surface slope map in Fig. 1c were determined using the National Elevation Dataset (NED) digital elevation model (Gesch et al., 2002), which has a horizontal spatial resolution of 9 m and a vertical resolution of 1.5 m in this area. Geospatial data were processed using ArcGIS v.10. All our data and calculations are provided as supporting information.

5. Results

i. Grain size measurements

In total, we measured 9000 grains across 80 individual sampling localities, distributed from apex to toe across 4 different alluvial fan surfaces (modern and Q2c on both the Backthrust canyon and Moonlight canyon fans). In Fig. 7, we plot these data as cumulative grain size distribution curves for each fan surface, including all localities. As such, these curves characterise the total body of sediment delivered to the fans, and do not capture any down-system changes in grain size. In general, the curves are similar, with the majority of particles between ~ 10 and 40 mm in diameter. The Q2c surface is marginally finer-grained than the modern surface by 2 to 3 mm on the Backthrust canyon fan. There is no significant difference between modern and Q2c sediments on the Moonlight canyon fan.

In Fig. 8, we plot the mean grain size, $\bar{D}$, at each locality, showing the trends from apex to toe on each fan surface. The Q2c localities are shown as open symbols and the modern localities as solid symbols. Exponential regressions fit the data well following Sternberg's law (Sternberg, 1875), with R^2 averaging 0.75. The input grain size, $\bar{D}_0$ at $x = 0$ km (the fan apices) is ~ 29 ($\pm < 1$) mm, the exception being the modern surface on the Backthrust canyon fan where $\bar{D}_0$ is slightly coarser at ~ 33 (± 1.2) mm. The rate at which grain size decreases down-fan is very similar on the two Moonlight canyon surfaces (5.6 and 5.9 % per km), and higher on the Backthrust canyon fan (6.7 % per km on the Q2c surface, rising to 8.9 % per km on the modern surface. Significantly, these fining rates do not overlap, even accounting for standard error. We have not included error bars reflecting the uncertainty on $\bar{D}$ at each locality, as Appendix 1 and the standard errors on $\bar{D}_0$ show, this is ~ 1 mm or less in terms of precision. Importantly, an increase in the fining rate from the Q2c surface to the modern surface on the Backthrust canyon fan indicates a relative decrease in sediment flux (see section 2), and we quantify this later on.

The coefficient of variation, C_v , (Eq. 6) for each locality down-fan is shown in Fig. 8c. There are no significant differences between the Backthrust canyon fan (circles) and Moonlight canyon fan (squares), or between the modern (open symbols) and Q2c (solid symbols) surfaces. The C_v averages 0.80 ($\pm 1\sigma = 0.09$) for the entire data set, in close agreement with other examples of gravel channel deposits, which generally have values of C_v between 0.7 and 0.9 (White et al., 1978; Ferguson et al., 1996; Fedele and Paola, 2007; Duller et al., 2010). A constant C_v requires that, for these fans, the standard deviation in grain size declines down-system at a similar rate to the mean grain size $\bar{D}$ (Fedele and Paola, 2007; Whittaker et al., 2011). This indicates that the grain size distributions are self-similar.

ii. Similarity variable, ξ

To test this idea explicitly, we calculated the probability distributions of the similarity variable, ξ , as described in Eq. 1 and Appendix 2. These are shown in Fig. 9. This was done for each individual locality (coloured lines), and each fan surface on average by combining all localities (black lines). The calculated values of the similarity variable are distributed around a value of 0, and as expected for self-similar deposits there is no change in the shape or position of these curves from apex to toe on any surface, between the two alluvial fans, or between the Q2c and modern deposits (Fig. 9e). The distribution of ξ can therefore be modelled as one representative curve for all the data (red dashed line, Fig. 9e), and this is further evidence for self-similar selective deposition. The ξ probability distributions have a long upper tail, reflecting the decreasing frequency of larger particles. The short lower tail reflects the truncation of the grain size distributions at 1 mm, as Wolman point counting cannot sample smaller particles.

We explore the best-fit modelling of the ξ probability distribution in detail in Appendix 2, and consider the implied relative mobility of clasts on these alluvial fans. Importantly, modelling of the similarity variable can be used to derive a value of constant C_1 , and as the best-fit model curve in Fig. 9e shows, this gives a value of $C_1 = 0.7$. Other workers have found C_1 to vary between 0.5 and 1.0 in different locations, typically averaging 0.7 to 0.8, and so our findings agree precisely with existing constraints (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011). With a preferred value of C_1 of 0.7 and an average value of C_v of 0.8, C_2 must be equal to 0.9 (see Eq. 6), and the governing equations (4, 5, and 7) are thereby calibrated for application to these systems. We test the effects of uncertainty on the value of C_1 explicitly later on.

iii. Fan comparison

The analyses above suggest the grain size fining on these fans is suitable to be modelled using the self-similarity approach. The Q2c fining rate profiles closely match on both fans, within standard error, indicating that these systems were behaving in the same way ~ 70 ka ago (Fig. 8a, b). On the Backthrust canyon fan, the modern fining rate is significantly greater (by $> 0.02 \text{ km}^{-1}$) than the Q2c fining rate, and the difference in the overall grain size distributions is also reflected in Fig. 7a. On this fan, modern incision into Q2c is negligible, only reaching 2-3 m at the fan apex (Fig. 2a) and quickly diminishing to almost no vertical separation for most of the fan (Fig. 1a); i.e., it is possible to step from the modern channel onto the Q2c surface in the field. Therefore, the modern deposits on the Backthrust canyon fan have not been significantly affected by recycling driven by fan-head incision. What does this statistically significant increase in modern grain size fining represent? In general terms,

an increase in grain size fining rate could be due to an increase in the amplitude and distribution of subsidence, and/or a decrease in the sediment supply from catchment to the fan (c.f., Whittaker et al., 2011; Parsons et al., 2012). A change in the subsidence profile is unlikely over such a short period of time, and because the vertical rates of movement in Death Valley are low and there is no evidence for significant changes in fault slip rates during this period (see section 2). Given the pronounced climate changes that have occurred between 70 ka and the present day, it is much more likely that a change in grain size fining rate on the fan represents a change in sediment flux (equation 7). We proceed under this assumption (section 5.4 below) and our ultimate goal is to estimate the change in Q_s needed to explain this change in the grain size fining rate on the Backthrust canyon fan.

However, on the Moonlight canyon fan, the modern and Q2c surfaces show no difference in their grain size fining rates (Fig. 8b). We suspect that this similarity is due to the heavy recycling of the Q2c terrace by the modern channels (Fig. 2b), via landsliding, scree cones, and the input of large blocks that we have observed in the field. We can test this hypothesis directly by estimating the order of magnitude of this recycled volume of sediment, compared to the flux of sediment exported from Moonlight canyon to the fan. Frankel et al. (2007a) reported ^{36}Cl cosmogenic nuclide estimates of catchment-wide erosion rates for Moonlight canyon, averaging 65 mm ka⁻¹. This is for the period of Q2c deposition, not the modern state, but gives an order of magnitude constraint on erosion rate. Converted to standard units and multiplied by the catchment area of 36.7 km² gives an estimate of sediment flux of ~2360 m³ yr⁻¹. In comparison, the incised length of the Q2c cliff is ~ 3 km, has an average depth of 40 m, and the modern channel surface has a width of 100 m in the canyon (Figs 1a, 2b). A cuboid of these dimensions has a volume of 12,000,000 m³, making this an order-of-magnitude estimate of the volume of terrace sediment cannibalized by the modern surface. This volume is much greater than the annual sediment flux, but of course the down-cutting and recycling was not instantaneous. It is impossible to know exactly when the incision started, however many alluvial fans in the south-western USA have been incising since the start of the Holocene (Bull, 1991; Pelletier, 2014), so the last 10 ka might be a reasonable assumption. Recycling this 12 Mm³ of material over 10 ka still gives a flux of 1200 m³ yr⁻¹, i.e., this number is within a factor of 2 of the estimated annual sediment flux to the fan apex, and is thus an equivalent order of magnitude to the sediment flux exported from the canyon. Consequently, the modern surface on the Moonlight canyon fan must have received a substantial fraction of sediment from the recycling of older terraces (Figs 8 and 9). Rather than adding to the sediment flux delivered at the fan apex, Q_{s0} , this represents a lateral source of sediment added to the modern surface at various points down-system. By counteracting the extraction of sediment by deposition (see Eq. 7), this kind of terrace recycling would be expected to decrease the

down-fan fining rate as we observe in Fig. 8b compared to Fig. 8a. Moreover, the exposure age constraints reported by Frankel et al. (2007a) indicate that sediment recycling is playing an important role in this system, because older clasts appear to have been inherited from remobilised deposits (Fig. 4b).

iv. Recovery of the subsidence profile

The first step in modelling grain size fining as a function of sediment flux and extraction is to recover the subsidence profile beneath the alluvial fans, $r * (x)$ (equation 5). We are able to do this by fitting equations 4, 5, and 7 to the observed grain size fining data for the Moonlight canyon fan Q2c surface, because we know Q_s for this particular case: the catchment-average erosion rate of 65 mm ka⁻¹ obtained by Frankel et al. (2007a) can be multiplied by the catchment area of 36.7 km² to estimate sediment flux as 2366 m³ yr⁻¹. This gives Q_{s0} , the sediment flux exported from the canyon mouth to the apex of the fan.

With Q_{s0} known (2366 m³ yr⁻¹) and equation 10 calibrated for the Moonlight canyon fan Q2c surface ($W_0 = 100$ m; $W_{growth} = 0.5$; $W_{max} = 7500$ m; see Methods), equation 7 can be fitted to the observed Q2c grain size data in order to recover the subsidence profile $r * (x)$ (Eq. 9), which is the only remaining unknown. We use a measured fan length, L , of 6 km and a porosity of 0.3, and take C_1 equal to 0.7 as determined by the similarity variable analysis in section 5.2, although we also explore the uncertainty on C_1 later. We model the subsidence profile using two constants, the input subsidence rate, r_0 , and the rate at which this decays away from the Grapevine fault zone, r_{decay} (Fig. 5). Constraints from InSAR suggest that the subsidence rate should be around 0.5 mm yr⁻¹ (Hammond et al., 2012), while geologic estimates are around 0.2 mm yr⁻¹ (Machette et al., 2002) (see study area). As r_0 is the largest rate in our formulation, we start by setting this as 0.5 mm yr⁻¹ and investigate how r_{decay} affects the shape of the grain size fining profile (Fig. 10a). The blue line in the background shows the regression fitted to the data in Fig. 8 ($R^2 = 0.62$), with pale blue shading illustrating the standard error of this regression. Dashed black lines show the fining profile generated using different values of r_{decay} . Higher values (e.g., 3 or 4 km⁻¹) mean that subsidence rate decreases quickly down-fan, reducing the accommodation available for sediment extraction, which in turn reduces the rate of fining by selective deposition. Lower values of the exponent (e.g., 1 or 1.5 km⁻¹) mean the subsidence rate remains greater along the length of the fan, and the fining rate is faster due to enhanced sediment extraction. The shape of the curve changes from convex to concave with increasing r_{decay} as a result of the way equations 9 and 10 trade off in the model. The Q2c data are best represented using a value of r_{decay} between 2 and 3 km⁻¹; the greatest

goodness of fit is obtained for $r_{decay} = 2.2 \text{ km}^{-1}$ and this value agrees well with normal fault geometry in other extensional settings (e.g., Anders et al., 1993; Schlische and Anders, 1996). In Fig. 10b, we show the effect of varying r_0 when r_{decay} is fixed at 2.2 km^{-1} . The fining rate becomes too slow when r_0 has low values of 0.2 or 0.3 mm yr^{-1} , and too fast when r_0 has high values of 0.7 or 0.8 mm yr^{-1} .

Of course, there are a range of solutions to equation 9 that could produce a fining rate with the correct overall gradient to fit the grain size measurements, but we can find a plausible fit for the subsidence profile by considering the geologic data and our grain size fining rates together. We compare four such scenarios in Fig. 10c. The first is a low subsidence scenario: If $r_0 = 0.1 \text{ mm yr}^{-1}$ then the sediment extraction can never be great enough to produce the observed fining rate, even if r_{decay} is set to 0 and the maximum subsidence rate (and accommodation) is maintained for the full length of the fan (dotted line). Consequently, the subsidence rate beneath the fans must be greater than 0.1 mm yr^{-1} . In the second model, a slightly faster r_0 of 0.25 mm yr^{-1} requires a r_{decay} of 0.5 km^{-1} to achieve a fining profile with the correct overall gradient, however the shape of the curve does not match the data well, becoming very convex along the fan (short dashed line). As r_0 is increased to 0.5 mm yr^{-1} , r_{decay} must also increase to 2.2 km^{-1} as seen above (Fig. 10a) to maintain the correct fining gradient, and the grain size profile is approximately linear down-fan, reproducing the measurements and the regression well (solid line). Finally, a high initial subsidence rate of $r_0 = 1 \text{ mm yr}^{-1}$ requires an extremely high r_{decay} of 4.0 km^{-1} to generate a plausible concave fining profile (long dashed line). This is a poorer fit to the regression than the $r_0 = 0.5 \text{ mm yr}^{-1}$ case, although it still lies within the scatter of the data. However, such high subsidence rates can be ruled out by (i) geodetic observations (Hammond et al., 2012); (ii) geologic constraints (Machette et al., 2002); and (iii) the unreasonable changes in subsidence rate magnitude required over small horizontal distances by an r_{decay} of 4.0 km^{-1} .

Our grain size fining measurements therefore support a subsidence profile that has a maximum rate of 0.4 to 0.6 mm yr^{-1} , and which decays away from the GFZ to 0.1 to 0.2 mm yr^{-1} at the fan toes. These profiles are shown in Fig. 10d, all of which agree well with existing constraints (Machette et al., 2002; Hammond et al., 2012). New data from Mormon Point—further south in Death Valley on the western front of the Black Mountains—give a vertical slip rate of $0.6 \pm 0.1 \text{ mm yr}^{-1}$ at the tip region of a range-bounding normal fault strand, much the same as the position of the systems we study near the tip of the GFZ (Frankel et al., 2015). This is in encouraging agreement with the value of r_0 we derive here. Our best-fit profile (solid line) is used for the subsequent sediment flux modelling.

v. Consideration of uncertainty effects

Other sources of uncertainty on the best-fit model grain size fining profile include our parameterisation of fan width, the catchment-averaged erosion rate and our estimate of input sediment grain size. Using the best-fit subsidence profile of $r_0 = 0.5 \text{ mm yr}^{-1}$; $r_{decay} = 2.2 \text{ km}^{-1}$ as a boundary condition for the Moonlight canyon Q2c surface, we explore how these additional sources of uncertainty affect our results. In Fig. 11a, we allow W_{growth} to vary from 0.3 to 0.7 km^{-1} . Figure 6 shows that this exponent does not occupy a wide range of values, and can be well-constrained to within 0.4 and 0.6 km^{-1} . The effect of this range on the modelled grain size fining profile is indistinguishable from the scatter in the observed measurements.

In Fig. 11b we show the effect of varying the catchment-averaged erosion rate between the maximum and minimum values reported by Frankel et al. (2007a) using ^{36}Cl cosmogenic nuclides. Arguably this is the largest source of uncertainty, because this changes the fining rate by directly modulating our estimate of sediment flux, for which we assumed the best-fit rate of 65 mm yr^{-1} in the modelling above. The maximum rate derived by Frankel et al. (2007a) fits within the upper bounds of our data, but we find the model grain size curve is more sensitive to a decrease in erosion rate (sediment flux). We return to this important finding later, but we note that if these minimum erosion rates were indeed ‘correct’, a plausible $r_0 \sim 0.4 \text{ mm yr}^{-1}$ would fit the data well with the same value of r_{decay} . This effect is therefore small, and as we assume subsidence is constant between 70 ka and today, it is also systematic in terms of calculating a change in sediment flux through time. In Fig. 11c we show the effect of the standard error on $\bar{D}_0$ obtained from the regression fitted in Fig. 8b; this uncertainty cannot be resolved within the scatter of the data and clearly does not influence our modelling. Finally, in Fig. 11d we show how sensitive the fining profile is to the constant C_1 . Our analyses use an estimated value of 0.7 obtained by evaluating the co-efficient of variation, C_v , directly from field data, and from our similarity variable, ξ , and which agrees well with previous workers (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011). In fact, values of C_1 between 0.5 and 0.8 cannot be discriminated from the standard error on the grain size regression.

These graphs show that reasonable uncertainties assigned to each of the parameters do not cause the grain size trend to deviate more than the standard error on the regression to which the model curve is being fitted. Our self-similarity model for alluvial fans can therefore tolerate the uncertainties present. Importantly, our next step is to explore what change in Q_{s0} is required to explain the enhanced modern grain size fining rate, compared to Q2c, on the Backthrust canyon fan. As we keep all other parameters constant, their uncertainties are systematic and have no substantial effect on the relative change in sediment flux reconstructed.

789

790 vi. Comparison of Q2c and modern fining rates

791 With the self-similarity model calibrated and the subsidence profile recovered using the
 792 Moonlight canyon Q2c case, a comparison can be made between the modern and Q2c
 793 deposits, which represent a climatic gradient through time (see section 2). As explained
 794 earlier, we cannot compare the Q2c and modern deposits on the Moonlight canyon fan
 795 because of the substantial recycling of grain size resulting from incision. Instead, a comparison
 796 is made on the Backthrust canyon fan, for which incision is minimal and documented changes
 797 in grain size fining rates are well-constrained. (Fig. 8a). We therefore explore the change in
 798 Q_{S0} needed to change the gradient of the Q2c fining profile to match the modern surface.

799 The calibrated grain size fining model is applied to the Backthrust canyon Q2c surface (Fig.
 800 12a). We assume the same catchment-wide erosion rate as the Moonlight Canyon, but as the
 801 catchment is slightly larger (46.2 km²), this produces a slightly greater Q_{S0} of 2981 m³ yr⁻¹. We
 802 also used a value of W_{max} of 9500 m (see section 4.2) from our fan width estimates (see also
 803 the supporting information). The Backthrust canyon fan is slightly longer, at 7 km, so we
 804 updated L accordingly in Eq. 7, and we used the input mean grain size $\bar{D}_0$ obtained from the
 805 regression in Fig. 8a. Otherwise, the same parameters are used for $r^*(x^*)$, $W^*(x^*)$, C_1 ,
 806 C_2 , C_v and porosity. Significantly, these same parameters and sediment flux estimates
 807 reproduce the observed Q2c grain size data very well (Fig 12a, white circles). Therefore, our
 808 interpretation is that the two fan systems are experiencing the same subsidence profile and
 809 can be modelled realistically using the simplifications in Fig. 5. We have also calculated the
 810 excess sediment fraction delivered to the alluvial fan, F_{excess} . We define this as the flux of
 811 sediment exported from the catchment, divided by the volume required to fill the
 812 accommodation space generated by the subsidence profile used (Fig. 10d), which in this
 813 scenario is 1494 m³ yr⁻¹. As such, a Q_{S0} of 2981 m³ yr⁻¹ represents a F_{excess} of 1.99, i.e., half
 814 of the sediment flux is transferred to fan stratigraphy and half is bypassed to the axial Death
 815 Valley wash. This is a reasonable figure, given that the size and amount of sediment carried
 816 by the axial system increase significantly as it toe-cuts the two alluvial fans (see Fig. 1).

817 We assume that the subsidence profile, rate, and fan geometry have not changed between
 818 the deposition of the Q2c surface ~ 70 ka ago and today. Therefore, we only allow $\bar{D}_0$ and the
 819 input sediment flux, Q_{S0} , to change when we fit the model to the modern surface of the
 820 Backthrust canyon fan (Fig. 12b). The $\bar{D}_0$ is taken from the regression in Fig. 8a, so this is
 821 already known, and in Fig. 12b we show how the fining profile changes with different values
 822 of Q_{S0} between 1800 and 3500 m³ yr⁻¹ (black dashed lines). This is compared to the best-fit
 823 regression through the measured data ± 1 standard error (red). As the modern fining rate is

faster than the Q2c fining rate, the sediment flux must be reduced in order to enhance the selective deposition of larger particles down-system, and so increase the overall slope of the model fining curve. A high Q_{S0} above $\sim 2800 \text{ m}^3 \text{ yr}^{-1}$ cannot model the observed data, as the fining rate is too low. Reducing Q_{S0} to $\sim 2400 \text{ m}^3 \text{ yr}^{-1}$ provides the best fit to the data; this is equivalent to a reduction in sediment flux from the catchment of $\sim 20 \%$ under modern conditions, compared to the mid-glacial climate of the Q2c period. Even lower values of Q_{S0} over-estimate the rate of fining and produce grain size profiles that are too fine-grained at the fan toe. A value of Q_{S0} of $2400 \text{ m}^3 \text{ yr}^{-1}$ is equal to a F_{excess} of 1.61, i.e., the accommodation space generated by the subsidence profile is still over-filled, but the percentage of the sediment flux that is eventually transferred to the axial system has decreased from 50 % to 38 %.

Figure 12c shows both model curves from Figs 14a and b against the grain size data. For the Q2c case, the fining model matches Fig. 12a as described above (blue); an uncertainty envelope (pale blue shading) shows the full uncertainty on Q_{S0} that arises from the uncertainty on the erosion rate ε (shown in Fig. 11b, this is the largest source of uncertainty). For the modern case, the model curve is for the best-fit reduction in Q_{S0} to $2400 \text{ m}^3 \text{ yr}^{-1}$ shown in Fig. 12b, but we have also included an uncertainty envelope of $Q_{S0} \pm 400 \text{ m}^3 \text{ yr}^{-1}$, i.e., equivalent to the 2000 and $2800 \text{ m}^3 \text{ yr}^{-1}$ curves in Fig. 12b. This is a large tolerance on the possible range of Q_{S0} that could satisfy the data, as it is greater than the standard error on the regression ($R^2 = 0.79$), however it accommodates the magnitude of the erosion rate uncertainty shown in Fig. 11b. Our approach shows that the modern and Q2c curves can be clearly discriminated, not just in terms of their respective grain size fining rates, but also in terms of the 20% reduction in sediment flux that generated the fan deposits over this time period.

6. Discussion

i. Sediment flux and past climate change

The analysis presented above suggests that down-system variations in grain size fining, in these alluvial fans over a 70 ka interval, can be linked to changes in sediment flux. A key question to address is what is driving these changes, given that there is no evidence for a change in tectonic subsidence rate during this time period. Climate change is an obvious cause for this mid-glacial to Holocene variation, and we return to the benthic Pacific $\delta^{18}\text{O}$ stack of Lisiecki and Raymo (2009) in Fig. 13a, onto which we have marked the Q2c (blue) and modern (red) surfaces, annotated with the estimated sediment fluxes and climatic conditions (see section 3) for the Backthrust canyon system as a summary. The implied decrease in sediment flux in the Holocene is associated with both warmer mean annual temperatures and

a decrease in mean annual rainfall. It should also be noted that a decrease in sediment flux is expected to promote fan incision (Van Den Berg Van Saparoea and Postma, 2008; Simpson and Castelltort, 2012), which reconciles with the incision of the modern surfaces into the Q2c surfaces on these fans. In other words, this sedimentological signal of climate change agrees well with the expression of fan morphology observed in the field.

The estimated reduction in sediment flux of $\sim 600 \text{ m}^3 \text{ yr}^{-1}$, between Q2c deposition and today, represents a decline of $\sim 20 \%$. This coincided with a $\sim 30 \%$ decline in the average annual precipitation rate (see section 2). Broadly, this agrees with numerical models, which predict a decrease in sediment flux resulting from a decrease in average precipitation rate (e.g., Paola et al., 1992a; Allen and Densmore, 2000; Morehead et al., 2001; Densmore et al., 2007; Armitage et al., 2011; Rohais et al., 2012; Allen et al., 2013). Therefore, these data from Death Valley reveal that, in some cases, the grain size fining rate of alluvial fan sediments is highly sensitive to climate changes over glacial-interglacial timescales. This suggests a short stratigraphic response timescale $< 10^5$ years, and implies that terrestrial sediments can provide high-resolution palaeoclimate information.

The estimated decline in sediment flux is slightly smaller in magnitude than the $\sim 30 \%$ decline in mean annual precipitation indicated by palaeoclimate proxies. If the maximum decrease in Q_{S0} to $2000 \text{ m}^3 \text{ yr}^{-1}$ is considered, this equates to a 33% decline in sediment flux, so while this is likely to be a slight over-estimate (Fig. 12b), the magnitude of the sediment flux response would then match the magnitude of the change in precipitation rate. The minimum decrease in Q_{S0} to $2800 \text{ m}^3 \text{ yr}^{-1}$ represents a 6% decline. This range of possible responses means the sediment flux response to a change in precipitation rate is potentially sub-linear, given that we expect no sediment flux from the catchment to the fan in the theoretical end-member case where precipitation rate is zero. In Fig. 13b, we plot the Q2c and modern sediment flux estimates for the Backthrust canyon fan against the estimated mean annual precipitation (black line). For the Q2c case, we have simply multiplied the modern average rainfall rate by a factor of 1.5; this is compatible with a range of palaeoclimate proxies including pollen records, pluvial lake reconstructions, glacier extents in the Sierra Nevada, and $\delta^{18}\text{O}$ records (see section 3 for details). Assuming our regression intersects the origin, the data are fitted by a power law with an exponent of ~ 0.5 . Using the maximum estimates of Q_{S0} in both cases (blue triangles), and the minimum estimates (red circles), changes this exponent to ~ 0.8 and ~ 0.2 , respectively. Therefore while there is a range of uncertainty on this exponent (and we have not attempted to quantify the uncertainty on the palaeoclimate constraints, as this is debatable), these data suggest that sediment flux to alluvial fans may in fact be less sensitive to precipitation than some models suggest (e.g., Armitage et al., 2011; Simpson and Castelltort, 2012; Armitage et al., 2013). Additionally, this result is important, because it

suggests that the sediment flux response to climate change may be more sensitive to a drying event than a wetting event.

It is worth considering what this change in sediment input to the alluvial fans represents. Our analyses only give an estimate of how the input sediment flux received at the apex of the fan has changed between mid-glacial and current interglacial conditions. Perhaps it equates to a change in the catchment-wide erosion rate, in which case the modern Q_{S0} of $2400 (\pm 400) \text{ m}^3 \text{ yr}^{-1}$ would be equivalent to an erosion rate of $52 (\pm 9) \text{ mm ka}^{-1}$ (adjusted from the average Q2c erosion rate of 65 mm ka^{-1}). However we caution against making this interpretation, because it could also be the case that hillslope erosion rates have remained the same or even accelerated as the climate warmed and vegetation cover declined (e.g., Pelletier, 2014), but the sediment is not being exported out of the catchments as efficiently under a drier climate. This would not be surprising, and there is a degree of sediment storage in the main channel of both canyons today, clearly visible in the field and in aerial imagery, so this possibility cannot be ruled out.

ii. Sediment flux sensitivity

In Fig. 13c, we take this sensitivity analysis a step further and investigate how this kind of system would respond to a wide range of sediment flux variations. We have used the Backthrust canyon-fan system as a model case, and simulated a much greater range of sediment flux scenarios from 50 to $20,000 \text{ m}^3 \text{ yr}^{-1}$ (see supplementary material for each model run). We have calculated the grain size at 1 km intervals from the fan apex to the toe, which we have normalised by a dimensionless input grain size of 1 in order to generalise the results. We have also equated the sediment flux with the excess sediment fraction, F_{excess} , given the particular subsidence profile derived in Fig. 10d. Note that when Q_{S0} is equal to the volume of sediment needed to fill accommodation ($1494 \text{ m}^3 \text{ yr}^{-1}$), $F_{excess} = 1$ and the basin is filled, and the grain size decays to exactly 0 at the 7 km point, i.e., the toe of the fan. There is no sediment bypassed to the axial system in this case, or with lower values of Q_{S0} . At higher values of Q_{S0} , the excess fraction increases. The range of sediment flux represented by the modern and Q2c cases is highlighted as a thin grey box; evidently much larger perturbations are explored here.

The system is less sensitive to an increase in sediment flux, which might correlate with even wetter conditions. The 7 km curve (the fan toe) is $< 20 \%$ finer than the input grain size above a Q_{S0} of $\sim 5000 \text{ m}^3 \text{ yr}^{-1}$ ($F_{excess} \sim 3.4$), and $< 10 \%$ finer above a Q_{S0} of $\sim 8000 \text{ m}^3 \text{ yr}^{-1}$ ($F_{excess} \sim 5.4$). Thus, in an extremely wet (high Q_{S0}) scenario, fan stratigraphy might be expected to record the progradation of a coarse-grained sheet conglomerate that supplies a large volume

of sediment to the axial system, making the fining rate difficult to measure (although the significant progradation of a thick conglomerate layer would be easy to identify in itself). However, we find the fining rate is much more sensitive to a decrease in sediment flux, which would correlate with a drying event. The grain size difference between the 1 km and 7 km curves becomes rapidly larger as Q_{S0} decreases, to a maximum of ~ 95 % at $F_{excess} = 1$. At sediment fluxes lower than $1494 \text{ m}^3 \text{ yr}^{-1}$, F_{excess} drops below 1 and the basin becomes under-filled. No sediment reaches the fan toe at 7 km, or at progressively shorter distances from the fan apex as Q_{S0} declines further. In the range of scenarios from Q_{S0} between 10^2 and $10^3 \text{ m}^3 \text{ yr}^{-1}$ and F_{excess} between ~ 0.1 and 1, the fining rate in the upper portion of fan stratigraphy is extremely sensitive to sediment flux. These hypotheses are based on an empirical calibration for a small glacial-interglacial range of Q_{S0} scenarios, but might offer useful insights into the effects of more dramatic climate changes on alluvial fan stratigraphy, and the sensitivity of the grain size response.

iii. Fan incision and sediment recycling

A final important comment on sensitivity is that these scenarios only apply if the alluvial fan sediments are not reworked. As shown by the Moonlight canyon fan, ~ 40 m of incision into older terraces (Fig. 2b) is sufficient to destroy any climate signal recorded in stratigraphy, because the timescale between sediment production and permanent storage in the basin exceeds the periodicity of orbital climate cycles, i.e., the signal is damped. Indeed, we are only able to recover the change in sediment flux since ~ 70 ka on the Backthrust canyon fan because there is negligible incision of the older deposits. One of the key assumptions in our modelling approach is that the sediment flux Q_{S0} is delivered to the fan at the apex and sediment is subsequently extracted down-system by deposition. Our model therefore does not account for significant lateral inputs of sediment downstream, by which the incision of an older fan unit would change the distribution of $Q_s(x^*)$ and complicate Eq. 8, as well as re-mobilise a potentially different grain size distribution. In section 5.3 we performed a first-order mass balance calculation, which demonstrated the recycled sediment flux from the incision of the Moonlight canyon Q2c surface is similar to the sediment flux exported from the catchment, and is therefore sufficient to disrupt the down-system pattern of grain size fining significantly. We do not attempt to incorporate lateral sediment fluxes into our model, meaning it is only effective when applied to fan systems with negligible sediment recycling, like the Backthrust canyon example. In principle, lateral sediment inputs could be parameterised with some assumptions and this is an opportunity for future work.

Our findings support the idea that a high sensitivity to climate change is promoted by rapid sediment transfer and minimal post-depositional recycling (e.g., McPhillips et al., 2013), but there is no single ‘response timescale’ for alluvial fans reacting to a climate change. Of course, we must also ask why the Moonlight canyon fan heavily incised itself during the Holocene while the Backthrust canyon fan did not. This difference in behaviour clearly cannot be attributed to climatic or tectonic differences on such a local spatial scale, nor to lithological or sediment supply processes in the parent catchments, which are the same (Fig. 1). Therefore, it is likely to emerge from autogenic processes operating in the alluvial fan systems. For example, Fig. 3 shows that the Moonlight canyon fan Q2c surface achieved the greatest slope (4.3 °) of all 4 surfaces sampled, and that after incision the fan slope has readjusted to 3.8 °. Consistent with equilibrium slope models (e.g., Van Den Berg Van Saparoea and Postma, 2008; Simpson and Castelltort, 2012) and physical experiments (Clarke et al., 2010), it may be that the Moonlight canyon fan simply reached a critical slope that triggered a period of incisional re-adjustment, independent of allogenic forcings like tectonics and climate. It is possible this was mediated by a change in the effective length of each fan resulting from the avulsion patterns. For example, avulsion on the Backthrust Canyon fan has lengthened the modern surface compared to the Q2c surface, on average. The opposite avulsion pattern has taken place on the Moonlight Canyon fan, and as the axial Death Valley wash provides a constant base level this may partly explain the incision observed here. We encourage more work to demonstrate how the effects of autogenic processes like avulsion and allogenic factors like climate can be decoupled in alluvial fan deposits such as these.

iv. Input grain size

Our analysis has explored the rate of grain size fining from fan apex to toe. However another topic of interest is the input grain size delivered to the alluvial fans from the catchments, and we consider this briefly here.

The $\bar{D}_0$ measured for the Q2c surfaces on both fans overlap within standard error (Fig. 8). This reflects how both surfaces were deposited synchronously under the same climate, and that the parent catchments are eroding the same bedrock lithologies with similar slope distributions and sediment supply (Fig 1). On the Moonlight canyon fan, where Q2c recycling contributes a large volume of sediment to the modern deposits, the modern $\bar{D}_0$ is also indistinguishable from the Q2c $\bar{D}_0$. In all three cases, the input grain size is 28 to 30 mm and fines to ~ 20 mm at the fan toes. In contrast, the modern $\bar{D}_0$ on the Backthrust canyon fan is coarser at ~ 33 mm, and does not overlap with the other input grain sizes within standard error. This may be slightly surprising, as the coarsest $\bar{D}_0$ is found on the surface for which the sediment flux is estimated

to be lower. One issue we have not discussed so far is the formation of desert pavement on the Q2c fan surfaces (Fig. 2d and f). A range of processes during desert pavement formation might conceivably alter the surface grain size distribution, including clast sorting, clast fragmentation and shattering, deflation, granular convection and upwards clast migration (Goudie, 2013). However few data sets are available that quantify the integrated effect of all these processes on the surface grain size distribution (Goudie, 2013).

Al-Farraj and Harvey (2000) measured grain size on alluvial fan surfaces in Wadi Al-Bih, Oman, which are also dominated by limestone clasts and have mature desert pavements similar to our study sites. They found that the paved surfaces have a slightly finer grain size distribution than the unexposed subsurface, an effect that becomes more pronounced with age. On ~ 100 ka surfaces, they find the average clast diameter on the paved surface to be ~ 25 mm, compared to ~ 30 mm clasts in the subsurface. These data indicate that in a comparable location, desert pavement formation (albeit over a ~ 30 % longer timescale than considered here) reduces the mean in the overall grain size distribution by ~ 16%. Importantly, this effect is not expected to change the rate of grain size fining down-system because desert pavement formation is a systematic process that takes place uniformly across the fan terraces we study, including across the spatial gradient from apex to toe. However it could alter the intercept ($\bar{D}_0$) of the fining curve. The magnitude of this effect observed in Oman would be sufficient to explain the input grain size difference between modern and Q2c values on the Backthrust canyon fan (Al-Farraj and Harvey, 2000). Therefore, we cannot rule out the possibility that the catchments supply a lithologically-mediated constant $\bar{D}_0$ of > 30 mm through time, but desert pavement formation on the Q2c terraces (or subsequent recycling of them) reduces the overall grain size distribution by a few millimetres in a systematic way.

Nevertheless, we underscore that our sediment flux analysis actually depends on the rate of grain size fining from apex to toe, and the relative change in the gradient of the fining profile through time. We do not expect any grain size changes resulting from desert pavement formation to vary spatially across the fan surfaces, and indeed in the field we observed uniform pavement formation on the Q2c terraces. Therefore, we consider our estimates of relative grain size fining rates, sediment flux, and subsidence to be reasonable.

v. The broader climate context

In this study, we have examined alluvial fan deposits formed under modern and mid-glacial (~ 70 ka) conditions. Of course, the two different climate states these time periods capture sit within the broader context of a full glacial-interglacial cycle, as shown in Fig. 4d, during which

climate was continuously evolving. It is therefore important to consider whether these catchment-fan systems are sensitive to glacial-interglacial climate cyclicity in general terms.

It may be significant that other dated alluvial fan systems in the Death Valley area also have substantial aggraded terraces dating to approximately 70 ka (e.g., Frankel et al., 2007b; Machette et al., 2008; Ganey et al., 2010). This represents the timing of fan surface abandonment, so while it might be coincidental, it could also reflect a synchronous change in the behaviour of different catchment-fan systems in response to climate change. This merits further study in the future, because ~ 70 ka was a time of rapid cooling and significant climatic reorganisation at the boundary between marine isotope stages 4 and 5 (see Fig. 4d). In fact, the shift in benthic $\delta^{18}\text{O}$ at this time, from 4.0 to 4.5 ‰ as recorded in the Pacific stack of Lisiecki and Raymo (2009) (Fig. 4d), shows that these fan deposits were formed during one of the most rapid and abrupt climate shifts in the entire glacial-interglacial cycle. In terms of the rate of climate change this period is comparable to the rapid warming that occurred after the LGM. Therefore, it may be that periods of rapid climate change in the past have governed the timings and locations of alluvial fan terraces that are available for us to examine today.

The analyses we present in this study offer a quantitative approach to inverting fan deposits for information about their sensitivity to past climate. We also encourage future studies to examine deposits from different time periods, e.g., the LGM. This was even cooler and wetter than at ~ 70 ka ago (see section 3.2), and our sensitivity analyses in Fig. 13 predict that LGM fan deposits would exhibit an even lower rate of grain size fining than the Q2c deposits, with a greater sediment bypass, F_{excess} , for the same accommodation, resulting from a larger input sediment flux, Q_{S0} . Palaeoclimate records indicate that the LGM was twice as wet as today (see section 3.2), so assuming our model calibration is correct, for the Backthrust canyon fan system we would predict an input sediment flux Q_{S0} of approximately 3500 m³ yr⁻¹ by extrapolating the trend in Fig. 13b. This is a hypothetical LGM scenario, but what would it mean for the grain size fining rate? Keeping all other parameters constant, adjusting Q_{S0} to 3500 m³ yr⁻¹ would decrease the grain size fining exponent in Fig. 8a to -0.05 (compared to -0.09 for the modern deposit and -0.07 for the Q2c deposit), and increase the F_{excess} to 2.3 (compared to 1.6 for the modern case and 2.0 for the Q2c case); see the supporting information for an interactive spreadsheet. These are testable predictions, the likes of which could be made for deposits dating to other points in time as well, e.g., the last interglacial period. We also note that there are additional fan surfaces present on both the Backthrust canyon and Moonlight canyon fans. Figure 1a clearly shows deposits at the intersection between the two fans (at approximately 36°53'N, 117°17'W) with an intermediate degree of varnishing, and these might therefore capture a time period between the Q2c and modern surfaces, perhaps the LGM. We have not sampled these deposits because they are not dated,

but clearly there are opportunities to explore additional alluvial fan surfaces (and systems) to constrain the sensitivity of sedimentary fluxes and deposits to past climate changes.

7. Conclusions

In this study, we have examined two mountain canyon-alluvial fan systems draining the Grapevine Mountains in northern Death Valley, California. We have demonstrated that the grain size fining rate is self-similar from apex to toe on four alluvial fan surfaces: a modern surface and a ~ 70 ka surface on each fan, dated by Frankel et al. (2007a). By adapting the self-similarity equations of Fedele and Paola (2007) for alluvial fans, we are able to first derive the subsidence profile in this part of the basin, and secondly estimate that a ~ 20 % decrease in sediment flux has occurred between the mid-glacial climate state and modern conditions. This coincides with a decrease in mean annual precipitation of approximately one third (Thompson et al., 1999; Quade et al., 2003; Menking et al., 2004; Kessler et al., 2006; Phillips, 2008; Lisiecki and Raymo, 2009), supporting the majority of numerical catchment-fan models that predict such a sediment flux response to climate change (e.g., Paola et al., 1992a; Allen and Densmore, 2000; Morehead et al., 2001; Densmore et al., 2007; Armitage et al., 2011; Rohais et al., 2012; Allen et al., 2013). This may be due to a proportionate decrease in catchment-wide erosion rates, but could equally be due to a decrease in the efficiency at which sediment is evacuated from the canyon.

Our approach offers one method of reconstructing sediment fluxes in the past from sedimentological data collected in the field, and demonstrates that grain size data can be used to quantify the primary controls (tectonics, climate, erodibility) on landscape evolution and the stratigraphic record. Our findings are supported by additional observations. (i) The maximum subsidence rate we recover for this part of northern Death Valley is ~ 0.5 mm yr⁻¹, and not only fits the observed grain size fining rate well, but also agrees with geodetic data (Hammond et al., 2012) and geologic constraints (Machette et al., 2002), offering new information about the subsidence rate in this valley. (ii) We observe that the alluvial fans have incised at a time when sediment flux has declined, and this also reconciles with numerical models such as Van Den Berg Van Saparoea and Postma (2008) and Simpson and Castelltort (2012), indicating that sedimentological signals of climate change in alluvial fans complement incision-aggradation architecture. (iii) The grain size data from the Death Valley fans also require a low-mobility calibration of the self-similarity model, in agreement with the real environment.

The two catchment-fan systems we examine in this study provide real examples of when sediment routing systems and their deposits are sensitive and insensitive to high-frequency climate changes (i.e., orbital, < 10⁵ year timescale). On the Moonlight canyon fan, sediment recycling is substantial due to 40 m of down-cutting and incisional recycling of older deposits.

As a result, the grain size signal of orbital climate change is damped because the sediment is remobilised over a time period longer than the climate forcing. Conversely, a climatic signal is preserved on the Backthrust canyon fan—recorded by a change in grain size fining rate down-system—because incision and recycling of older terraces is minimal. This implies that landscapes, and the terrestrial sedimentary record, can have a range of response timescales that depend on the time taken for sediment to be permanently locked into stratigraphy, without further recycling taking place. Our sensitivity analysis also indicates that alluvial fan grain size might be more sensitive to drying than wetting. This has implications for future climate change scenarios, and suggests that at least the arid and semi-arid landscapes of the south-western United States may be increasingly sensitive to further drying as the climate continues to warm.

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10. Appendix 1: Uncertainty analysis of photo Wolman point counting

We take this opportunity to evaluate the Wolman point counting technique, using scaled field photographs, as a method for characterising the grain size distribution of the gravel fraction. Using all the grain size counts we make in this study, in Fig. A1a, we plot how $\bar{D}$ changes as additional clasts are measured, up to a total of 100 particles, for every individual Wolman point count locality. The grain size has been normalised by the final mean grain size (at 100 counts), so that all 80 curves converge on a value of 1. Therefore, this plot shows how $\bar{D}$ converges on a stable value as more clasts are sampled. With only 20 clasts, for example, $\bar{D}$ might be 40 % larger or smaller than the final value. This error declines to within ~ 10 % by approximately 70 clasts, and to within ~ 5 % by 80-90 clasts (see inset). The envelope containing all these curves represents the maximum limits of the variation in $\bar{D}$ with increasing counts, and declines exponentially as more particles are measured. Many curves converge on a normalised value of 1 after 50 or 60 clasts.

To visualize how these curves are distributed around a value of 1, in Fig. A1b we have plotted probability densities using all curves, across slices of the inset Fig. A1a. At sample sizes of

80, 90, 95, and 99 clasts, these show the relative deviation of the mean particle size from that estimated using 100 clasts. The majority of mean values are within 2 % of the final estimate, even after 80 counts. There is little improvement in the uncertainty of the mean diameter between 80 and 99 counts. Figure A1 therefore shows that sampling 100 clasts is sufficient to converge on a stable mean grain size within ~ 2 % in the clear majority of cases, i.e., for a $\bar{D}$ of 20 mm, increasing the sample size by more than 100 particles will only refine the value of $\bar{D}$ within a typical uncertainty of < 0.5 mm. In fact, the exponential decline in the outer envelope of Fig. A1a means that to significantly improve upon the uncertainty obtained by averaging 100 clasts, one would need to average an order of magnitude more grains. Wolman point counting cannot sample anything below the resolution of the images being used (or what can be measured in the field, if performed in situ), which is 1 mm in this study. Therefore it only characterises the > 1 mm gravel fraction of sediment. On these alluvial fans, this represents the majority of sediment (see Figs 2e and 2f), and we use the self-similarity equations of Fedele and Paola (2007) that are specifically formulated for the gravel fraction only. Therefore, we consider this Wolman point counting method to be suitable for the purposes of our investigation.

11. Appendix 2: Analysis of the similarity variable, ξ

Values of C_1 and C_2 can be obtained by analysis of the similarity variable, ξ , defined by Fedele and Paola (2007). We calculate values of this variable for each particle measured in each Wolman point count, according to:

$$\xi = \frac{D - \bar{D}(x_*)}{\sigma(x_*)} \quad [\text{A1}]$$

where D is the diameter of each individual clast, and ξ is dimensionless. We calculated frequency distributions for values of ξ at intervals of 0.5, which also reveal that these alluvial fan deposits obey self-similarity (Fig. 9). Frequency distributions of ξ can be modelled using equations from Fedele and Paola (2007):

$$f(\xi) = C e^{-\phi(\xi)} \quad [\text{A2}]$$

Consequently, $f(\xi)$ depends on the exponent $\Phi(\xi)$, which is the integral of a parameter $\phi(\xi)$ (Eq. A3, below) and thus relates to the grain size variance parameters C_1 , C_2 (Eq. 5) and the relative mobility function, J .

$$\phi(\xi) = - \int \phi(\xi) d\xi \quad [A3]$$

$$\phi(\xi) = \frac{1}{c_1 \left(1 + \frac{c_2 \xi}{c_1}\right)} \left(1 - \frac{1}{J}\right) - \frac{J'}{J} \quad [A4]$$

J , the self-similar relative mobility function is defined as:

$$J = a_g e^{-b_g \xi} + c_g \quad [A5]$$

where a_g , b_g and c_g are constants, and J is also equal to the ratio of the fraction of a given grain size in transport to the fraction transferred to the deposit (i.e., it increases with greater particle mobility).

The probability distribution of ξ can be used to derive the values of the constant C_1 , providing that the relative mobility function J can be estimated (Eq. A5). Once C_1 is derived, then C_2 is implied from Eq. 6, given that we know the average value of C_v equal to 0.80 (Fig. 8c). Previous studies have found c_g to have a constant value of 0.15 (Fedele and Paola, 2007; Duller et al., 2010), and we maintain this value here, as it fits our data well. Documented values of a_g vary between 0.5 (Duller et al., 2010) and 0.9 (Fedele and Paola, 2007), while values of b_g vary between 0.2 (Fedele and Paola, 2007) and 0.8 (Duller et al., 2010). Equation A5 shows that a_g scales with the mobility of all particles, while b_g describes the rate at which particles of increasing size become less mobile than smaller particles; therefore, these constants embody information about the relative mobility of clasts and are expected to vary between study areas. Existing work has calibrated these constants for rivers in which clasts are presumably more mobile than on the arid alluvial fan surfaces of Death Valley. The constant C_1 may be as low as 0.5 (Duller et al., 2010) or have a higher value of 0.7 to 0.8 (Fedele and Paola, 2007), but in general lies between 0.5 and 1.0.

In Fig. A2a, we have collapsed all of the single-locality ξ distributions from Fig. 9a-d into a single plot (grey lines), along with the four surface average ξ distributions (black lines). We

have then graphically derived the best-fit values of C_1 , a_g and b_g that reproduce the shape of these distributions. We find the greatest goodness of fit using values of $C_1 = 0.7$, $a_g = 0.15$, and $b_g = 2.2$; and all our analyses are available as interactive spreadsheets in the supporting information. In Fig. A2b to d, we vary each of these three constants in turn, keeping the other two at their optimum values, to demonstrate the sensitivity of the similarity distributions to their values (coloured lines). Clearly, C_1 may take a range of values between 0.6 and 0.9, with a preferred value of 0.7 (Fig. A2b), and we therefore evaluate the uncertainty associated with varying C_1 within this range in our modelling. With a preferred value of C_1 of 0.7 and an average value of C_v of 0.8, C_2 must be equal to 0.9 (Eq. 6), and the governing equations (4, 5, and 7) are thereby calibrated for application to these systems. These values of the constants are in very close agreement with previous work and other locations (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011).

Although the values of the constants a_g and b_g are not important for the governing equations, and are therefore tangential to our analyses, they contain useful information about particle mobility on these alluvial fans. As Fig. A2 shows, the ξ distributions can only be effectively modelled with values of a_g less than ~ 0.2 and values of b_g greater than ~ 1.5 to 2.0. This low value of a_g and high value of b_g (compared to other studies, e.g., Fedele and Paola, 2007, and Duller et al., 2010) clearly reflect a low mobility transport environment. This is encouraging, as it arises from the data without any prior knowledge of the study area, but matches well the arid and low-mobility conditions on these Death Valley alluvial fans. This observation suggests that the self-similar fining model can accurately describe sediment transport in these systems.

Fig. 1. Maps locating the two targeted catchment-fan systems in northern Death Valley, California. (A) Landsat 8 contrast-enhanced (bands 642-RGB) false colour image of the alluvial fans. Modern deposits appear bright blue, Q2c deposits reflect brown-red and were dated to ~ 70 ka using ^{10}Be cosmogenic nuclides by Frankel et al. (2007a); stars show their sampling localities. Dots show the down-fan grain size sampling localities in this study (black on modern surfaces, white on Q2c surfaces). Two fault systems are shown: the Northern Death Valley Fault Zone (NDVFZ), a dextral strike-slip fault with a horizontal displacement rate of ~ 4.5 mm yr^{-1} (Frankel et al., 2007aa); and the Grapevine Fault Zone (GFZ), a range-bounding normal fault system across which the vertical displacement rate is poorly constrained (we provide new data in this study). The two fans are toe-cut by the axial Death Valley wash, flowing towards the south-east. (B) Aerial imagery of both catchments (outlined in black). They have similar forms and

1608 geomorphology, and drainage areas of 46.2 km² (Backthrust canyon) and 36.7 km² (Moonlight canyon).
 1609 The catchments are mostly eroding early Palaeozoic carbonates, with smaller outcrops of Miocene
 1610 volcanics at the headwaters and Pliocene conglomerates near the canyon mouths (Niemi, 2012; see text
 1611 for details). (C) Slope map of the catchments calculated from the National Elevation Dataset, with a
 1612 horizontal/vertical elevation of 9/1.5 m at this location.

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1615 **Fig. 2.** Field photographs of the alluvial fan systems sampled. (A) Photograph taken on the modern surface
 1616 of the Backthrust canyon fan near the apex, looking upstream towards the catchment. The Q2c terrace is
 1617 highlighted by yellow arrows, and has been incised by 2-3 m by the modern surface. This incision quickly
 1618 diminishes down-fan and it is possible to step from one to the other for most of the length of the fan. A

ridge of Pliocene conglomerates is visible in the background, with carbonate bedrock in the mountain range beyond. (B) Photograph taken on the modern surface of the Moonlight canyon fan near the apex, looking upstream. On this fan, the Q2c surface has been heavily incised by the modern surface, exposing a ~ 40 m tall cliff that is recycling material into the modern channels via large blocks, landslides, and steep scree cones. The carbonate bedrock strata are visible in the Grapevine Mountains (background), and the lack of significant vegetation cover is clear. (C) Representative photo of the modern fan surfaces, which comprise gravels, pebbles and cobbles distributed by low-relief channels. The channels are active during storms, owing to the arid climate of Death Valley. This photo is near the fan apex, and a ridge of Pliocene conglomerates is visible in the background. (D) An equivalent photograph of the Q2c surface exposed near the apex of Moonlight canyon fan. The surface has a mature desert pavement, the clasts are heavily varnished and oxidised and the depositional relief has been lost. (E) Representative photograph of the modern surface grain size distribution. The notebook scale bar is 15 cm long with 1 cm intervals. Clasts are mostly derived from carbonates. (F) Representative photograph of the Q2c surface grain size distribution. The clasts have been varnished and arranged into an interlocking pattern characteristic of desert pavements.

Fig. 3. Longitudinal profiles of the modern (solid lines) and Q2c (dashed lines) fan surfaces along the sampling routes shown in Fig. 1a. Elevation is given above sea level and was measured from the National Elevation Dataset model with a vertical precision of 1.5 m. The Backthrust canyon fan lies at a higher overall elevation as it is further north in Death Valley. It has similar modern (4.0 °) and Q2c (4.1 °) surface slopes, reflecting the negligible degree of modern incision. The Moonlight canyon fan has a slightly steeper Q2c surface (4.3 °), which has been heavily incised by a gentler (3.8 °) modern surface.

Fig. 4. Exposure dating of the Q2c surface, copied from Frankel et al. (2007a). Probability distributions of the 6 ^{10}Be samples measured on the Backthrust canyon fan (A) and the 10 samples measured on the Moonlight canyon fan (B) both give peaks at ~ 70 ka. Frankel et al. (2007a) combined these Q2c age estimates to obtain an overall exposure age of 70 (+ 22, - 20) ka (C). See the original study for further details. In (D), we plot this period of activity as a grey box on the benthic $\delta^{18}\text{O}$ stack for the Pacific Ocean reported by Lisiecki and Raymo (2009). The Q2c surface was deposited in mid-glacial conditions during the middle of the cooling phase of the previous glacial-interglacial cycle, and we estimate a temperature depression of 2-3 °C and a 1.5 factor increase in mean annual precipitation relative to modern conditions (see text for details).

Fig. 5. Schematic diagram of the model approach taken in this study. The input sediment flux at the fan apex, Q_{s0} , is the total sediment export from the canyon, via a channel of initial width W_0 . Grain size fines down-fan from $x = 0$ to $x = 1$ by selective deposition of larger clasts, and the sediment extraction depends on (i) how sediment is distributed across the fan surface according to its changing width, $W^*(x^*)$, and (ii) the accommodation generated by the changing subsidence rate beneath the fan, $r^*(x^*)$. We use exponential equations to describe both of these relationships (see inset graphs), which can be easily parameterised and represent our target alluvial fans well. Due to the lateral extraction of sediment on alluvial fans, the application of the self-similarity equations requires this 3D solution.

Fig. 6. Observed widening of modern alluvial fan surfaces on the Backthrust and Moonlight canyon alluvial fans. High-resolution aerial imagery (A) was used to measure the width of the sediment distribution surfaces, W^* , at 500 m intervals down-fan (B). These widths are plotted against the normalised down-fan distance, x^* , in (C), and simulated using the modelling scheme given in Fig. 5 (dashed curves). The starting width, W_0 , can be measured directly as the width of the modern surfaces where they emerge from the canyons; this is 100 m in both cases. The theoretical maximum width of the fans if they were not toe-

cut by the axial system, W_{max} , is approximated at 8500 m, giving the simulated curves the correct convexity. We allow the growth exponent, W_{growth} , to vary at intervals of 0.1, and the data are best-fitted by an exponent of ~ 0.5 (solid curve). The exponent is dimensionless in this plot because the length scale has been normalised to x^* .

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Fig. 7. Cumulative grain size distribution curves for all localities measured on modern (solid lines) and Q2c surfaces (dashed lines) on the Backthrust canyon fan (A) and the Moonlight canyon fan (B). The number of clasts (n), the mean grain size, $\bar{D}$, and the 50th and 84th percentile grain sizes, D_{50} and D_{84} , are quoted for each surface. Around 80 % of clasts are between 5 and 50 mm in diameter, with a smaller fraction of smaller and larger grains. Our sampling strategy does not include sediment finer than 1 mm (see Methods). In general, the surfaces all have comparable grain size distributions. The modern surface on the Backthrust canyon fan is slightly coarser-grained by 2-3 mm.

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Fig. 8. Mean grain size, $\bar{D}$, for each locality plotted against distance down fan (where the apex = 0 km), for modern (solid symbols) and Q2c (open symbols) surfaces on the Backthrust canyon fan (A) and the Moonlight canyon fan (B). Exponential regressions fit the data well, with R^2 averaging 0.75, and provide an estimate of $\bar{D}_0$ at the fan apex that has a typical uncertainty of ~ 1 mm. The $\bar{D}_0$ is ~ 28 to 30 mm on the Moonlight canyon fan and both Q2c surfaces, and slightly coarser (~ 33 mm) on the modern surface of the Backthrust canyon fan. On the Backthrust canyon fan, the down-system grain size fining rates are $\sim 6.7\%$ km^{-1} (Q2c) and $\sim 8.9\%$ km^{-1} (modern), and do not overlap within standard error. On the Moonlight canyon fan, where significant sediment recycling is observed (Fig. 2b), the fining rates are indistinguishable (5.6 and 5.9% km^{-1} on the modern and Q2c surfaces, respectively), matching the Q2c regression in (A). In (C) we plot the coefficient of variation, C_v (equation 6) for every locality. There is no significant variation in C_v down-fan or between the surfaces, which averages $0.80 (\pm 0.09)$ and demonstrates that the standard deviation and mean grain sizes decay similarly along the length of each fan surface.

Fig. 9. Observed probability distributions of the similarity variable, ξ , on the Backthrust canyon fan (modern surface in A, Q2c surface in B) and the Moonlight canyon fan (modern surface in C, Q2c surface in D). Coloured lines show the distributions for individual sampling localities, bold black lines show the average distribution of ξ for the entire surface. There is no systematic variation in ξ down-system on each surface, between modern and Q2c deposits, or between the two fans. This indicates that grain size fining along the fan lengths obeys self-similarity as defined by Fedele and Paola (2007). See section 2 and Appendix 2 for equations. (E) All observed probability distributions of ξ from panels A to D collapsed onto a single plot, for all localities on all 4 fan surfaces (grey curves), and the 4 surface average distributions (bold black

curves). A self-similar model of selective deposition can be used to model these probability distributions (red dashed line) given a number of empirical constants. We use $C_V = 0.8$ (Fig. 8), and find a value of $C_1 = 0.7$ provides the best fit to the data; see Appendix 2 for full details.

Fig. 10. Recovery of the subsidence profile beneath the fans, derived using the Moonlight canyon Q2c surface for which $Q_{S0} = 2366 \text{ m}^3 \text{ yr}^{-1}$, and using the expression for the subsidence profile given in equation 9. (A) The input subsidence rate, r_0 is set to 0.5 mm yr^{-1} in agreement with InSAR measurements (Hammond et al., 2012), and r_{decay} is allowed to vary (black dashed lines). The grain size data are fitted with the best fit regression (blue curve) from Fig. 8 and the pale blue shading shows the standard error on this regression. The best-fit solution of r_{decay} is 2.2 km^{-1} . (B) We fix r_{decay} as 2.2 km^{-1} and test the effect of varying r_0 . Only a small range of rates (~ 0.4 to 0.6 mm yr^{-1}) can be tolerated by the grain size data. (C) There are multiple unique solutions of r_0 and r_{decay} that give the correct overall fining gradient. The subsidence rate must be $> 0.1 \text{ mm yr}^{-1}$, as even with no decay (maximum sediment extraction), the fining rate is too slow. For $r_0 = 0.25 \text{ mm yr}^{-1}$ and $r_{decay} = 0.5 \text{ km}^{-1}$, the overall gradient of the fining profile is correct but the form is too convex for the observed data. For a fast $r_0 = 1 \text{ mm yr}^{-1}$, r_{decay} must be unreasonably large (4 km^{-1}), and the fining profile becomes concave. While this is within the scatter of the data, geodetic and geologic constraints rule out such a fast subsidence rate (Machette et al., 2002;

Hammond et al., 2012). A predicted calibration of $r_0 = 0.5 \text{ mm yr}^{-1}$ and $r_{decay} = 2.2 \text{ km}^{-1}$ offers the best fit to the Q2c grain size data. (D) The best-estimate subsidence profile beneath the fans (solid line). Tolerating the uncertainty on r_0 of $\pm 0.1 \text{ mm yr}^{-1}$ (A) and r_{decay} between 2 to 3 km^{-1} (B) makes little difference to the subsidence pattern observed.

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Fig. 11. The effect of parameter uncertainties on the fining rate predicted for the Moonlight canyon fan Q2c surface. In each panel, we use the subsidence profile recovered in Fig. 10, and known sediment flux details (see text) to explore how each parameter affects the grain size fining rate in our model. The blue line is the regression from Fig. 8, and the pale blue shading shows ± 1 standard error on this regression. Apart from each parameter being varied, we keep all other parameters at their best-estimate values ($W_{growth} = 0.5$; $W_0 = 100 \text{ m}$; $W_{max} = 7500 \text{ m}$; $\epsilon = 65 \text{ mm ka}^{-1}$; $\bar{D}_0 = 29.0 \text{ mm}$; $C_1 = 0.7$; $C_v = 0.8$; $r_0 = 0.5 \text{ mm yr}^{-1}$; $r_{decay} = 2.2 \text{ km}^{-1}$). (A) The uncertainty on exponent W_{growth} , which is measured as $\sim 0.5 \text{ km}^{-1}$ (solid line) in Fig. 6 lies within the scatter of the data and the error on the regression. Higher and lower values (dashed lines) produce slower and faster fining rates, respectively. (B) The maximum and minimum catchment-wide erosion rates, ϵ , estimated by Frankel et al. (2007a) produce slower and faster fining rates, respectively. The average value of 65 mm ka^{-1} fits the data well (solid line) and the grain size profile is more sensitive to slower erosion rates (and lower sediment fluxes). (C) The standard error on the input

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1805 grain size distribution, $\bar{D}_0$, (dashed lines) cannot be discriminated from the scatter in the data. (D) The
 1806 value of C_1 of 0.7 derived in Fig. 9 fits the fining profile well, but the scatter in the data can tolerate a range
 1807 of values of C_1 between 0.6 and 0.8. These analyses show that reasonable uncertainties on each of these
 1808 parameters do not cause the fining rate to deviate significantly more than the standard error on the
 1809 regression to which it is being fitted. Therefore, our model setup can tolerate these uncertainties well.

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Fig. 12. A comparison of modern (solid symbols) and Q2c (open symbols) Q_{50} scenarios on the Backthrust canyon fan. The best-estimate values of all parameters are used ($W_{growth} = 0.5$; $W_0 = 100$ m; $W_{max} = 9500$ m; $C_1 = 0.7$; $C_v = 0.8$; $r_0 = 0.5 \text{ mm yr}^{-1}$; $r_{decay} = 2.2 \text{ km}^{-1}$). The grain size regressions from Fig. 8 are shown as blue (Q2c) and red (modern) lines, with associated pale shading showing ± 1 standard error on the regressions. The input grain size, $\bar{D}_0$, has been taken from Fig. 8 in both cases. (A) Q_{50} is calculated by multiplying the Q2c erosion rate of 65 mm ka^{-1} (Frankel et al., 2007aa) by the catchment area of 46.2 km^2 , giving $2981 \text{ m}^3 \text{ yr}^{-1}$. The parameterisation of the model fits the observed fining rate very well. (B) For the modern case, where $\bar{D}_0 = 33.3 \text{ mm}$, the observed fining rate is faster. We have allowed Q_{50} to vary between 1800 and $3500 \text{ m}^3 \text{ yr}^{-1}$ (black dashed lines), of which the $2400 \text{ m}^3 \text{ yr}^{-1}$ scenario fits the observed data best, representing a 20% decrease in Q_{50} compared to Q2c. We propose a maximum uncertainty of $\pm 400 \text{ m}^3 \text{ yr}^{-1}$, tolerating the 2000 to $2800 \text{ m}^3 \text{ yr}^{-1}$ scenarios. (C) The best-fit fining models are shown for the Q2c surface (blue, with uncertainty displayed as the full uncertainty on Q_{50} deriving from ϵ in Fig. 11b) and the modern surface (red, with $Q_{50} = 2400 \pm 400 \text{ m}^3 \text{ yr}^{-1}$). The modelling approach taken here reproduces the observed grain size data well.

Fig. 13. Summary diagram of the Backthrust canyon fan sensitivity to past climate change. (A) The modern (red) and Q2c (blue) surfaces marked on the benthic $\delta^{18}\text{O}$ Pacific stack of Lisiecki and Raymo (2009) and annotated with the estimated climatic conditions (see text) and reconstructed sediment fluxes. The change in Q_{S0} we estimate here corresponds to a mid-glacial to interglacial climatic gradient. (B) Best estimates of sediment flux (black squares) plotted against modern and estimated Q2c climate (see text for details). A power law regression that intersects the origin has an exponent of ~ 0.5 . Using maximum (blue triangles) and minimum (red circles) sediment flux estimates (see Fig. 12c) gives exponents of ~ 0.8 and ~ 0.2 , respectively. Thus, the relationship between sediment flux to the fan and precipitation rate is likely to be sub-linear. (C) Predicted mean grain size, $\bar{D}$, at length intervals of 1 km (coloured curves) down-system on the Backthrust canyon fan, modelled using the calibration in Fig. 12 for a wide range of hypothetical sediment fluxes between 50 and 20,000 $\text{m}^3 \text{yr}^{-1}$. Grain size is normalised to an input value of 1 to generalise the results. The excess sediment fraction, F_{excess} , is given on the top x-axis (see text for explanation), and modern and Q2c scenarios for Q_{S0} are highlighted solid grey lines. Much larger perturbations are explored here. As Q_{S0} increases above Q2c values, the fining rate (the difference between $\bar{D}$ at 1 and 7 km) becomes

increasingly small and sensitivity to Q_{S0} decreases. The difference between $\bar{D}$ at 1 and 7 km is greatest ($\sim 95\%$) at $F_{\text{excess}} = 1$ ($Q_{S0} = 1494 \text{ m}^3 \text{yr}^{-1}$). As Q_{S0} decreases further, the basin is under-filled and the grain size decays to zero at progressively shorter distances from the apex. The sensitivity of the fining rate is much higher to a drying perturbation (reduced Q_{S0}) than a wetting perturbation (increased Q_{S0}), implying directionality in the grain size response to climate change. For illustrative purposes, a predicted LGM scenario is highlighted with a dashed grey line (see section 6.5 for details).

Fig. A1. (A) This plot shows, for each photographic Wolman point count sampled ($n = 80$ localities), how the estimated mean grain size, $\bar{D}$, changes as additional clasts are sampled from 1 to 100 particles. The $\bar{D}$ is normalised by the $\bar{D}$ obtained using 100 clasts so all curves converge on a value of 1, and the inset shows an expanded view between 80 and 100 grain size counts. The spread of the curves around a normalised $\bar{D}$ of 1 shows the uncertainty on the measurement precision, which decreases exponentially as more clasts are counted. Averaging only ~ 20 clasts means the uncertainty on the precision of $\bar{D}$ will be approximately $\pm 40\%$, and this decreases to within $\pm 10\%$ after approximately 70 particles, although some curves reach this precision after fewer counts. In (B), we show probability distributions of the normalised $\bar{D}$ at slices across the inset of (A) at 80, 90, 95 and 99 counts. For the majority of localities, the precision on $\bar{D}$ estimated using these sample sizes is within $\sim 2\%$. The probability of obtaining a precision within 2% or less (the integrated area under the probability distributions within this range) improves from 0.57 with 80 clasts to 0.74 with 95 clasts. The probability of obtaining a precision within 5% or less improves from 0.79 with 80 clasts to 0.92 with 95 clasts. For a true $\bar{D}$ of 25 mm, for example, precision within 5% gives a measurement uncertainty of ± 1.25 mm, and within 2% gives ± 0.5 mm. We therefore argue that this grain size sampling technique is acceptable for our investigation, and uncertainty on measurement precision is smaller than other sources of uncertainty.

Fig. A2. (A) Observed probability distributions of the similarity variable, ξ , for all localities on all 4 fan surfaces (grey curves), and the 4 surface average distributions (bold black curves). This graph collapses the 4 panels from Fig. 9 into one plot. A self-similar model of selective deposition can be used to model these probability distributions given a number of empirical constants. We use a value of C_v of 0.8 obtained from Fig. 8c, and a value of c_g of 0.15 (Fedele and Paola, 2007; Duller et al., 2010) to graphically derive the values of C_1 (0.7), a_g (0.15) and b_g (2.2) that best fit the observed data. In panels B to D we demonstrate how the probability distribution changes as each constant is varied in turn, with the other 2 constants kept at their optimum values. An interactive model is available in the supporting information. Values of C_1 between 0.6 and 0.8 fit the observed distributions well, and agree with previous findings (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011). The short negative tail of the distribution is due to the truncation of the grain size distribution at 1 mm by our sampling technique, and we therefore do not try to reproduce it. Values of a_g must be between ~ 0.1 and 0.2, and values of b_g must be between ~ 2 and 2.5. These ranges are smaller and larger, respectively, than previous constraints obtained for channels (Fedele and Paola, 2007), however these constants are expected to vary geographically and indicate low-mobility transport conditions proportionate to alluvial fan surfaces in Death Valley.