Chapter 24

The Role of Climatic Change in Alluvial Fan Development

Ronald I. Dorn

The Persistence of Climatic Change in Alluvial-Fan Studies

Alluvial fans develop at the base of drainages where feeder channels release their solid load (Blair and McPherson, 2009; Leeder et al., 1998; Harvey et al., 2005). A classic fan-shape forms where there is a well-defined topographic apex. Multiple feeder channels, however, often blur the fan-shape resulting in a merged bajada. Alluvial fans can be found in almost all terrestrial settings. These include alpine (Beaudoin and King, 1994), humid tropical (Iriondo, 1994; Thomas, 2003), humid mid-latitude (Bettis, 2003; Mills, 2005), Mediterranean (Robustelli et al., 2005; Thorndrycraft and Benito, 2006), periglacial (Lehmkuhl and Haselein, 2000), and different paraglacial settings (Ballantyne, 2002). The geographical focus of this chapter, however, rests on alluvial fans in regions that are currently deserts or that experienced episodes of aridity in the Quaternary.

The research literature contains a host of different ways of thinking about and conducting research on desert alluvial fans (Table 24.1). Despite the wealth of research hypotheses and perspectives, many researchers keep returning to climate change as a vital forcing factor on desert fan evolution. Although some reject climatic change as important (De Chant et al., 1999; Webb and Fielding, 1999; Rubustelli et al., 2005), the following sorts of judgments commonly pepper the literature on fans found in arid and semi-arid regions:

> Hence, climate is an exclusive controlling factor of the transition from periods of geomorphodynamic activity to periods of stability (Gunster and Skowronek, 2001: 27).
>
> The field evidence indicates that the Tabernas fan/lake system responded to regional tectonics, but that the fan sediment sequences were primarily climatically driven (Harvey et al., 2003: 160).
>
> It is probably no coincidence that the first major episode of fan sedimentation occurred in MIS 5, the longest and more severe episode of cold and arid climates during the Pleistocene... (Pope and Wilkinson, 2005: 148).

Even along Dead Sea, climatic changes appear to be more important in fan development than base level or tectonic changes (Bowman, 1988; Klinger et al., 2003).

A persistent return to the importance of variable climate may result, in some small part, to the history of geomorphic thought where climatic change remains a major theme (Tricart and Cailleux, 1973; Besler, 1976; Mabbutt, 1977; Büdel, 1982; Hagedorn and Rapp, 1989; Derbyshire, 1993; Twidale and Lageat, 1994; Wendland, 1996; Elorza, 2005). Even if the tradition of climatic geomorphology shapes thought, it is the newly gathered evidence that drives researchers towards climate as an allocyclic process along with tectonic and base-level fluctuations (Roberts, 1995; Bettis, 2003; Harvey et al., 2005). The next section, however, argues that there are substantial obstacles to scientific investigations of the role of climatic change in desert alluvial-fan research.

Limitations of a Climatic Change Focus

This section makes three arguments that climatic change studies of desert alluvial fans should be viewed with considerable methodological skepticism. Sedimentology cannot be used to match fan depositional

---

R.I. Dorn (✉)
School of Geographical Sciences, Arizona State University, Tempe, AZ 85287, USA
e-mail: ronald.dorn@asu.edu

A.J. Parsons, A.D. Abrahams (eds.), *Geomorphology of Desert Environments*, 2nd ed.,
DOI 10.1007/978-1-4020-5719-9_24,

Table 24.1 Examples of different research foci on desert alluvial fan research

Focus	Synopsis
Accommodation space	Different tectonic (Viseras et al., 2003), sea-level (Robustelli et al., 2005), base-level (Harvey, 1984; Calvache et al., 1997), basin width and sediment supply (Weissmann et al., 2005), accommodation space (Posamentier and Vail, 1988; Muto and Steel, 2000) conditions alter fan dynamics.
Catastrophism	Catastrophic changes dramatically alter fans (Beaty, 1974) where sediment-generating events can derive from fire (Wohl and Pearthree, 1991; Moody and Martin, 2001), anthropogenic landscape use (Eriksson et al., 2000; Gomez et al., 2003; Gómez-Villar et al., 2006), release of glacial damned lakes (Benn et al., 2006), rock avalanches (Blair, 1999), or high magnitude floods (Beaty, 1974; Kale et al., 2000; Baker, 2006).
Complex response	A variable response to the same external stimuli (Schumm, 1977) has been used interpreting alluvial fans experiencing different responses to similar conditions of climate, land cover and sediment supply (Harvey, 1997; Kochel et al., 1997; Coulthard et al., 2002).
Coupling	Coupling fosters linkage of processes at different spatial, temporal scales (Brunsden, 1993; Allen, 2005). As applied to alluvial fans (Harvey, 2002a), coupling analyses explain fan events over short and long time scales and small and large drainage basins.
Dynamic Equilibrium	Alluvial fans may represent a dynamic equilibrium in transportation of course debris from range to basin (Denny, 1965; Denny, 1967), but a dynamic equilibrium that may require millennial (Davies and Korup, 2006) or longer (Tricart and Cailleux, 1973) time scales.
Hazards	Fan hazard studies include process geomorphology (Chawner, 1935; Schick et al., 1999; Field, 2001), historical geomorphology (Kochel et al., 1997; Crosta and Frattini, 2004), Quaternary studies (Keefer et al., 2003; House, 2005), as well as engineering and policy issues (Committee on Alluvial Fan Flooding, 1996).
Megafans	The causes of and processes on megafans may involve periods of aridity (Krohling and Iriondo, 1999; Leier et al., 2005), and arid drainages may require different conditions to produce megafans (Rodgers and Gunatilaka, 2002; Arzani, 2005) than in other climates.
Modeling	Modeling (Schumm et al., 1987; Coulthard et al., 2002) helps understand sediment waves (Tucker and Slingerland, 1997), high-frequency variations in sediment supply (Hardy and Gawthorpe, 2002; Davies and Korup, 2006), landscape evolution (Coulthard et al., 2002; Clevis et al., 2003), how fan morphology affects groundwater recharge (Blainey and Pelletier, 2008) and understanding linkages between specific geomorphic processes and corresponding forms (Weaver and Schumm, 1974).
Morphometry	Rich understanding of fan and landscape change develops from morphometry studies (Hooke and Rohrer, 1977; Kostaschuk et al., 1986; Jansson et al., 1993; Calvache et al., 1997; Harvey et al., 1999a; Viseras et al., 2003; Staley et al., 2006; Volker et al., 2007; Wasklewicz et al., 2008), including links to steady-state (Hooke, 1968), allometry (Bull, 1975; Crosta and Frattini, 2004) and other larger concepts.
Process studies	Process research forms the core of fan theory development (Hooke, 1967; Kostaschuk et al., 1986; Blair, 1987; Wohl and Pearthree, 1991; Blair and McPherson, 1994; Blair, 1999; Schick et al., 1999; Al Farraj and Harvey, 2004; Crosta and Frattini, 2004; Benn et al., 2006; Griffiths et al., 2006).
Remote Sensing	Digital image processing of satellite (White, 1993; Farr and Chadwick, 1996; Robinson, 2002; Garcia-Melendez et al., 2003) and ground-based imagery (Crouvi et al., 2006) generates valuable perspectives on mapping and fan processes.
Sedimentology	Sedimentary and stratigraphic analyses (Robinson, 2002) yields insight about processes (Blair and McPherson, 1994; Robinson, 2002; Harvey et al., 2005), high magnitude events (Lafortune et al., 2006), low-magnitude changes in a basin (Calvache et al., 1997; Robinson, 2002), fan fossilization (Stokes et al., 2007), and sometimes potential sources (Krzyszkowski and Zielinkski, 2002; Harvey et al., 2003).
Tectonics	Tectonic setting permits most fan development (Singh et al., 2001; Hartley et al., 2005). Although some disregard tectonics as important in certain settings (Klinger et al., 2003; Colombo, 2005), tectonism can alter relief, generate headward erosion, alter stratigraphy, change fan gradients, drop base levels, and change accommodation space (Kesel and Spicer, 1985; Owen et al., 1997; Clevis et al., 2003; Guerra-Merchan et al., 2004; Pope and Wilkinson, 2005; Rubustelli et al., 2005; Quigley et al., 2007; Sancho et al., 2008).

records with climatic changes. Dating methods are simply not up to the task of correlating geomorphic events with climatic changes, and even a new method that directly connects climatic change with aggradational events can only suggest millennial-scale correlations. Lastly, controlled experiments are not possible with field-based studies.

Sedimentology Limitations

Processes leading to alluvial-fan deposits "differ remarkably little between humid and arid environments, or between arctic and subtropical environments" (Harvey et al., 2005: 3), a conclusion reached in many different studies (Brierley et al., 1993; Ibbeken et al., 1998; Ballantyne, 2002; Krzyszkowski and Zielinkski, 2002; Lafortune et al., 2006). Although researchers sometimes connect climatic changes to sedimentological changes using independent chronometric control (Calvache et al., 1997; Singh et al., 2001), there is a danger that sediment-based analyses alone could suffer from circular reasoning in inferring the importance of climatic change (Jain and Tandon, 2003).

> No matter how detailed the geomorphological and stratigraphic examination that is undertaken of alluvial fan systems, no estimate of age obtained by these methods can ever be deemed reliable except in the grossest possible terms. It is only with the application of chronometric dating that a reliable temporal framework can be constructed, and only with such a framework can the triggers of fan-forming processes be independently assessed (Pope and Wilkinson, 2005: 149).

Unlike lake shorelines, periglacial features and glacial moraines whose existence directly connects to climatic events, alluvial-fan studies cannot currently infer climatic change through sedimentological, stratigraphic, or geomorphological analyses.

Are Dating Methods Up to the Task?

The Target is Decadal, Century and Millennial Climatic Changes

With the growth of increasingly precise proxy records, the last few decades has seen a substantial transformation in palaeoclimatology. Whereas much of the alluvial-fan research in the twentieth century focused on correlations with Milankovitch-scale (Shaffer et al., 1996) oscillations (Wells et al., 1987; Bull, 1991; Reheis et al., 1996), twenty-first century geomorphic research must articulate to records of millennial, century and even decadal climatic change (Starkel, 1999; Birks and Ammann, 2000; Viles and Goudie, 2003; Thomas, 2004; Anderson, 2005). There exists a clearly identified need for research on fluvial responses to allogenic forcing over sub-Milankovitch time scales of 10^2–10^3 years (Blum and Tornqvist, 2000: 2).

The vast preponderance of newer palaeoclimatological research now emphasizes sub-Milankovitch high frequency and high magnitude climatic events (Fig. 24.1). Examples of millennial events include iceberg surges generating Heinrich Events (Vidal et al., 1997) and Dansgaard-Oeschger cycles with an asymmetry of decadal warming (Taylor et al., 1997) and then longer cooling (Bond et al., 1997; Curry and Oppo, 1997).

Climatic variability exists at all timescales, and processes that drive climatic changes are closely coupled. Accordingly, there has been increased attention to ever

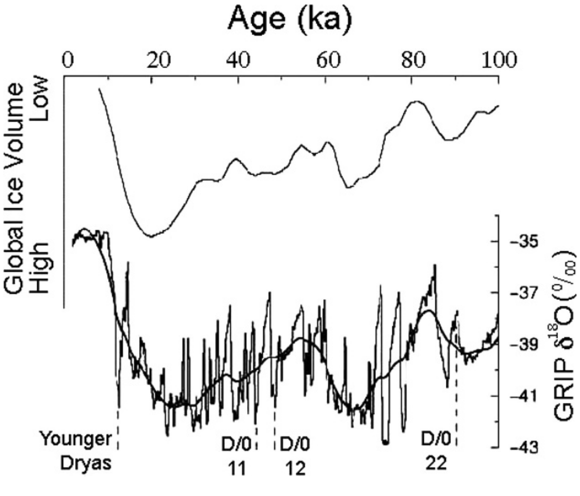

Fig. 24.1 Researchers advocating the importance of climatic change on desert fans originally argued for the role of (A) Milankovitch-scale oscillations reflecting global ice volume. A new generation of palaeoclimatic studies emphasize sub-Milankovitch sudden climate shifts such as the (B) changing location of global moisture recorded in Greenland Ice Core Project (GRIP) records. Vertical lines identify examples of rapid climatic change GRIP events of the Younger Dryas and Dansgaard-Oeschger (D/O) cycles 11, 12 and 22. Diagram is adapted from (Masson-Delmotte et al., 2005)

shorter climate-change time scales. These fluctuations include the El Niño Southern Oscillation over a subdecade time scale (Philander, 1999), the North Atlantic Oscillation over a decadal scale (Wanner et al., 2001), the Pacific Decadal Oscillation over a bi-decade scale (Houghton et al., 2001), the Atlantic Multidecal Oscillation over a seventy-year scale (Enfield et al., 2000) and others. Sub-Milankovitch oscillations show up in a variety of high resolution biotic and geological proxy records (Arz et al., 1998; Proctor et al., 2000; House and Baker, 2001; Benson et al., 2002; Madsen et al., 2003; Rohling and Palike, 2005; Ellwood and Gose, 2006; Henderson, 2006; Schaefer et al., 2006), but not in desert-fan research for reasons made clear in the next section.

Fan Dating Methods Have Trouble Distinguishing High Frequency Events

At issue here is whether methods used to date alluvial-fan events are up to the task of a correlation with millennial-scale changes, let alone century or decadal oscillations. This challenge was issued a decade ago with the argument that climatic change hypotheses for desert alluvial fans are not testable, because even the most precise time intervals for a fan event could be assigned to wet, dry, or transition climatic events (Dorn, 1996). The problem was repeated again: "no detailed assessment of the response of the clastic sedimentary depositional environment to such abrupt, high amplitude changes... is available." (Fard, 2001) The same difficulty was explained a bit later for northeast Queensland:

> The switch from fan building to fanhead trenching constitutes an 'abrupt' change in the behaviour of the fluvial system, but we have little idea of the transitional time from one mode of flow to the other. It is likely that such changes were (a) diachronous between basins, and (b) in response to more than one threshold-crossing event. But both these sources of variation may have occurred within 10^1–10^2 years, and when viewed across a 10^3 year time period may appear synchronous (Thomas, 2004: 112).

The challenge was issued yet again in the context of modelling and field-based studies:

> we wish to demonstrate that persistent alluvial fanhead morphology may result from rare, large sediment inputs not necessarily related to climatic or tectonic perturbations. This possibility has largely been ignored when using alluvial fans as indicators of past climatic or tectonic regimes (Davies and Korup, 2006).

Proponents of fan-climate correlations have yet to address these critiques.

The mainstay of alluvial-fan climatic change research in the arid western USA has been soil-stratigraphic studies punctuated with occasional tephrachronology and radiometric (e.g. U-series, ^{14}C, cosmogenic) data (Wells et al., 1987; Bull, 1991; Harvey et al., 1999a; Harvey et al., 1999b; McDonald et al., 2003; Western Earth Surface Processes Team, 2004; Harkins et al., 2005; Knott et al., 2005). These studies yield fan depositional events where the highest precision generates broad age ranges for correlated surfaces that span 10^3 to 10^5 years. Even lower precision derives from such morphologic evolution dating strategies as scarp diffusion (Hsu and Pelletier, 2004). This is not to infer that geomorphic or traditional soil-stratigraphy strategies have no value. They certainly do (Huggett, 1998), but not to test scientific hypotheses of alluvial-fan development related to climatic change. No method has yet enabled a correlation of fan surfaces, based on soils and geomorphic parameters, with sub-Milankovitch climatic fluctuations.

Radiocarbon measurement is certainly precise enough to discriminate millennial-scale climatic events, especially with the use of accelerator mass spectrometry (Keefer et al., 2003). Aside from tremendous problem of a general lack of availability of suitable material on arid fans, there are concerns about whether precise measurements are truly accurate. Worries occur over the effect of groundwater (Bird et al., 2002), whether extant models of pedogenic carbonate accumulation are appropriate (Stadelman, 1994; Wang et al., 1996; Alonso-Zarza et al., 1998), over contamination by old carbon sources (Chitale, 1986; Falloon and Smith, 2000; Six et al., 2002), contamination by younger carbon (Ljungdahl and Eriksson, 1985), and the importance of experienced and rigorous lab processing (Gillespie et al., 1992).

Alluvial-fan climate change researchers outside of the USA often employ optically stimulated luminescence (OSL) (White et al., 1996; Krohling and Iriondo, 1999; Roberts et al., 1999; Eriksson et al., 2000; Singh et al., 2001; Suresh et al., 2002; Stokes et al., 2003; McLaren et al., 2004; Robinson et al., 2005; Gardner et al., 2006; Suresh et al., 2007; Spencer et al., 2008; Zazo et al., 2008), while OSL has seen very limited application in the arid southwestern USA (Hanson, 2005; DeLong and Arnold, 2007; Mahan et al., 2007; Sohn et al., 2007). With the best available protocol it is difficult, but possible, for OSL to obtain reliable and precise enough ages to discriminate millennial-scale oscillations (Olley et al., 2004).

Considerable recent attention has been paid to cosmogenic nuclide dating on alluvial fans (Liu et al., 1996; Phillips et al., 1998; Keefer et al., 2003; Matmon et al., 2005; Evenstar et al., 2006; DeLong and Arnold, 2007; Dühnforth et al., 2007; Frankel et al., 2007). By itself, cosmogenic nuclides do not yield accurate enough results for millennial-scale correlations. There exists 5% error in counting, 50% error in chemical and blank corrections, and 10–15% in production rates (Brown et al., 2003; Benn et al., 2006). This is all before other uncertainties are considered, such as boulder erosion rates, changes in the geomorphic position of sampled surfaces, potential sampling bias that often goes unidentified, prior exposure history, and periodic cover by snow or soil—all leading to potential offsets from reported exposure dates. It is the rare researcher (Robinson, 2002; Brown et al., 2003; Benn et al., 2006) who actually presents real uncertainties associated with cosmogenic results. This is not to say that cosmogenic nuclide data on fan sediment lacks value. Far from it. New and creative strategies for unraveling complex signals are under development (Robinson, 2002). The simple point here is that the magnitude of identified and often unidentified errors simply makes it impossible at the present time to link cosmogenic ages on fan sediment to sub-Milankovitch climatic events.

New Strategy Linking Fan Events with Climatic Change

The ideal research method would be one where the deposit can be directly correlated with a climatic event. One such method has just passed from the experimental realm, varnish microlaminations (VML) developed by Tanzhuo Liu. Liu subjected his VML method to a successful blind test administered by Richard Marston, editor of *Geomorphology* (Liu, 2003; Marston, 2003; Phillips, 2003). Both general and specific aspects of extracting palaeoclimatic information from varnish layering have also been replicated (Dorn, 1984, 1990; Cremaschi, 1992; Cremaschi, 1996; Diaz et al., 2002; Lee and Bland, 2003; Thiagarajan and Lee, 2004). The method was originally applied to Milankovitch-scale correlations of alluvial fan units (Fig. 24.2) (Liu and Dorn, 1996). However, since this original exploration VML dating had another decade of development based on scrutiny of more than 10,000 varnish microsedimentary basins.

The latest technical advances in VML dating now permit the resolution of twelve millennial-scale events during the Holocene, at least in the southwestern USA (Liu and Broecker, 2007). Such high resolution permits the assignment of specific ages to deposits such as found on a well-photographed debris-flow fan on the east side of Death Valley (Fig. 24.3) (Liu, 2008). Seven analyzed fan units were correlated with "relatively wet periods during the Holocene" (Liu and Broecker, 2007).

VML directly links climatic change with aggradational events on alluvial-fan surfaces, but at its best VML can only resolve millennial-scale correlations. Two difficulties still remain if this methodology is to fulfill its potential of testing the importance of climatic change in alluvial-fan development. First, there must be a clear linkage between climatic thresholds needed to change VML and the millennial-scale climatic events altering alluvial fans. In other words, the drainage-basin/fan under examination may not necessarily respond to the same climatic forcings as the varnish. Second, if century and decade-scale wet phases were vital in generating fan surfaces during a millennial-scale dry period, even this finest-scale methodology could misidentify the fan/climate correlation. For example, it might be extreme events in decadal dry phases during a millennial wet phase that actually generated the alluvial-fan deposits in Fig. 24.3, and VML would not be able to identify such high resolution patterns.

The best strategy available today rests in utilizing several high resolution methods together. For example VML might be used in tandem with OSL, much in the way that several fan researchers utilize as many different methods as possible to identify systemic uncertainties with a single method that might otherwise go undetected (e.g., Roberts et al., 1999; Poisson and Avouac, 2004; Owen et al., 2006).

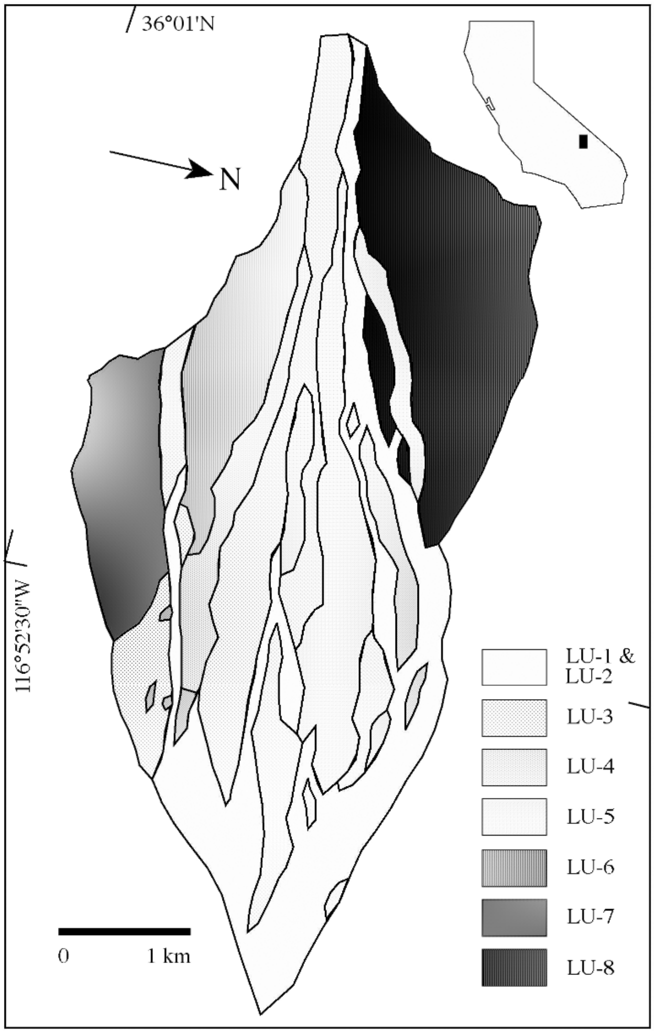

Fig. 24.2 Six Springs Alluvial Fan, Death Valley, where fan mapping corresponds with the varnish microlamination (VML) sequence. In broad Milankovitch-scale terms, VML layering units (LU) 2, 4, 6 and 8 correspond with marine oxygen isotope stages 2, 4, 6 and 8. At this course scale of resolution, there is no clear relationship between Death Valley fan aggradation and Milankovitch-scale climatic change (Dorn, 1996; Liu and Dorn, 1996)

Intrinsic Lags

Beyond the chronometric limitations of a fan event/climate event correlation, there are well known inherent challenges offered by the geomorphic system (Brunsden, 2001; Harvey, 2002a; Viles and Goudie, 2003; Oguchi and Oguchi, 2004; Thomas, 2004). A few of these correlation challenges include time lags in how fast a climatic change impacts the ability of the geomorphic system to adjust with changes of slope and drainage systems, mediation by slow or fast (e.g. wildfire) shifts in vegetation cover, available sediment stores and lags in its exhaustion, the nature of climatic-vegetation discontinuities at the onset of a change, magnitude of the change, rate of change at the discontinuity, and complex responses. When we do not understand drainage basin sediment production, storage or transport, it becomes extraordinarily difficult to connect climatic change with alluvial-fan deposits over sub-Milankovitch timescales.

Lack of a Control

Scientific research requires independent controls to isolate the effect of a variable. Different types of modelling (e.g. Clevis et al., 2003) do sometimes permit researchers to isolate the impact of climatic change. A quasi-steady approximation "suggests that environmental variables (e.g. climate, lithology) play

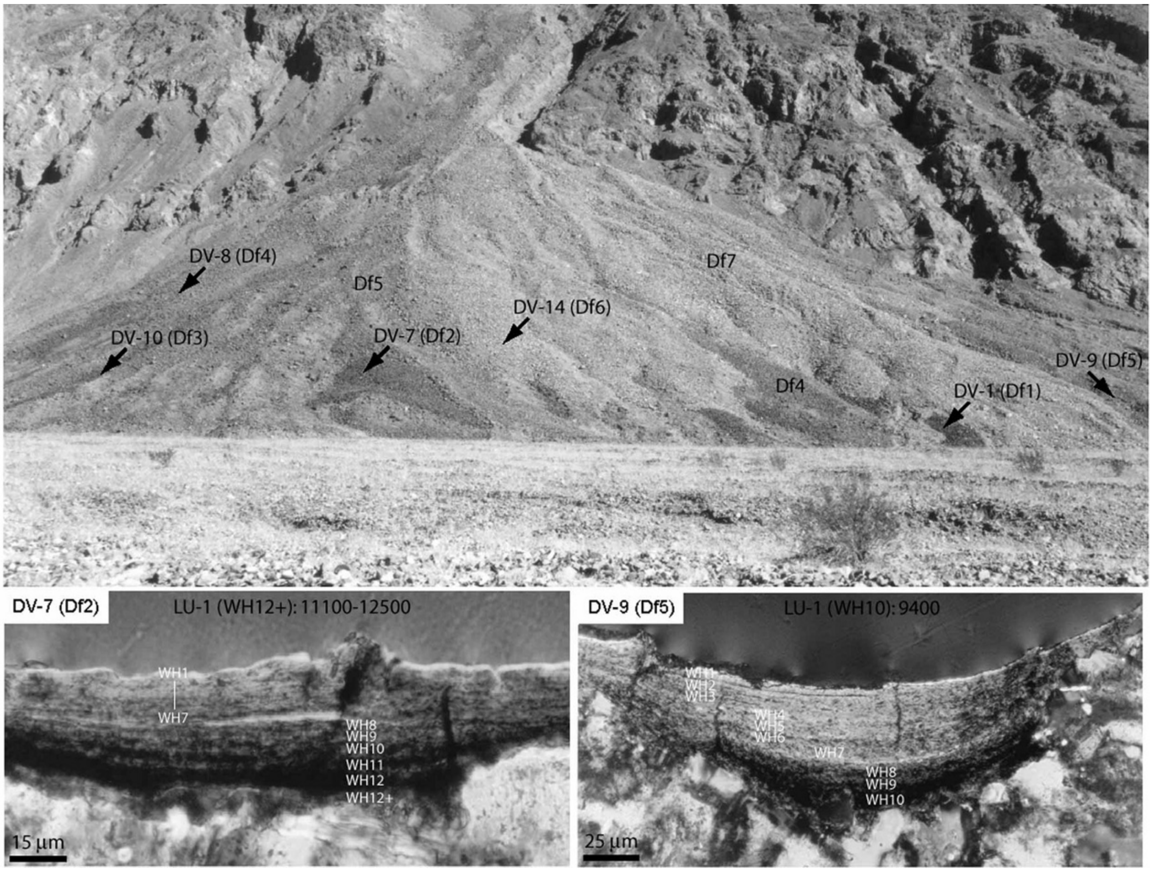

Fig. 24.3 A small debris-flow fan approximately 0.05 km^2 reveals distinct Holocene VML. Optical thin sections of varnish on two of the older deposits are exemplified here, revealing VML ages of ~11,100–12,500 cal BP and ~9400 cal BP (These images are courtesy of T. Liu.) The seven distinct fan depositional units appear to be correlated with millennial-scale wetter periods during the Holocene (Liu and Broecker, 2008)

a less significant role in overall fan morphology than do basic sedimentary and flow processes." (De Chant et al., 1999: 651). A cellular automaton model, in contrast, "shows that the sediment discharge upstream of the alluvial fan closely follows the climate signal" (Coulthard et al., 2002: 280). Models can explore the implication of climatically forced sediment waves moving down channel networks (Tucker and Slingerland, 1997) or the implication of climatic changes for fan progradation and aggradation (Hardy and Gawthorpe, 2002).

Controlled studies evaluating the role of climatic change, however, are simply not possible in field-based research. Unlike tectonic and base-level allocyclic processes, where it is possible to reasonably assume no tectonic or base-level change influences to compare with field sites impacted by these variables (Harvey, 2002b; Harkins et al., 2005), all desert alluvial fans have experienced climatic oscillations. This makes it impossible to craft an experimental design isolating just climate change. Thus, modelling research will inevitably play an increasingly important role in the future of the scientific study of the role of climatic change on desert fans.

20th Century USA Research and the Transition-To-Drier-Climate Model

The notion has been around a long time. A drier climate leads to a sparser cover of woody vegetation.

As infiltration capacity decreases, the location of the channel head moves upslope and excavates weathered material. Alluvium then moves down channels towards alluvial fans. This transition-to-drier-climate model (Fig. 24.4) had its birth in the southwestern USA (Huntington, 1907; Eckis, 1928; Melton, 1965; Knox, 1983; Wells et al., 1987; Bull, 1991). The hypothesis of regional desiccation as the key process forcing fan aggradation continues to dominate the conclusions of southwestern USA research (Throckmorton and Reheis, 1993; Dorn, 1994; Bull, 1996; Harvey and Wells, 1994; Harvey et al., 1999b; Monger and Buck, 1999; Baker et al., 2000; McDonald et al., 2003; Western Earth Surface Processes Team, 2004; Mahan et al., 2007; Sohn et al., 2007). The following conclusions are typical of the regional literature:

> Fan deposition was probably triggered by a change from relatively moist to arid conditions causing a decrease in vegetation cover and increases in flash floods and sediment yield. We think that this scenario applies to most of the other valleys in the southern Basin and Range (Reheis et al., 1996: 279).
>
> Thus, it appears that the initiation of hillslope erosion, fan building, and valley deposition was associated with a climatic shift from moister to drier conditions and a significant change in the nature of uplands vegetation (Miller et al., 2001: 385).

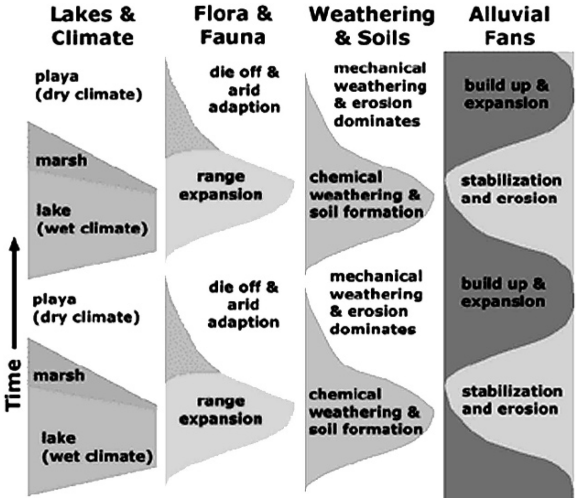

Fig. 24.4 The transition-to-a-drier-climate model has been adopted by the U.S. Geological Survey's Western Earth Surface Processes Team (2004) that explains: "when dry conditions return, the plant cover would eventually become reduced, and episodic desert storms would strip away soil (formed during the proceeding wet period), contributing to the influx of greater amounts of sediments downstream onto alluvial fans"

The transition-to-drier-climate model has certainly been used outside of the USA, in India (Kale and Rajaguru, 1987), Israel (Bull and Schick, 1979; Klinger et al., 2003), and elsewhere. In South Australia incision into a ∼45–40 ka surface (Dorn, 1994: 607), perhaps correlated with a ∼40–30 ka paleosol (Quigley et al., 2007), led to subsequent inset aggradation thought to derive from a transition "from more humid to more arid continental climatic conditions" (Quigley et al., 2007). In Argentina, an abrupt desiccation led to a condition where "the large rivers of the province built alluvial fans in their lower tracts". (Carignano, 1999: 130)

Although there has been international use of the concept, the transition-to-dry hypothesis dominates USA desert alluvial-fan thinking. One signal that a strict mindset exists is when available information is stretched to fit a desired conclusion. For example, very precise pronouncements sometimes emerge from what are truly very broad age ranges: "global climate changes that caused synchronous pulses of alluviation in the Mojave Desert at about 125, 55, and 10 (12 and 8) ka" (Bull, 1996: 217). No such pin-point millennial precision actually supports such a sweeping regional generalization. Another signal of a fixed paradigm comes when one's own evidence is passed over in reaching a conclusion. Despite presenting evidence of ongoing aggradation during transitions from drier to wetter conditions, during wetter conditions, and during a particular high magnitude event, cumulative evidence is still interpreted according to the acceptable southwestern USA paradigm: "[t]he pulse of sediment at the Pleistocene-Holocene transition is consistent with other depositional events identified elsewhere and with geomorphic models (Bull, 1991; McDonald et al., 2003)." (Nichols et al., 2006: 8).

In summary, Southwestern USA researchers have largely restricted themselves to a narrow theoretical framework and methodology that has very little potential to resolve correlation difficulties outlined in the second section of this chapter.

Diversity of Thought Outside of the USA

Alluvial-fan research on arid and semi-arid fans has burgeoned in the last few decades outside of the USA. Furthermore, this non-USA literature that explores connections between dryland fans and climatic change has shown a far greater theoretical flexibility, hosting a large number of alternatives to "transition-to-drier" thinking.

One alternative model is that of paraglacial processes (Ballantyne, 2002) generating large fans found in deserts that can, in some cases, be traced back directly to moraines (Krzyszkowski and Zielinkski, 2002). Many of the large desert fan complexes in central Asia appear to be paraglacial in origin (Rost, 2000; Stokes et al., 2003; Owen et al., 2006). In the southwestern USA, some researchers in the 20th (Huntington, 1907; Dorn, 1994) and 21st centuries (Weissmann et al., 2002; Benn et al., 2006; Dühnforth et al., 2007) have invoked glacial processes as the source of nearby desert-fan sediment. Similarly, enhanced snowfall or periglacial processes might increase sediment flow to fan heads (Dorn, 1994; Carignano, 1999).

A number of researchers argue for enhanced alluvial-fan aggradation during drier periods. The case is made for Calabria, Italy (Sorriso-Valvo, 1988) and in southern Greece (Pope and Millington, 2000; Pope and Wilkinson, 2005). Drier conditions are also thought to generate fan aggradation in the northeastern Tibetan Plateau (Hetzel et al., 2004), western India (Chamyal et al., 2003), and coastal Ecuador (Iriondo, 1994).

Other study sites produce evidence that fan aggradation occurs during the transition period from drier to wetter conditions (Roberts and Barker, 1993). OSL dating in Death Valley, California indicates that the "25 ka Q2d alluvial-fan deposits correlate to a globally and regionally low-effective moisture that is followed by a relatively rapid increase in moisture" (Sohn et al., 2007: 57), and cosmogenic ages from Death Valley suggest fan aggradation also occurred at the dry-wet transition between 63 and 70 ka (Frankel et al., 2007). In western India, it is thought that:

> A sudden change from dry to wet climate can lead to a sudden increase in the discharge resulting in gravel or sand bedload streams with high aggradation rates in the presence of high sediment availability (from the preceding dry phase)...On the other hand, a climatic transition from wet to dry will eventually lead to decimation of the fluvial activity and a simultaneous increase in aeolian activity (Jain and Tandon, 2003: 2231).

A similar argument was made for Tanzania where: in the northeast Irangi Hills, the shift from a dry to a wet climate [deposition occurred]... during this "window" of high erosivity formed by increasing rainfall combined with incomplete vegetation cover. (Eriksson et al., 2000: 123). Commensurately, many argue that a transition from dry to wetter conditions can be one cause of fan-head incision (Owen et al., 1997; Nott et al., 2001; Brown et al., 2003; Jain and Tandon, 2003; Bowman et al., 2004; Poisson and Avouac, 2004) explained as follows:

> [A climate change from cold and dry to warm and humid] encouraged the expansion of vegetation cover over basin slopes, thereby reducing the volume of sediment supplied by each basin. With streams transferring less sediment, an increase in the discharge (Q) to sediment load (Qs) ratio (or more water per unit of sediment) resulted in major entrenchment of the fanhead and proximal fan surfaces (Pope and Millington, 2000: 611).

Another common model, mostly rejected in southwestern USA research, invokes enhanced aggradation during wetter periods. Wet-phase fan aggradation is thought to occur during high lake periods in the Qaidam Basin (Owen et al., 2006), in the Gobi-Altay, Mongolia (Fitz et al., 2003), Australia (Nanson et al., 1992; Kershaw and Nanson, 1993), western India (Bhandari et al., 2005), the northern United Arab Emerites (Al Farraj and Harvey, 2004), Arabia (Glennie and Singhvi, 2002), Oman (Mazels, 1990; Rodgers and Gunatilaka, 2002), southern Spain (Zazo et al., 2008), and Jordan (McLaren et al., 2004). Only a few western USA studies have argued against the transition-to-dry model, suggesting that wetter conditions may generate southwestern USA fan aggradation during the late Pleistocene (Dorn, 1988; Hanson, 2005; DeLong and Arnold, 2007; Dühnforth et al., 2007; DeLong et al., 2008) and Holocene (Liu and Broecker, 2007).

Although the limitation of fan chronometry cannot currently test these different climatic models of fan aggradation, this methodological restriction may not always be the case. The rich and diverse international theory, based on detailed case study analysis, will offer future chronometricians ample opportunity to evaluate these and future theoretical options.

Coupling may also offer potential to sort out the seemingly overwhelming problem of linking intrinsic geomorphic lags and dating uncertainties. Coupling is a fluvial geomorphology concept that conceptually links processes at different spatial and temporal scales (Brunsden, 1993; Allen, 2005). As applied to alluvial fans, coupling could potentially explain fan aggradation during all of the aforementioned climatic conditions: dry intervals, wet phases, as well as transitions to and from aridity (Harvey, 2002a: 189).

Increasing Importance of High Magnitude Floods

There exists a growing momentum in international alluvial-fan research favouring the importance of high magnitude, low frequency floods—regardless of whether the general climatic state is in an arid, humid or transitional phase. Certainly, geomorphologists have long recognized the importance of large, but infrequent floods in deserts (Beaty, 1974; Schick, 1974; Wolman and Gerson, 1978; Talbot and Williams, 1979; Frostick and Reid, 1989; Pickup, 1991; Ely et al., 1993; Schick and Lekach, 1993). However, the last decade has seen a great expansion of interest in and evidence for high magnitude storms as being vital to the interpretation of desert alluvial fans.

Areas first recognized as being heavily impacted by ENSO have been the focus of some of this research (Grosjean et al., 1997). In northern Chile large floods appear to be the dominant cause of sedimentation on fans during the late Pleistocene and Holocene (Mather and Hartley, 2005). Aggradational events in southern Peru are "evidently associated with extremely heavy El Nino-induced precipitation" (Keefer et al., 2003: 70), and these events do appear to be generated by "Mega-Niños" with "higher amplitude climatic perturbations than any in the Peruvian historical record except for the AD 1607–1608 event." (Keefer et al., 2003: 74). The alluvial record in Ecuador indicates changing periodicity of ENSO aggradation over the last 15,000 years (Rodbell et al., 1999). Similarly in Argentina:

> Holocene sedimentary accumulations which are present over a large region, could have been controlled by one specific climatic favor, the activity of the El Niño Southern Oscillation (ENSO). The dynamics of this oscillation suggest. . .that very intense and randomly distributed rainfall could cause floods that are locally very important (Colombo, 2005: 81).

The importance of ENSO events has also been recognized in other deserts (Ely, 1997).

Arid southern Asia also yields research pointing to the key role of large storms. Western India studies suggests that such events may have been more important in the late Pleistocene ∼10–14 ka (Jain and Tandon, 2003) and during marine oxygen isotope stages 3 and 5 (Juyal et al., 2000). "Development of alluvial fans [in Pinjaur Dun] requires intense but infrequent precipitation to create flash-flood discharge needed for transporting sediments from the drainage basin to the fan site. . ." (Suresh et al., 2002: 1273).

In southwestern Asia, in Iran's Abadeh Basin "episodic thundershowers, in an arid-semi-arid climate, resulted in periodic high magnitude runoff and created flash floods towards the feeder channel at the fan apex" (Arzani, 2005: 58). In Syria, there is field evidence of "[a]brupt increases in storm activity, steep talus slopes sensitive to erosion, and the hillslopes directly connected to the alluvial fan over very short distances together accounted for the rapid geomorphic response." (Oguchi and Oguchi, 2004: 138).

The Australian literature has long recognized the importance of extreme events (Pickup, 1991). Even in a situation where the Milankovitch-scale changes suggest a correlation of fan aggradation during a transition-to-drier climate, there is clear recognition of the importance of high magnitude events:

> Despite the general drying of the climate [after approximately 27 ka], the occurrence of major debris flows during this period suggests that extreme rainfall events must have occurred. These high rainfall events would have resulted in dramatic erosion of soils and regolith on slopes covered by the sparser vegetation communities (Nott et al., 2001: 881).

In southeastern Australia, high-energy flood events took place just before the last glacial maxima (Gardner et al., 2006). The Wilkatana alluvial fan displays evidence of "very large magnitude flood events" at millennial-scale intervals (Quigley et al., 2007) during the Holocene.

Century-scale (Thorndrycraft and Benito, 2006) and millennial-scale (Gunster and Skowronek, 2001) increases in large magnitude floods are also recognized as important in Spain. Millennial-scale increases in flooding is viewed as important to understand fans in the hyper-arid intermontane basins of central Asia (Owen et al., 2006), in central Turkey (Kashima, 2002), and in Italy where "infrequent but intense rainfalls" played a key role in mobilizing slope debris (Zanchetta et al., 2004). Recent southwestern USA fan research also indicates importance of high magnitude floods, at least during the Holocene (Griffiths and Webb, 2004;

Lave and Burbank, 2004; Anderson, 2005; Griffiths et al., 2006).

Information on event frequency and magnitude are obviously critical for developing accurate hazard assessment and mitigation strategies (Soeters and van Westen, 1996). This is certainly the case in the Sonoran Desert of Arizona where large infrequent floods have led to channel avulsions on alluvial fans (Field, 2001). Current strategies to assess hazards generate probabilistic flood hazard maps with a constancy in climate (Pelletier et al., 2005), an assumption that may not be valid. Sub-Milankovitch oscillations may change the frequency of high magnitude events in the southwest (Ely, 1997) and elsewhere (Viles and Goudie, 2003).

Given this uncertainty, a study of VML in south-central Arizona in metropolitan Phoenix has been focusing on understanding whether fan avulsion events took place during dry or wet phases of the Holocene. This study utilizes the revolution in the VML technique for analyzing Holocene desert surfaces (Liu and Broecker, 2007). Old channel avulsions are represented by abandoned alluvial-fan segments that occur throughout the metropolitan Phoenix region (Committee on Alluvial Fan Flooding, 1996). In all 42 abandoned Holocene fan surfaces exiting three ranges hosting development on the urban fringe (Fig. 24.5) have been sampled for VML.

There does appear to be a weak association between fan avulsion events and millennial-scale climate change in this northern portion of the Sonoran Desert (Fig. 24.6). Avulsions leading to fan-surface abandonment appear to have occurred three-quarters of the time during wetter periods of the Holocene. Thus, there may be a need to adjust current probabilistic strategies (Pelletier et al., 2005) for assessment of fan hazards in this sprawling urban centre.

As indicated previously, there are inherent limitations in the use of VML results to connect these central Arizona fan events with climatic change. First, the avulsion events—likely from large floods but not necessarily (Field, 2001)—could have taken place during decadal or century droughts that reduced vegetation cover, all nested within a millennial-scale wet phase. Second, single chronometric tools should always be eschewed, especially when attempting correlations with sub-Milankovitch-scale events. The use of multiple chronometric tools such as OSL in tandem with VML will help identify definitive clustering of fan-altering flood events. Third, intrinsic geomorphic

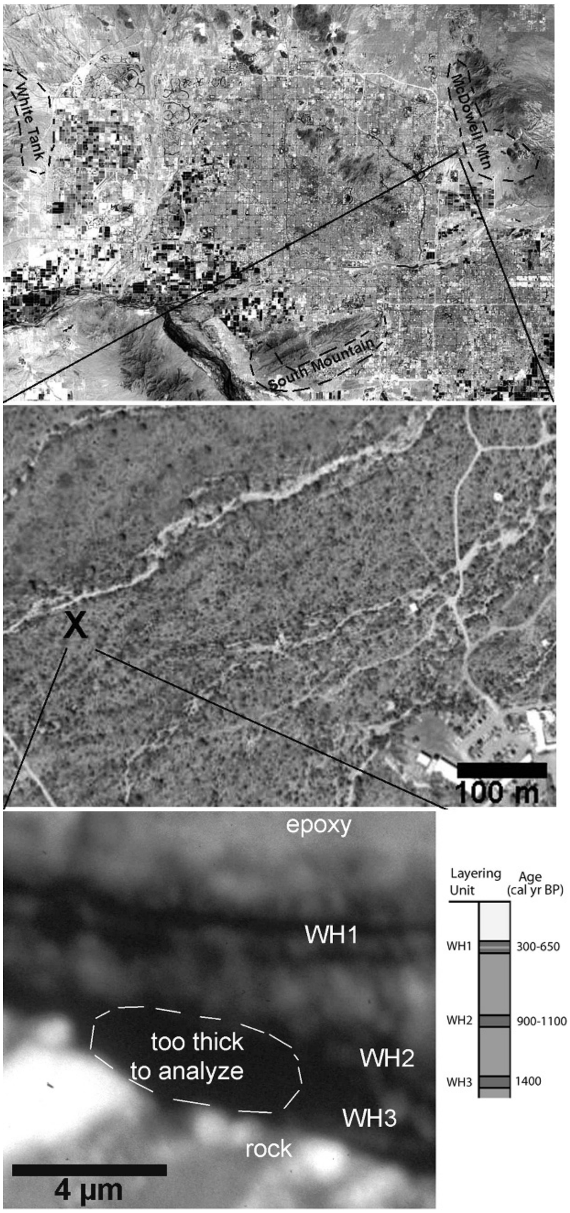

Fig. 24.5 VML analysis is used to study fan avulsion events on the edges of a sprawling desert metropolis. Three study areas are on the southern (South Mountain piedmont), western (western White Tank Mountains piedmont), and northeastern (western McDowell Mountains piedmont) fringes of metropolitan Phoenix, Arizona, as identified on a 2005 Landsat image ~75 km across. The middle aerial photograph from the McDowell Piedmont identifies the collection location of the lower image of an ultra-thin section from this site. Annotations correspond with the VML Holocene calibration (Liu and Broecker, 2007)

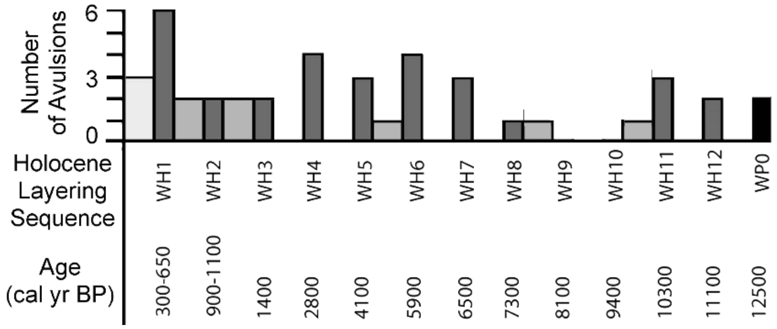

Fig. 24.6 Number of different fan avulsions on the fringe of metropolitan Phoenix, Arizona, associated with different millennial-scale climatic intervals in the Holocene—as recorded by varnish microlaminations (Liu and Broecker, 2007). For example, WH1 is the wet Holocene period 1. Six identified avulsion events took place during this Little Ice Age interval. Three avulsions took place in the time since WH1, and two avulsions took place in the dry interval between WH1 and WH2

adjustments likely differ from one drainage basin to another, setting the geomorphic table at different times with differential time lags. Fourth, the climatic conditions needed to cause a change in varnish layering may not necessarily match the threshold needed to alter alluvial fans. Lastly, just because these results for central Arizona match a debris fan in Death Valley (Liu and Broecker, 2007) should not in anyway be used to infer a regional pattern. Similar studies in other areas may identify broad correlations between extreme fan-flooding events and drier periods of the Holocene. Thus, even using the highest resolution dating method available to desert alluvial-fan researchers, linkages between fan development and climatic change are tenuous.

Summary

The connection between desert alluvial fans and climatic change runs very deep in desert geomorphology. Initial thoughts in the early 20th century connected fan evolution to wetter glacial periods and to times when climate change reduced protective vegetation cover. The mid-20th century saw desert fan research focused in the southwestern USA, and a climatic-change paradigm evolved for this region. The vast majority of southwestern USA alluvial-fan research carried out in the last two decades promotes the hypothesis that alluvial-fan surfaces found throughout the region were produced during transitions between wetter and drier Milankovitch-scale climatic intervals.

International desert alluvial-fan studies have burgeoned in the last decade and now carry the lead of innovation in method and theory building. This extensive literature includes hypotheses that fan building may have taken place during dry periods, wet phases, transitions from dry to wet conditions, as well as transitions from wet to dry times.

Despite the persistent focus by desert geomorphologists on linkages between climatic change and alluvial-fan development, there are major limitations to this entire subfield of desert geomorphology. First, fan deposits are not diagnostic of any particular climatic condition, and thus sedimentology and stratigraphy cannot be used as an indicator of climatic change without independent chronometric support. Second, dating methods are not capable of correlating geomorphic events to sub-Milankovitch climatic changes with any degree of certainty. The highest resolution methods available to desert geomorphologists can only suggest groupings of events with millennial-scale climatic periods. The ability to connect fan-building events to decadal or century-scale oscillations is highly speculative at best. Third, controlled research designs rest at the foundation of our science, yet controlled experiments are not possible in field research because all study sites have experienced climatic change. Thus, modelling studies that control climate must play an increasingly important role in the future. Fourth, high magnitude storms have taken on increased importance in the past decade in alluvial-fan research, and there exists no mechanism to falsify the hypothesis that "catastrophic" meteorological storms truly form desert fans, regardless of the climatic period of the event. Fifth, perhaps the single largest obstacle to understanding the role of climatic change rests in the uncertainty of time scales of internal geomorphic adjustments to climatic changes (Brunsden, 2001; Harvey, 2002a; Viles and Goudie, 2003; Oguchi and Oguchi, 2004; Thomas, 2004). For these reasons, understanding the role of climatic change on desert alluvial-fan development remains an incredibly challenging task.

Acknowledgments Thanks to Arizona State University for providing sabbatical support, to T. Liu for permission to adapt graphics for use in Fig. 24.3, and to reviews from colleagues and students. The views stated here, however, are those of the author.

References

Al Farraj, A., and Harvey, A. M., 2004. Late Quaternary interactions between aeolian and fluvial processes: A case study in the northern UAE. *Journal of Arid Environments* **56**: 235–248.

Allen, P., 2005. Striking a chord. *Nature* **434**: 961.

Alonso-Zarza, A. M., Silva, P. G., Goy, J. L., and Zazo, C., 1998. Fan-surface dynamics and biogenic calcrete development: Interactions during ultimate phases of fan evolution in the semiarid SE Spain (Murcia). *Geomorphology* **24**: 147–167.

Anderson, D. E., 2005. Holocene fluvial geomorphology of the Amargosa River through Amargosa Canyon, California. *Earth-Science Reviews* **73**: 291–307.

Arz, H. W., Patzold, J., and Wefer, G., 1998. Correlated millennial-scale changes in surface hydrography and terrigenous sediment yield inferred from last-glacial marine deposits off northeastern Brazil. *Quaternary Research* **50**: 157–166.

Arzani, N., 2005. The fluvial megafan of Abarkoh Basin (Central Iran): an exmaple of flash-flood sedimentation in arid lands. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 41–59.

Baker, R. G., Fredlund, G. G., Mandel, R. D., and Bettis III, E. A., 2000. Holocene environments of the central Great Plains: multi-proxy evidence from alluvial sequences, southeastern Nebraska. *Quarternary International* **67**: 75–88.

Baker, V. R., 2006. Palaeoflood hydrology in a global context. *Catena* **66**: 161–168.

Ballantyne, C. K., 2002. Paraglacial geomorphology. *Quaternary Science Reviews* **21**: 1935–2017.

Beaty, C. B., 1974. Debris flows, alluvial fans, and a revitalized catastrophism. *Zeitschrift für Geomorphology N.F. Supplement Band* **21**: 39–51.

Beaudoin, A. B., and King, R. H., 1994. Holocene palaeoenvironmental record preserved in a paraglacial alluvial fan, Sunwapta Pass, Jasper National Park, Alberta, Canada. *Catena* **22**: 227–248.

Benn, D. I., Owen, L. A., Finkel, R. C., and Clemmens, S., 2006. Pleistocene lake outburst foods and fan formation along the eastern Sierra Nevada,California:implications for the interpretation of intermontane lacustrine records. *Quaternary Science Reviews* **25**: 2729–2748.

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., and Lindstrom, S., 2002. Holocene multidecadal and multicentennial droughts affecting northern California and Nevada. *Quaternary Science Reviews* **21**: 659–682.

Besler, H., 1976. Climatic conditions and climatic geomorphology with respect to zoning in central Namib (Southwest Africa). *Geographische Zeitschrift* **64**: 155.

Bettis III, E. A., 2003. Patterns in Holocene colluvium and alluvial fans across the prairie-forest transition in the midcontinent USA. *Geoarchaeology* **18**: 779–797.

Bhandari, S., Maurya, D. M., and Chamyal, L. S., 2005. Late Pleistocene alluvial plain sedimentation in Lower Narmada Valley, Western India: Palaeoenvironmental implications. *Journal of Asian Earth Sciences* **24**: 433–444.

Bird, M. I., Turneya, C. S. M., Fifield, L. K., Jones, R., Aylifee, L. K., Palmer, A., Cresswell, R., and Robertson, S., 2002. Radiocarbon analysis of the early archaeological site of Nauwalabila I, Arnhem Land, Australia: implications for sample suitability and stratigraphic integrity. *Quaternary Science Reviews* **21**: 1061–1075.

Birks, H. H., and Ammann, B., 2000. Two terrestrial records of rapid climatic change during the glacial-Holocene transition (14,000–9,000 calendar years BP) from Europe. *Proceedings of the National Academy of Sciences of The United States of America* **97**(4): 1390–1394.

Blair, T. C., 1987. Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park. *Journal of Sedimentary Petrology* **57**: 1–18.

Blair, T. C., 1999. Alluvial fan and catchment initiation by rock avalanching, Owens Valley, California. *Geomorphology* **28**: 201–221.

Blainey, J. B., and Pelletier, J. D., 2008. Infiltration on alluvial fans in arid environments: Influence of fan morphology. *Journal of Geophysical Research – Earth Surface* **113**: Article number F03008.

Blair, T.C., and McPherson, J.G., 1994. Alluvial Fan processes and Forms. In: *Geomorphology of Desert Environments*. A.J. Parsons and A.D. Abrahams (eds.), Chapman and Hall, London, pp. 344–402.

Blair, T. C., and McPherson, J. G., 2009. Alluvial fan processes and forms. In: *Geomorphology of Desert Environments (2nd Edn)*, A. D. Abrahams and A. J. Parsons (eds.)

Blum, M. D., and Tornqvist, T. E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology* **47**: 2–48.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* **278**: 1257–1266.

Bowman, D., 1988. The declining but non-rejuvinating base level – Lisan Lake, the Dead Sea area, Israel. *Earth Surface Processes and Landforms* **13**: 239–249.

Bowman, D., Korjenkov, A., Porat, N., and Czassny, B., 2004. Morphological response to Quaternary deformation at an intermontane basin piedmont, the northern Tien Shan, Kyrghyzstan. *Geomorphology* **63**: 1–24.

Brierley, G. J., Liu, K., and Crook, K. A. W., 1993. Sedimentology of coarse- grained alluvial fans in the Markham Valley, Papua New Guinea. *Sedimentary Geology* **86**: 297–324.

Brown, E. T., Bendick, R., Bourles, D. L., Gaur, V., Molnar, P., Raisbeck, G., and Yiou, F., 2003. Early Holocene climate recorded in geomorphological features in Western Tibet. *Palaeogeography, Palaeoclimatology, Palaeoecology* **199**: 141–151.

Brunsden, D., 1993. Barriers to geomorphological change. In: *Landscape Sensitivity*, D. S. G. Thomas and R. J. Allison (eds.), Wiley, Chichester, pp. 7–12.

Brunsden, D., 2001. A critical assessment of the sensitivity concept in geomorphology. *Catena* **42**: 83–98.

Büdel, J., 1982. *Climatic Geomorphology. Translated by Lenore Fischer and Detlef Busche*. Princeton University Press, Princeton, New Jersey, 443p.

Bull, W. B., 1975. Allometric change of landforms. *Geological Society of America Bulletin* **86**: 1489–1498.

Bull, W. B., 1991. *Geomorphic responses to climatic change*. Oxford University Press, Oxford, 326p.

Bull, W. B., 1996. Global climate change and active tectonics: effective tools for teaching and research. *Geomorphology* **16**: 217–232.

Bull, W. B., and Schick, A. P., 1979. Impact of climatic change on an arid watershed: Nahal Yael, southern Israel. *Quaternary Research* **11**: 153–171.

Calvache, M. L., Viseras, C., and Fernandez, J., 1997. Controls on fan development – evidence from fan morphometry and sedimentology; Sierra Nevada, SE Spain. *Geomorphology* **21**: 69–84.

Carignano, C. A., 1999. Late Pleistocene to recent climate change in Cordoba Province, Argentina: Geomorphological evidence. *Quaternary International* **57/58**: 117–134.

Chamyal, L. S., Maurya, D. M., and Raj, R., 2003. Fluvial systems of the drylands of western India: a synthesis of Late Quaternary environmnetal and tectonic changes. *Quaternary International* **104**: 69–86.

Chawner, W. D., 1935. Alluvial fan flooding. *Geographical Review* **25**: 255–263.

Chitale, J. D., 1986. Study of Petrography and Internal Structures in Calcretes of West Texas and New Mexico (Microtextures, Caliche). Ph.D. Dissertation, Thesis thesis, 120pp., Texas Tech University, Lubbock.

Clevis, Q., de Boer, P., and Wachter, M., 2003. Numerical modelling of drainage basin evolution and three-dimensional alluvial fan stratigraphy. *Sedimentary Geology* **163**: 85–110.

Colombo, F., 2005. Quaternary telescopic-like alluvial fans, Andean Ranges, Argentina. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 69–84.

Committee on Alluvial Fan Flooding, N. R. C., 1996. *Alluvial fan flooding*. National Academy of Science Press, Washington D.C., 172p.

Coulthard, T. J., Macklin, M. G., and Kirkby, M. J., 2002. A cellular model of Holocene upland river basin and alluvial fan evolution. *Earth Surface Processes and Landforms* **27**: 269–288.

Cremaschi, M., 1992. Genesi e significato paleoambientale della patina del deserto e suo ruolo nello studio dell'arte rupestre. Il caso del Fezzan meridionale (Sahara Libico). In: *Arte e Culture del Sahara Preistorico*, M. Lupaciollu (ed.), Quasar, Rome, pp. 77–87.

Cremaschi, M., 1996. The desert varnish in the Messak Sattafet (Fezzan, Libryan Sahara), age, archaeological context and paleo-environmental implication. *Geoarchaeology* **11**: 393–421.

Crosta, G. B., and Frattini, P., 2004. Controls on modern alluvial fan processes in the central Alps, northern Italy. *Earth Surface Processes and Landforms* **29**: 267–293.

Crouvi, O., Ben-Dor, E., Beyth, M., Avigad, D., and Amit, R., 2006. Quantitative mapping of arid alluvial fan surfaces using field spectrometer and hyperspectral remote sensing. *Remote Sensing of the Environment* **104**: 103–117

Curry, W. B., and Oppo, D. O., 1997. Synchronous high frequency oscillations in tropical sea-surface temperatures and North Atlantic deep water production during the last glacial cycle. *Paleooceanography* **12**: 1–14.

Davies, T. R. H., and Korup, O., 2006. Persistent alluvial fanhead trenching resulting from large, infrequent sediment inputs. *Earth Surface Processes and Landforms* **32**: 725–742.

De Chant, L. J., Pease, P. P., and Tchakerian, V. P., 1999. Modelling alluvial fan morphology. *Earth Surface Processes and Landforms* **24**: 641–652.

DeLong, S. B., and Arnold, L. J., 2007. Dating alluvial deposits with optically stimulated luminescence, AMS C-14 and cosmogenic techniques, western Transverse Ranges, California, USA. *Quaternary Geochronology* **2**: 129–136.

DeLong, S. B., Pelletier, J. D., and Arnold, L. J., 2008. Climate change triggered sedimentation and progressive tectonic uplift in a coupled piedmont-axial system: Cuyama Valley, California, USA. *Earth Surface Processes and Landforms* **33**: 1033–1046.

Denny, C. S., 1965. Alluvial fans in the Death Valley region of California and Nevada. *U.S. Geological Survey Professional Paper* **466**.

Denny, C. S., 1967. Fans and pediments. *American Journal Science* **265**: 81–105.

Derbyshire, E. D., 1993. *Climatic Geomorphology*. Macmillan, London, 296p.

Diaz, T. A., Bailley, T. L., and Orndorff, R. L., 2002. SEM analysis of vertical and lateral variations in desert varnish chemistry from the Lahontan Mountains, Nevada. *Geological Society of America Abstracts with Programs* **May 7–9 Meeting**: <///gsa.confex.com/gsa/2002RM/finalprogram/abstract_33974.htm>.

Dorn, R. I., 1984. Cause and implications of rock varnish microchemical laminations. *Nature* **310**: 767–770.

Dorn, R. I., 1988. A rock varnish interpretation of alluvial-fan development in Death Valley, California. *National Geographic Research* **4**: 56–73.

Dorn, R. I., 1990. Quaternary alkalinity fluctuations recorded in rock varnish microlaminations on western U.S.A. volcanics. *Palaeogeography, Palaeoclimatology, Palaeoecology* **76**: 291–310.

Dorn, R. I., 1994. Alluvial fans an an indicator of climatic change. In: *Geomorphology of Desert Environments*, A. D. Abrahams and A. J. Parsons (eds.), Chapman & Hall, London, pp. 593–615.

Dorn, R. I., 1996. Climatic hypotheses of alluvial-fan evolution in Death Valley are not testable. In: *The Scientific Nature of*

Geomorphology, B. L. Rhoads and C. E. Thorn (eds.), Wiley, New York, pp. 191–220.

Dühnforth, M., Densmore, A. L., Ivy-Ochs, S., Allen, P. A., and Kubik, P. W., 2007. Timing and patterns of debris flow deposition on Shepherd and Symmes creek fans, Owens Valley, California, deduced from cosmogenic ^{10}Be. *Journal of Geophysical Research* **112**: Art. No. F03S15.

Eckis, R., 1928. Alluvial fans in the Cucamonga district, southern California. *Journal of Geology* **36**: 111–141.

Ellwood, B. B., and Gose, W. A., 2006. Heinrich H1 and 8200 yr B.P. climate events recorded in Hall's Cave, Texas. *Geology* **34**: 753–756.

Elorza, M. G., 2005. *Climatic geomorphology*. Elsevier, Amsterdam, 774p.

Ely, L., 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. *Geomorphology* **19**: 175–201.

Ely, L. L., Enzel, Y., Baker, V. R., and Cayan, D. R., 1993. A 5000-year-record of extreme floods and climate change in the southwestern United States. *Science* **262**: 410–412.

Enfield, D. B., Mestas-Nunez, A. M., and Trimble, P. J., 2000. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research letters* **28**: 2077–2080.

Eriksson, M. G., Olley, J. M., and Payton, R. W., 2000. Soil erosion history in central Tanzania based on OSL dating of colluvial and alluvial hillslope deposits. *Geomorphology* **36**: 107–128.

Evenstar, L., Hartley, A., Rice, C., Stuart, F., Mather, A. E., and Guillermo, C., 2006. Miocene-Pliocene climate change in the Peru-Chile Desert. *6th International Symposium on Andean Geodynamics (ISAG 2005, Barcelona)* **Extended Abstracts**: 258–260.

Falloon, P. D., and Smith, P., 2000. Modeling refractory soil organic matter. *Biology and fertility of soils* **30**: 388–398.

Fard, A. M., 2001. Recognition of abrupt climatic changes in clastic sedimentary environments: an introduction. *Global and Planetary Change* **28**: ix–xii.

Farr, T. G., and Chadwick, O. A., 1996. Geomorphic processes and remote sensing signatures of alluvial fans in the Kun Lun mountains, China. *Journal of Geophysical Research-Planets* **101**(E10): 23091–23100.

Field, J., 2001. Channel avulsion on alluvial fans in southern Arizona. *Geomorphology* **37**: 93–104.

Fitz, J.-F., Bourles, D., Brown, E. T., Carretier, S., Chery, J., Enhtuvshin, B., Galsan, P., Finkel, R. C., Hanks, T. C., Kendrick, K. J., Philip, H., Raisbeck, G., Schlupp, A., Schwartz, D. P., and Yiou, F., 2003. Late Pleistocene to Holocene slip rates for the Gurvan Bulag thrust fault (Gobi-Altay, Mongolia) estimated with ^{10}Be dates. *Journal of Geophysical Research* **108**(B3): 2162, doi:10.1029/2001JB000553, 2003.

Frankel, K. L., Brantley, K. S., Dolan, J. F., Finkel, R. C., Klinger, R. E., Knott, J. R., Machette, M. N., Owen, L. A., Phillips, F. M., Slate, J. L., and Wernicke, B. P., 2007. Cosmogenic Be-10 and Cl-36 geochronology of offset alluvial fans along the northern Death Valley fault zone: Implications for transient strain in the eastern California shear zone. *Journal of Geophysical Research – Solid Earth* **112**: Art. No. B06407.

Frostick, L. E., and Reid, I., 1989. Climatic versus tectonic control of fan sequences – lessons from the Dead Sea, Israel. *Journal of the Geological Society, London* **146**: 527–538.

Garcia-Melendez, E., Goy, J. L., and Zazo, C., 2003. Neotectonics and Plio-Quaternary landscape development within the eastern Huercal-Overa Basin (Betic Cordilleras, southeast Spain). *Geomorphology* **50**: 111–133.

Gardner, T. W., Webb, J., Davis, A. G., Cassel, E. J., Pezzia, C., Merritts, D. J., and Smith, B., 2006. Late Pleistocene landscape response to climate change: eolian and alluvial fan deposition Cape Liptrap, southeastern Australia. *Quaternary Science Reviews* **25**: 1552–1569.

Gillespie, R., Prosser, I. P., Dlugokencky, E., Sparks, R. J., Wallace, G., and Chappell, J. M. A., 1992. AMS Dating of Alluvial Sediments on the Southern Tablelands of New-South-Wales, Australia. *Radiocarbon* **34**: 29–36.

Glennie, K. W., and Singhvi, A. K., 2002. Event stratigraphy, paleoenvironment and chronology of SE Arabian deserts. *Quaternary Science Reviews* **21**: 853–869.

Gomez, B., Banbury, K., Marden, M., Trustrum, N. A., Peacock, D. H., and Hoskin, P. J., 2003. Gully erosion and sediment production: Te Weroroa Stream, New Zealand. *Water Resources Research* **39**(7): 1187.

Gómez-Villar, A., Álvarez-Martínez, J., and García-Ruiz, J. M., 2006. Factors influencing the presence or absence of tributary-junction fans in the Iberian Range, Spain. *Geomorphology* **81**: 252–264.

Griffiths, P. G., Hereford, R., and Webb, R. H., 2006. Sediment yield and runoff frequency of small drainage basins in the Mojave Desert, USA. *Geomorphology* **74**: 232–244.

Griffiths, P. G., and Webb, R. H., 2004. Frequency and initiation of debris flows in Grand Canyon, Arizona. *Journal of Geophysical Research* **109**: F04002.

Grosjean, M., Nunez, L., Castajena, I., and Messerli, B., 1997. Mid-Holocene climate and culture changes in the Atacama Desert, northern Chile. *Quaternary Research* **48**: 239–246.

Guerra-Merchan, A., Serrano, F., and Ramallo, D., 2004. Geomorphic and sedimentary Plio–Pleistocene evolution of the Nerja area (northern Alboran basin, Spain). *Geomorphology* **60**: 89–105.

Gunster, N., and Skowronek, A., 2001. Sediment- soil sequences in the Granada Basin as evidence for long-and short-term climatic changes during the Pliocene and Quaternary in the Western Mediterranean. *Quaternary International* **78**: 17–32.

Hagedorn, H., and Rapp, A., 1989. *Geomorphology and Geoecology: Climatic Geomorphology. Proceedings of the Second International Conference on Geomorphology and Geoecology*. Zeitschrift für Geomorphologie Supplementbände Band 84, Frankfurt, 201p.

Hanson, P. R., 2005. Alluvial fan response to climate change along the lower Colorado River. *Geological society of America Abstracts with Program, Salt Lake City Meeting* **37**(7): 110.

Hardy, S., and Gawthorpe, R., 2002. Normal fault control on bedrock channel incision and sediment supply: Insights from numerical modeling. *Journal of Geophysical Research* **107**(B10): 2246.

Harkins, N. W., Anastasio, D. J., and Pazzaglia, F. J., 2005. Tectonic geomorphology of the Red Rock fault, insights into segmentation and landscape evolution of a developing range front normal fault. *Journal of Structural Geology* **27**: 1925–1939.

Hartley, A., Mather, A. E., Jolley, E., and Turner, P., 2005. Climatic controls on alluvial-fan activity, Coastal Cordillera, northern Chile. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 95–115.

Harvey, A. M., 1984. Aggradation and dissection sequences on Spanish alluvial fans: influence on morphological development. *Catena* **11**: 289–304.

Harvey, A. M., 1997. The role of alluvial fans in arid zone fluvial systems. In: *Arid Zone Geomorphology*, D. S. G. Thomas (ed.), Wiley, Chichester, pp. 231–260.

Harvey, A. M., 2002a. Effective timescales of coupling within fluvial systems. *Geomorphology* **44**: 175–201.

Harvey, A. M., 2002b. The role of base-level change in the dissection of alluvial fans: case studies from southeast Spain and Nevada. *Geomorphology* **45**: 67–87.

Harvey, A. M., Foster, G., Hannam, J., and Mather, A., E., 2003. The Tabernas alluvial fan and lake system, southeast Spain: applications of mineral magnetic and pedogenic iron oxide analyses towards clarifying the Quaternary sediment sequences. *Geomorphology* **50**: 151–171.

Harvey, A. M., Mather, A. E., and Stokes, M., 2005. Alluvial fans: geomorphology, sedimentology, dynamics – introduction. A review of alluvial-fan research. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 1–7.

Harvey, A. M., Silva, P. G., Mather, A. E., Goy, J. L., Stokes, M., and Zazo, C., 1999a. The impact of Quaternary sea-level and climatic change on coastal alluvial fans in the Cabo de Gata ranges, southeast Spain. *Geomorphology* **28**: 1–22.

Harvey, A. M., and Wells, S. G., 1994. Late Pleistocene and Holocene changes in hillslope sediment supply to alluvial fan systems: Zzyzx, California. In: *Environmental Change in Drylands: Biogeographical and Geomorphological Perspectives*, A. C. Millington and K. Pye (eds.), Wiley & Sons, London, pp. 67–84.

Harvey, A. M., Wigand, P. E., and Wells, S. G., 1999b. Response of alluvial fan systems to the late Pleistocene to Holocene climatic transition: contrasts between the margins of pluvial Lakes Lahontan and Mojave, Nevada and California, USA. *Catena* **36**: 255–281.

Henderson, G. M., 2006. Caving in to new chronologies. *Science* **313**: 620–622.

Hetzel, R., Tao, M., Stokes, S., Niedermann, S., Ivy-Ochs, S., Gao, B., Strecker, M. R., and Kubik, P. W., 2004. Late Pleistocene//Holocene slip rate of the Zhangye thrust (Qilian Shan, China) and implications for the active growth of the northeastern Tibetan Plateau. *Tectonics* **23**: TC6006.

Hooke, R. L., 1967. Processes on arid region alluvial fans. *Journal Geology* **75**: 438–460.

Hooke, R. L., 1968. Steady-state relationships on arid-region alluvial fans in closed basins. *American Journal Science* **266**: 609–629.

Hooke, R. L., and Rohrer, W. L., 1977. Relative erodibility of source-area rock types, as determined from second order variations in alluvial fan size. *Geological Society of America Bulletin* **88**: 1177–1182.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., Climate change 2001. *The scientific basis*. Cambridge University Press, Cambridge, p. 881.

House, P. K., 2005. Using geology to improve flood hazard management on alluvial fans – An example from Laughlin, Nevada. *Journal of the American Water Resources Association* **41**: 1431–1447.

House, P. K., and Baker, V. R., 2001. Paleohydrology of flash floods in small desert watersheds in western Arizona. *Water Resources Research* **37**: 1825–1839.

Hsu, L., and Pelletier, J. D., 2004. Correlation and dating of Quaternary alluvial-fan surfaces using scarp diffusion. *Geomorphology* **60**: 319–335.

Huggett, R. J., 1998. Soil chronosequences, soil development, and soil evolution: a critical review. *Catena* **32**: 155–172.

Huntington, E., 1907. Some characteristics of the glacial period in non-glaciated regions. *Geological Society of America Bulletin* **18**: 351–388.

Ibbeken, H., Warnke, D. A., and Diepenbroek, M., 1998. Granulometric study of the Hanaupah fan, Death Valley, California. *Earth Surface Processes and Landforms* **23**: 481–492.

Iriondo, M., 1994. The Quaternary of Ecuador. *Quaternary International* **21**: 101–112.

Jain, M., and Tandon, S. J., 2003. Fluvial response to Late Quaternary climate changes, western India. *Quaternary Science Reviews* **22**: 2223–2235.

Jansson, P., Jacobson, D., and Hooke, R. L., 1993. Fan and playa areas in southern California and adjacent parts of Nevada. *Earth Surface Processes and Landforms* **18**: 109–119.

Juyal, N., Rachna, R., Maurya, D. M., Chamyal, L. S., and Singhvi, A. K., 2000. Chronology of Late Pleistocene environmental changes in the lower Mahi basin, Western India. *Journal of Quaternary Science* **15**: 501–508.

Kale, V. S., and Rajaguru, S. N., 1987. Late Quaternary alluvial history of the Northwestern Deccan upland region. *Nature* **325**: 612–614.

Kale, V. S., Singhvi, A. K., Mishra, P. K., and Banerjee, D., 2000. Sedimentary records and luminescence chronology of Late Holocene palaeofloods in the Luni River, Thar Desert, northwest India. *Catena* **40**: 337–358.

Kashima, K., 2002. Environmental and climatic changes during the last 20,000 years at Lake Tuz, central Turkey. *Catena* **48**: 3–20.

Keefer, D. K., Moseley, M. E., and deFrance, S. D., 2003. A 38 000-year record of floods and debris flows in the Ilo region of southern Peru and its relation to El Niño events and great earthquakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* **194**: 41–77.

Kershaw, A. P., and Nanson, G. C., 1993. The last full glacial cycle in the Australian region. *Global and Planetary Change* **7**: 1–9.

Kesel, R. H., and Spicer, B. E., 1985. Geomorphologic relationships and ages of soils on alluvial fans in the Rio General Valley, Costa Rica. *Catena* **12**: 149–166.

Klinger, Y., Avouac, J. P., Bourles, D., and Tisnerat, N., 2003. Alluvial deposition and lake-level fluctuations forced by Late Quaternary climate change: the Dead Sea case example. *Sedimentary Geology* **162**: 119–139.

Knott, J. R., Sarna-Wojcicki, A. M., Machette, M. N., and Klinger, R. E., 2005. Upper Neogene stratigraphy and tectonics of Death Valley – A review. *Earth Science Reviews* **73**: 245–270.

Knox, J. C., 1983. Responses of river systems to Holocene climates. In: *Late Quaternary Environments of the United States. Vol. 2. The Holocene*, H. E. J. Wright (ed.), University Minnesota Press, Minneapolis, pp. 26–41.

Kochel, R. G., Miller, J. R., and Ritter, J. B., 1997. Geomorphic response to minor cyclic climate changes, San Diego County, California. *Geomorphology* **19**: 277–302.

Kostaschuk, R. A., MacDonald, G. M., and Putnam, P. E., 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. *Earth Surface Processes and Landforms* **11**: 471–484.

Krohling, D. M., and Iriondo, M., 1999. Upper Quaternary Palaeoclimates of the Mar Chiquita area, North Pampa, Argentina. *Quaternary International* **57/58**: 149–163.

Krzyszkowski, D., and Zielinkski, T., 2002. The Pleistocene end moraine fans: controls on the sedimentation and location. *Sedimentary Geology* **149**: 73–92.

Lafortune, V., Filion, L., and Hétu, B., 2006. Impacts of Holocene climatic variations on alluvial fan activity below snowpatches in subarctic Québec. *Geomorphology* **76**: 375–391.

Lave, J., and Burbank, D., 2004. Denudation processes and rates in the Transverse Ranges, southern California: Erosional response of a transitional landscape to external and anthropogenic forcing. *Journal of Geophysical Research* **109**: F01006.

Lee, M. R., and Bland, P. A., 2003. Dating climatic change in hot deserts using desert varnish on meteorite finds. *Earth and Planetary Science Letters* **206**: 187–198.

Leeder, M. R., Harris, T., and Kirkby, M. J., 1998. Sediment supply and climate change: implications for basin stratigraphy. *Basin Research* **10**: 7–18.

Lehmkuhl, F., and Haselein, F., 2000. Quaternary paleoenvironmental change on the Tibetan Plateau and adjacent areas (Western China and Western Mongolia). *Quaternary International* **65**: 121–145.

Leier, A. L., DeCelles, P. G., and Pelletier, J. D., 2005. Mountains, monsoons, and megafans. *Geology* **33**: 289–292.

Liu, B., Phillips, F. M., Pohl, M. M., and Sharma, P., 1996. An alluvial surface chronology based on cosmogenic ^{36}Cl dating, Ajo Mountains (Organ Pipe Cactus National Monument), Southern Arizona. *Quaternary Research* **45**: 30–37.

Liu, T., 2003. Blind testing of rock varnish microstratigraphy as a chronometric indicator: results on late Quaternary lava flows in the Mojave Desert, California. *Geomorphology* **53**: 209–234.

Liu, T., 2008. VML Dating Lab. *http://www.vmldatinglab.com/*: accessed June 24, 2006.

Liu, T., and Broecker, W., 2007. Holocene rock varnish microstratigraphy and its chronometric application in drylands of western USA. *Geomorphology* **84**: 1–17.

Liu, T., and Broecker, W.S., 2008. Rock varnish microlamination dating of late Quaternary geomorphic features in the drylands of western USA. *Geomorphology* **93**: 501–523.

Liu, T., and Dorn, R. I., 1996. Understanding spatial variability in environmental changes in drylands with rock varnish microlaminations. *Annals of the Association of American Geographers* **86**: 187–212.

Ljungdahl, L., and Eriksson, K., 1985. Ecology of microbial cellulose degradation. *Advances in Microbial Ecology* **8**: 237–299.

Mabbutt, J. C., 1977. *Desert landforms*. Australian National University Press, Canberra, 340p.

Madsen, D. B., Chen, F., Oviatt, G., Zhu, Y., Brantingham, P. J., Elston, R. G., and Bettinger, R. L., 2003. Late Pleistocene/Holocene wetland events recorded in southeast Tengger Desert lake sediments, NW China. *Chinese Science Bulltin* **48**: 1423–1429.

Mahan, S. A., Miller, D. M., Menges, C. M., and Yount, J. C, 2007. Late Quaternary stratigraphy and luminescence geochronology of the northeastern Mojave Desert. *Quaternary International* **166**: 61–78.

Marston, R. A., 2003. Editorial note. *Geomorphology* **53**: 197.

Masson-Delmotte, V., Jouzel, J., Landais, A., Stievenard, M., Johnsen, S. J., White, J. W. C., Werner, M., Sveinbjornsdottir, A., and Fuhrer, K., 2005. GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin. *Science* **209**: 118–121.

Mather, A. E., and Hartley, A., 2005. Flow events on a hyper-arid alluvial fan: Quebrada Tambores, Salar de Atacama, northern Chile. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 9–29.

Matmon, A., Schwartz, D. P., Finkel, R., Clemmens, S., and Hanks, T. C., 2005. Dating offset fans along the Mojave section of the San Andreas fault using cosmogenic ^{26}Al and ^{10}Be. *Geological Society of America Bulletin* **117**: 795–807.

Mazels, J. L., 1990. Long-term palaeochannel evolution during episodic growth of an exhumed alluvial fan, Oman. In: *Alluvial Fans: A Field Approach*, A. H. Rachocki and M. Church (eds.), Wiley, Chichester, pp. 271–304.

McDonald, E. V., McFadden, L. D., and Wells, S. G., 2003. Regional response of alluvial fans to the Pleistocene-Holocene climatic transition, Mojave Desert, California. *Geological Society of America Special Paper* **368**: 189–205.

McLaren, S. J., Gilbertson, D. D., Grattan, J. P., Hunt, C. O., Duller, G. A. T., and Barker, G. A., 2004. Quaternary palaeogeomorphologic evolution of the Wadi Faynan area, southern Jordan. *Palaeogeography, Palaeoclimatology, Palaeoecology* **205**: 131–154.

Melton, M. A., 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. *Journal Geology* **73**: 1–38.

Miller, J. R., Germanoski, D., Waltman, K., Rausch, R., and Chambers, J., 2001. Influence of late Holocene hillslope processes and landforms on modern channel dynamics in upland watersheds of central Nevada. *Geomorphology* **38**: 373–391.

Mills, H. H., 2005. Relative-age dating of transported regolith and application to study of landform evolution in the Appalachians. *Geomorphology* **67**: 63–96.

Monger, H. C., and Buck, B. J., 1999. Stable isotopes and soil-geomorphology as indicators of Holocene climate change, northern Chihuahuan Desert. *Journal of Arid Environments* **43**: 357–373.

Moody, J. A., and Martin, D. A., 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado

Front Range. *Earth Surface Processes and Landforms* **26**: 1049–1070.

Muto, T., and Steel, R. J., 2000. The accomodation concept in sequence stratigraphy: some dimensional problems and possible redefinition. *Sedimentary Geology* **130**: 1–10.

Nanson, G. C., Price, D. M., and Short, S. A., 1992. Wetting and drying of Australia over the past 300 ka. *Geology* **20**: 791–794.

Nichols, K. K., Bierman, P. R., Foniri, W. R., Gillespie, R., Caffee, M., and Finkel, R., 2006. Dates and rates of arid region geomorphic processes. *GSA Today* **16**(8): 4–11.

Nott, J. F., Thomas, M. F., and Price, D. M., 2001. Alluvial fans, landslides and Late Quaternary climaticchange in the wet tropics of northeast Queensland. *Australian Journal of Earth Sciences* **48**: 875–882.

Oguchi, T., and Oguchi, C. T., 2004. Late Quaternary rapid talus dissection and debris flow deposition on an alluvial fan in Syria. *Catena* **55**: 125–140.

Olley, J. M., Pietsch, T., and Roberts, R. G., 2004. Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz. *Geomorphology* **60**: 337–358.

Owen, L. A., Finkel, R. C., Haizhou, M., and Barnard, P. L., 2006. Late Quaternary landscape evolution in the Kunlun Mountains and Qaidam Basin, Northern Tibet: A framework for examining the links between glaciation,lake level changes and alluvial fan formation. *Quaternary International* **154–155**: 73–86.

Owen, L. A., Windley, B. F., Cunningham, W. D., Badamgarav, J., and Dorjnamjaa, D., 1997. Quaternary alluvial fans in the Gobi of southern Mongolia: evidence for neotectonics and climate change. *Journal of Quaternary Science* **12**: 239–252.

Pelletier, J. D., Mayer, L., Pearthree, P. A., House, P. K., Demsey, K. A., Klawon, J. E., and Vincent, K. R., 2005. An integrated approach to flood hazard assessment on alluvial fans using numerical modeling, field mapping, and remote sensing. *Geological Society of America Bulletin* **117**: 1167–1180.

Philander, S. G., 1999. El Niño and La Nina predictable climate fluctuations. *Reports on Progress in Physics* **62**: 123–142.

Phillips, F. M., 2003. Cosmogenic ^{36}Cl ages of Quaternary basalt flows in the Mojave Desert, California, USA. *Geomorphology* **53**: 199–208.

Phillips, W. M., McDonald, E. V., and Poths, J., 1998. Dating soils and alluvium with cosmogenic Ne-21 depth profiles: Case studies from the Pajarito Plateau, New Mexico, USA. *Earth and Planetary Science Letters* **160**: 209–223.

Pickup, G., 1991. Event frequency and landscape stability on the floodplain systems of arid central Australia. *Quaternary Science Reviews* **10**: 463–473.

Poisson, B., and Avouac, J. P., 2004. Holocene hydrological changes inferred from alluvial stream entrenchment in North Tian Shan (northwestern China). *Journal of Geology* **112**: 231–249.

Pope, R. J. J., and Millington, A. C., 2000. Unravelling the patterns of alluvial fan development using mineral magnetic analysis: Examples from the Sparta Basin, Lakonia, southern Greece. *Earth Surface Processes and Landforms* **25**: 601–615.

Pope, R. J. J., and Wilkinson, K. N., 2005. Reconciling the roles of climate and tectonics in Late Quaternary fan development on the Spartan piedmont, Greece. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 133–152.

Posamentier, H. W., and Vail, P. R., 1988. Eustatic control on clasticdeposition: II. Sequence and systems tracts models. In: *Sea Level Changes: An Integrated Approac*, C. K. Wilgus, B. S. Hastings, C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner (eds.), Society of Economic Paleontologists and Mineralogists Special Publication 42, Tulsa, pp. 125–154.

Proctor, C. J., Baker, A., Barnes, W. L., and Gilmour, M. A., 2000. A thousand year speleothem proxy record of North Atlantic climate from Scotland. *Climate Dynamics* **16**: 815–820.

Quigley, M. C., Sandiford, M., and Cupper, M. L., 2007. Distinguishing tectonic from climatic controls on range-front sedimentation. *Basin Research* **19**: 491–505.

Reheis, M. C., Slate, J. L., Throckmorton, C. K., McGeehin, J., P., SarnaWojcicki, A. M., and Dengler, L., 1996. Late Qaternary sedimentation on the Leidy Creek fan, Nevada-California: Geomorphic responses to climate change. *Basin Research* **8**: 279–299.

Roberts, N., 1995. Climatic forcing of alluvial fan regimes during the Late Quaternary in Konya basin, south central Turkey. In: *Mediterranean Quaternary River Environment*, J. Lewin, M. G. Macklin and J. Woodward (eds.), Balkema, Rotterdam, pp. 205–217.

Roberts, N., and Barker, P., 1993. Landscape stability and biogeomorphic response to past and future climatic shifts in intertropical Africa. In: *Landscape sensitivity*, D. S. G. Thomas and R. J. Allison (eds.), Wiley, London, pp. 65–82.

Roberts, N., Black, S., Boyer, P., Eastwood, W. J., Griffiths, H. I., Lamb, H. F., Leng, M. J., Parish, R., Reed, J. M., Twigg, D., and Yigitbasioflu, H., 1999. Chronology and stratigraphy of Late Quaternary sediments in the Konya Basin, Turkey: Results from the KOPAL Project. *Quaternary Science Reviews* **18**: 611–630.

Robinson, R. A. J., Spencer, J. Q. G., Strecker, M. R., Richter, A., and Alonso, R. N., 2005. Luminescence dating of alluvial fans in intramontane basins of NW Argentina. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 153–168.

Robinson, S. E., 2002. Cosmogenic nuclides, remote sensing, and field studies applied to desert piedmonts, Dissertation thesis, 387pp., Arizona State University, Tempe.

Robustelli, G., Muto, F., Scarciglia, F., Spina, V., and Critelli, S., 2005. Eustatic and tectonic control on Late Quaternary alluvial fans along the Tyrrhenian Sea coast of Calabria (South Italy). *Quaternary Science Reviews* **24**: 2101–2119.

Rodbell, D. T., Seltzer, G. O., Anderson, D. M., Abbott, M. B., Enfield, D. B., and Newman, J. H., 1999. 15000-year record of El Niño-driven alluviation in southwetsern Ecuador. *Science* **283**: 516–520.

Rodgers, D. W., and Gunatilaka, A., 2002. Bajada formation by monsoonal erosion of a subaerial forebuldge, Sultanate of Oman. *Sedimentary Geology* **154**: 127–147.

Rohling, E. J., and Palike, H., 2005. Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. *Nature* **434**: 975–979.

Rost, K. T., 2000. Pleistocene paleoenvironmental changes in the high mountain ranges of central China and adjacent regions. *Quaternary International* **65/66**: 147–160.

Rubustelli, G., Muto, F., Scarciglia, F., Spina, V., and Critelli, S., 2005. Eustatic and tectonic control on Late Quaternary alluvial fans along the Tyrrhenian Sea coast of Calabria (South Italy). *Quaternary Science Reviews* **24**: 2101–2119.

Sancho, C., Pena, J. L., Rivelli, F., Rhodes, E., and Munoz, A., 2008. Geomorphological evolution of the Tilcara alluvial fan (Jujuy Province, NW Argentina): Tectonic implications and palaeoenvironmental considerations. *Journal of South American Earth Sciences* **26**: 68–77.

Schaefer, J. M., Denton, G. H., Barrell, D. J. A., Ivy-Ochs, S., Kubik, P. W., Andersen, B. G., Phillips, F. M., Lowell, T. V., and Schluchter, C., 2006. Near-synchronous interhemisheric termination of the last glacial maximum in mid-latitudes. *Science* **213**: 1510–1513.

Schick, A. P., 1974. Formation and obliteration of desert stream terraces – a conceptual analysis. *Zeitschrift fur Geomorphology N.F. Supplement Band* **21**: 81–105.

Schick, A. P., Grodek, T., and Wolman, M. G., 1999. Hydrologic processes and geomorphic constraints on urbanization of alluvial fan slopes. *Geomorphology* **31**: 325–335.

Schick, A. P., and Lekach, J., 1993. An evaluation of two ten-year sediment budgets, Nahal yael, Israel. *Physical Geography* **14**: 226–238.

Schumm, S. A., 1977. *The fluvial system*. Wiley, New York, 338p.

Schumm, S. A., Mosley, M. P., and Weaver, W. E., 1987. *Experimental fluvial geomorphology*. Wiley & Sons, New York, 413p.

Shaffer, J. A., Cerveny, R. S., and Dorn, R. I., 1996. Radiation windows as indicators of an astronomical influence on the Devil's Hole chronology. *Geology* **24**: 1017–1020.

Singh, A. K., Parkash, B., Mohindra, R., Thomas, J. V., and Singhvi, A. K., 2001. Quaternary alluvial fan sedimentation in the Dehradun Valley Piggyback Basin, NW Himalaya: tectonic and palaeoclimatic implications. *Basin Research* **13**: 449–471.

Six, J., Conant, R. T., Paul, E. A., and Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil* **241**: 155–176.

Soeters, R., and van Westen, C. J., 1996. Slope instability, recognition, analysis and zonation. In: *Landslides: Investigation and Mitigation*, vol. 247, A. K. Turner and R. L. Schuster (eds.), National Research Council, Transportation Research Board, Washington D.C., pp. 129–177.

Sohn, M. F, Mahan, S. A., Knott, J. R., and Bowman, D. D, 2007. Luminescence ages for alluvial-fan deposits in Southern Death Valley: Implications for climate-driven sedimentation along a tectonically active mountain front. *Quaternary International* **166**: 49–60.

Sorriso-Valvo, M., 1988. Landslide-related fans in Calabria. *Catena Supplement* **13**: 109–121.

Spencer, J. Q. G., and Robinson, R. A. J., 2008. Dating intramontane alluvial deposits from NW Argentina using luminescence techniques: Problems and potential. *Geomorphology* **93**: 144–155.

Stadelman, S., 1994. Genesis and post-formational systematics of carbonate accumulations in Quaternary soils of the Southwestern United States, Ph.D. Dissertation thesis, 124pp., Texas Tech University, Lubbock.

Staley, D. M., Wasklewicz, T. A., and Blaszczynski, J. S., 2006. Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping data. *Geomorphology* **74**: 152–163.

Starkel, L., 1999. Space and time scales in geomorphology. *Zeitschrift für Geomorphologie Supplementband* **115**: 19–33.

Stokes, M., Nash, D. J., and Harvey, A. M., 2007. Calcrete 'fossilisation' of alluvial fans in SE Spain: The roles of groundwater, pedogenic processes and fan dynamics in calcrete development. *Geomorphology* **85**: 63–84.

Stokes, S., Hetzel, R., Bailey, R. M., and Mingzin, T., 2003. Combined IRSL-OSL single aliquot regeneration (SAR) equivalent dose (De) estimates from source proximal Chinese loess. *Quaternary Science Reviews* **22**: 975–983.

Suresh, N., Bagati, T. N., Thakur, V. C., Kumar, R., and Sangode, S. J., 2002. Optically stimulated luminescence dating of alluvial fan deposits of Pinjaur Dun, NW Sub Himalaya. *Current Science* **82**: 1267–1274.

Suresh, N., Bagati, T. N., Kumar, R., and Thakur, V. C., 2007. Evolution of Quaternary alluvial fans and terraces in the intramontane Pinjaur Dun, Sub-Himalaya, NW India: interaction between tectonics and climate change. *Sedimentology* **54**: 809–833.

Talbot, M. R., and Williams, M. A. J., 1979. Cyclic alluvial fan sedimentation on the flanks of fixed dunes, Janjari, central Niger. *Catena* **6**: 43–62.

Taylor, K. C., Mayewski, P. A., Alley, R. B., Brook, E. J., Gow, J., Grootes, P. M., Meese, D. A., Saltzmann, E. S., Severinghaus, J. P., Twickler, M. S., White, J. W. C., Whitlow, S., and Zelinsky, G. A., 1997. The Holocene-Younger Dryas transition recorded at Summit, Greeland. *Science* **278**: 825–827.

Thiagarajan, N., and Lee, C. A., 2004. Trace-element evidence for the origin of desert varnish by direct aqueous atmospheric deposition. *Earth and Planetary Science Letters* **224**: 131–141.

Thomas, M. F., 2003. Late Quaternary sediment fluxes from tropical watersheds. *Sedimentary Geology* **162**: 63–81.

Thomas, M. F., 2004. Landscape sensitivity to rapid environmental change – a Quaternary perspective with examples from tropical areas. *Catena* **55**: 107–124.

Thorndrycraft, V. R., and Benito, G., 2006. Late Holocene fluvial chronology of Spain: The role of climatic variability and human impact. *Catena* **66**: 34–41.

Throckmorton, C. K., and Reheis, M. C., 1993. Late Pleistocene and Holocene environmental changes in Fish Lake Valley, Nevada-California: Geomorphic response of alluvial fans to climate change. *U.S. Geological Survey Open File Report* **93–620**: 1–82.

Tricart, J., and Cailleux, A., 1973. *Introduction to Climatic Geomorphology. Translated from the French by Conrad J. Kiewiet de Jonge*. St. Martin's Press, New York, 295p.

Tucker, G. E., and Slingerland, R., 1997. Drainage basin responses to climate change. *Water Resources Research* **33**: 2031–2047.

Twidale, C. R., and Lageat, Y., 1994. Climatic geomorphology. A Critique. *Progress in Physical Geography* **18**: 319–334.

Vidal, L., Laberyie, L., Cortijo, E., Arnold, M., Duplessy, J. C., Michel, E., Becque, S., and vanWearing, T., 1997. Evidence for changes in the North Atlantic deep water linked to meltwater surges during the Heinrich events. *Earth and Planetary Science Letters* **146**: 13–27.

Viles, H. A., and Goudie, A. S., 2003. Interannual, decadal and multidecadal scale climatic variability and geomorphology. *Earth-Science Reviews* **61**: 105–131.

Viseras, C., Calvache, M. L., Soria, J. M., and Fernandez, J., 2003. Differential features of alluvial fans controlled by tectonic or eustatic accommodation space. Examples from the Betic Cordillera, Spain. *Geomorphology* **50**: 181–202.

Volker, H. X., Wasklewicz, T. A., and Ellis, M. A., 2007. A topographic fingerprint to distinguish alluvial fan formative processes. *Geomorphology* **88**: 34–45.

Wang, Y., McDonald, E., Amundson, R., McFadden, L., and Chadwick, O., 1996. An isotopic study of soils in chronological sequences of alluvial deposits, Providence Mountains, California. *Geological Society of America Bulletin* **108**: 379–391.

Wanner, H., Bronniman, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D. B., and Xoplaki, E., 2001. North Atlantic Oscillation: concepts and studies. *Surveys in Geophysics* **22**: 321–382.

Wasklewicz, T. A., Mihir, M., and Whitworth, J., 2008. Surface variability of alluvial fans generated by disparate processes, Eastern Death Valley, CA. *Profesional Geographer* **60**: 207–223.

Weaver, W. E., and Schumm, S. A., 1974. Fan-head trenching: an example of a geomorphic threshold. *Geological Society America Abstracts with Program* **6**: 481.

Webb, J. A., and Fielding, C. R., 1999. Debris flow and sheetflood fans of the northern Prince Charles Mountains, East Antarctica. In: *Varieties of Fluvial Form*, A. J. Miller and A. Gupta (eds.), Wiley, Chichester, pp. 317–341.

Weissmann, G. S., Bennett, G. L., and Lansdale, A. L., 2005. Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA. In: *Alluvial fans: Geomorphology, sedimentology, dynamics*, A. M. Harvey, A. E. Mather and M. Stokes (eds.), Geological Society Special Publications 251, London, pp. 169–186.

Weissmann, G. S., Mount, J. F., and Fogg, G. E., 2002. Glacially driven cycles in accumulation space and sequence stratigraphy of a stream-dominated alluvial fan, San Joaquin Valley, California, USA. *Journal of Sedimentary Research* **72**: 270–281.

Wells, S. G., McFadden, L. D., and Dohrenwend, J. C., 1987. Influence of late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California. *Quaternary Research* **27**: 130–146.

Wendland, W. M., 1996. Climatic changes: Impacts on geomorphic processes. *Engineering Geology* **45**: 347–358.

Western Earth Surface Processes Team, U. S. G. S., 2004. Stream Channel Development in the Changing Mojave Climate. *http://deserts.wr.usgs.gov/mojave/* **Last Updated 1–14–2004**: Accessed 7/25/06.

White, K., 1993. Image processing of Thematic Mapper data for discriminating piedmont surficial materials in the Tunisian Southern Atlas. *International Journal of Remote Sensing* **14**: 961–977.

White, K., Drake, N., Millington, A., and Stokes, S., 1996. Constraining the timing of alluvial fan response to Late Quaternary climatic changes, southern Tunisia. *Geomorphology* **17**: 295–304.

Wohl, E. E., and Pearthree, P. P., 1991. Debris flows as geomorphic agents in the Huachuca Mountains of Southeastern Arizona. *Geomorphology* **4**: 273–292.

Wolman, M. G., and Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth Surface Processes and Landforms* **3**: 189–208.

Zanchetta, G., Sulpizio, R., and Di Vito, M. A., 2004. The role of volcanic activity and climate in alluvial fan growth at volcanic areas: an example from southern Campania (Italy). *Sedimentary Geology* **168**: 249–280.

Zazo, C., Mercier, N., Lario, J., Roquero, E., Goy, J., Silva, P., Cabero, A., Borja, F., Dabrio, C., Bardaji, T., Soler, V., Garcia-Blazquez, A., and de Luque, L., 2008. Palaeoenvironmental evolution of the Barbate-Trafalgar coast (Cadiz) during the last 140 ka: Climate, sea-level interactions and tectonics. *Geomorphology* **100**: 212–222.