Table 8.1 Twentieth-century geomorphological models used in alluvial-fan research

Model	Summary
Evolutionary	Alluvial fans occur in a youthful stage in the arid lands cycle of erosion (Davis 1905)
Climatic	Climatic changes influence the weathering, stream flow, mass movement and sediment supply in the drainage basin above the fan. Climatic changes influence the base-level of closed basins, gullying, weathering and soil development on fan deposits (Bull 1991; Dorn 1994; Lustig 1965; Melton 1965; Tuan 1962; Wells et al. 1990)
Dynamic equilibrium	Alluvial fans represent a dynamic equilibrium in the transportation of coarse debris from range to basin (Denny 1967)
Steady state	The relationship of fan area and drainage basin area tends toward a steady state, that can shift as forcing relationships change (Hooke 1968; Jansson et al. 1993)
Tectonic	Faulting influences the entrenchment and location of deposition on a fan, the preservation of older fan deposits, and morphometric parameters (Bull and McFadden 1977; Clarke 1989; Hooke 1972; Rockwell et al. 1984)
Intrinsic factors	Fan-head trenching and movement of the intersection point downfan can be explained by intrinsic threshold responses, for example by oversteepening of the fan-head slope, or by drainage basin ruggedness influencing fan incision (Hawley and Wilson 1965; Hooke and Rohrer 1979; Humphrey and Heller 1995; Schumm et al. 1987; Viseras and Fernández 1995; White 1991)
Allometry	Alluvial fans are not in a steady state. Boundary conditions of drainage basin, climate, and tectonism change over time (Bull 1975)
Combination	Alluvial fans aggrade in response to a combination of forcing factors (Bull 1977; Germanoskiy and Miller 1995; Hooke and Dorn 1992; Ritter et al. 1995)

been to relate morphogenetic events on alluvial fans to climatic changes – supported in part by the corollary pillars of climatic interpretations of weathering (Pedro and Sieffermann 1979), soil development (Wright 1992), hillslope erosion (Gerson 1982), and a *perspective* that 'a fundamental goal of earth science is to develop a more complete understanding of mechanisms and rates of climate change so that credible estimates of past global conditions can be constructed' (Drummond et al. 1995, p. 1031). The purpose of this chapter is to assess whether it is possible to test climatic hypotheses of alluvial-fan evolution, at least for the fans in Death Valley, eastern California.

The first section of this chapter introduces how geomorphologists link climatic changes to the evolution of dryland fans. By drylands, I mean semiarid, arid, and hyperarid climates – as defined by Meigs (1953). A comprehensive review of the different climatic hypotheses is beyond the scope of this chapter. My purpose, instead, is to present the general categories of climatic models under consideration as explanations for dryland-fan evolution. Although I focus on Death Valley, I draw analogs from fans in other drylands.

The second section provides an introduction into the nature of climatic changes experienced in the last 100 000 years. This time period covers the last glacial/postglacial cycle, and it is the best dated glacial cycle in terms of dryland-fan research. There are many scales of climatic change in this period (Gates and Mintz 1975), with higher-frequency fluctuations nested within longer-term oscillations. In this chapter I deal with three time scales: decades, where meteorological records are applicable; centuries to millennia, the focus of high-resolution paleoclimatic datasets; and tens of thousands of years, appropriate for analysis by orbital forcing mechanisms. Within the last three years, there has been a shift in the paradigm of paleoclimatology. Before, climatic changes were thought to occur gradually and over time scales of 10^4–10^5 years. The new paradigm, introduced in the second section, stresses the importance of sudden and dramatic climatic fluctuations on millennial and century time scales.

The key issue of this chapter revolves around whether these sudden climatic changes can be linked to alluvial-fan evolution. Linkages are clear where fanglomerate is in physical contact with glacial moraines or with lacustrine sediment. Outside of such contexts, making the climate–fan connection is more difficult. It cannot be accomplished through sedimentological analyses, because all types of fan sediment occur in all climates. Instead, most researchers have been forced into making temporal correlations with the aid of dating techniques. The third section of this chapter, therefore, explores whether it is possible to use dating techniques to correlate aggradation (or hiatuses in deposition) with millennial-or century-scale climatic changes.

I had previously advocated a position that climatic changes exerted a major control on fan morphogenesis in southern Death Valley (Dorn 1988, 1994; Dorn et al. 1987). In the fourth and fifth sections of this chapter, I now argue that climatic hypotheses of alluvial-fan evolution are not testable in Death Valley – even with the application of a new, higher-resolution chronometric technique. I conclude with the position that climatic hypotheses of alluvial-fan evolution in Death Valley (and probably in other drylands), while still possibly correct, are not testable at the present time.

CLIMATIC HYPOTHESES OF DRYLAND ALLUVIAL-FAN EVOLUTION

Climatic changes have been related to alluvial-fan morphogenesis through four different process-based explanations. These hypotheses are not necessarily mutually exclusive, even for the same fan. Often, however, different hypotheses are used in different climatic settings. In drainage systems that have been glaciated, the *paraglacial* hypothesis holds that debris generated by glaciers overwhelms the fluvial system, producing alluvial fans. In the *periglacial* hypothesis, cryogenic processes weather and transport enough debris to build fans. The most popular perspective today, *transition to a drier climate*, invokes a reduction in vegetative resistance to particle erosion from slopes. Other authors contend that *humid-period aggradation* did occur when deserts had a more moisture-effective, semiarid climate.

Paraglacial Hypothesis

The importance of glaciers on alluvial-fan development in drylands was recognized early in the twentieth century (Trowbridge 1911, p. 739):

> Glaciation has played a large part in the deposition of the [eastern] Sierra bajada [in the Owens Valley of California]. Glaciers prepared immense amounts of material in the mountain canyons for transportation by streams. At the same time they furnished great volumes of water to act as the transporting agent during the melting-season.

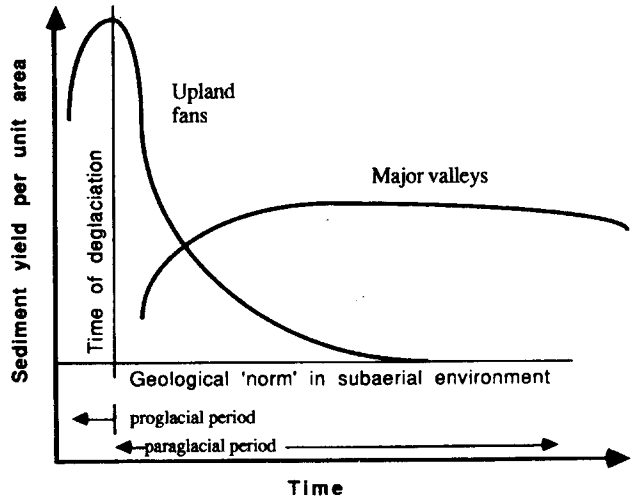

Figure 8.1 The paraglacial model of alluvial-fan aggradation in response to an abundance of sediment generated by glaciers, adapted from Church and Slaymaker (1989)

Six decades later the term 'paraglaciation' was applied to uplands in British Columbia (Church and Ryder 1972; Ryder 1971) to mean:

> ... nonglacial processes that are directly conditioned by glaciation. It refers both to proglacial processes, and to those occurring around and within the margins of a former glacier that are the direct result of the earlier presence of the ice. It is specifically contrasted with the term 'periglacial', which does not imply the necessity of glacial events occurring ... (Church and Ryder 1972, p. 3059).

The paraglacial model (Figure 8.1) has also been used in lower latitudes (e.g., Dorn 1994; Dorn et al. 1991; Meyer et al. 1995; Ritter et al. 1995).

The problem of whether climatic hypotheses of fan aggradation are testable is not at issue where deposits are traceable to glacial moraines (e.g. Birkeland 1965, p. 56; Coleman and Pierce 1981). In these circumstances, there is a direct-spatial linkage between the climatically driven forcing function of glaciation and fan aggradation. The testability of the other three climatic hypotheses in Death Valley is the focus of this chapter.

Periglacial Hypothesis

A classic hypothesis for dryland-fan aggradation in unglaciated drainages is that Pleistocene frost weathering and solifluction on upland slopes generated an abundant load that overwhelmed fluvial systems and led to Pleistocene aggradation on alluvial fans (Zeuner 1959). During colder periods, periglacial activity dominated many western US upland elevations that flank drylands (Dohrenwend 1984; Péwé 1983). Periglacial processes are capable of weathering and transporting (Clark 1987) enough sediment to build alluvial fans in cold regions (Blikra and Longva 1995) and drylands (Catto 1993; Dorn 1988, 1994; Melton 1965; Wasson 1977; Williams 1973).

Transition to a Drier Climate

The importance of a reduction of vegetation cover in enhancing hillslope erosion and fan aggradation has long been recognized (Eckis 1928; Huntington 1907; Zeuner 1959). Bull and Schick (1979) and later Bull (1991) refined the basic model (Figure 8.2), for example, by explaining that the response of fans can be time-transgressive, and depends upon the direction and magnitude of the climatic change:

> Replenishment of the hillslope sediment reservoir is as important as erosion in the production of an aggradation event. Conditions that favor rapid and progressive increases in hillslope plant and soil cover may be infrequent or may require long time spans ... Aggradation of desert valleys occured because of rapid stripping of a thin hillslope sediment reservoirs after a change to markedly less vegetation cover or an increase in intense summer-type precipitation events, or both (Bull 1991, pp. 281, 284).

This general hypothesis has become the most popular explanation for alluvial-fan evolution in drylands (Blair et al. 1990; Dorn 1988, 1994; Gile et al. 1981; Harvey 1990; Iriondo 1993; Kale and Rajaguru 1987; Meyer et al. 1992; Peterson et al. 1995; Ritz et al. 1995; Slate 1991; Throckmorton and Reheis 1993; Wells et al. 1987, 1990).

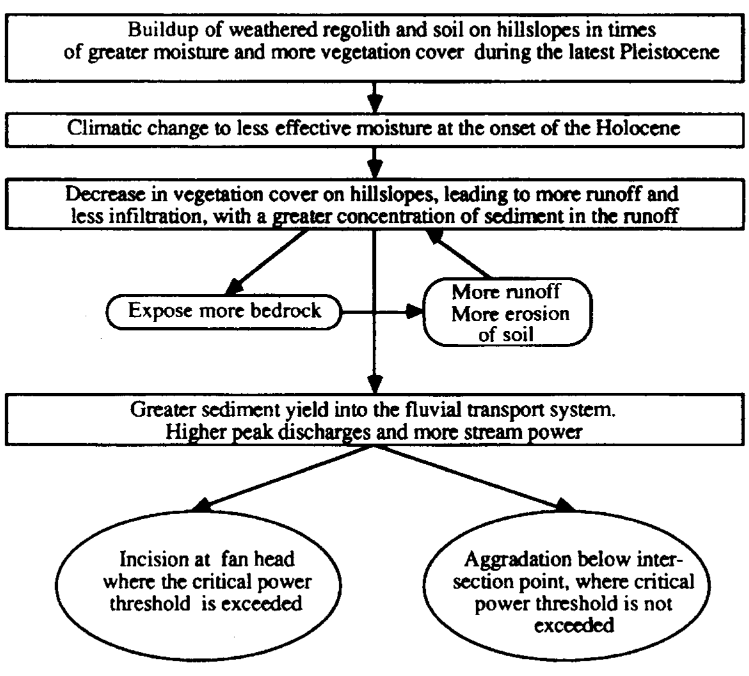

Figure 8.2 Alluvial-fan aggradation during times of transition from more humid to more arid climates, where sediment is generated in a drainage not influenced by periglacial or glacial activity, adapted from Bull (1991)

Aggradation During Humid Periods

A persistent thread in studies of dryland fans is that streams were actively depositing sediment during moisture-effective periods. This theme repeats in the literature for drylands in Australia (Williams 1973), Africa and the Middle East (Dardis et al. 1988; Goldberg 1984; Maizels 1990; Talbot and Williams 1979; Wilson 1990), and North America (Barsch and Royse 1972; Bull 1991, p. 55; Dorn 1994; Harvey and Wells 1994; Huckleberry 1996; Lustig 1965; Mills 1982; Mulhern 1982; Peterson et al. 1995; Ponti 1985; Tuan 1962). Lustig (1965, p. 185) argued that stream flows with high water-to-sediment ratios in wetter periods would deposit material widely over a fan surface. In contradistinction, others argue for the effectiveness of debris flows (Harvey and Wells 1994), or the start of a more humid period being able to transport sediment more effectively (Melton 1965; Thomas and Thorp 1995, p. 203). I have argued that even with a slight increase in biomass, from desert scrub to dwarf conifer woodland, erosion of hillslopes would continue (Dorn 1988, 1994) and might increase since erosion maxima occur in semiarid regions today (Knox 1983; Langbein and Schumm 1958).

The aforementioned models link periods of aggradation or hiatuses in sediment transport to climatic changes. Hence, the next section turns to a review of current advances in paleoclimatology – focusing on the last glacial/postglacial cycle.

PARADIGM SHIFT IN QUATERNARY RESEARCH

During the last glaciation (Wisconsinian, marine oxygen isotope stages 2, 3, 4), periodic 'armadas' of icebergs were released from the Laurentide ice sheet into the northern Atlantic. Iceberg releases produced layers in marine cores that are poor in foraminifera shells and rich in ice-rafted debris derived from Canada. These layers, first recognized by Hartmut Heinrich (1988), have been found in cores throughout the North Atlantic (Bond et al. 1993; Dowdeswell 1995; Mayewskiy et al. 1994). The most recent 'Heinrich layer' corresponds to the Younger Dryas (Andrews et al. 1995), and there were six others from 10 000 to 70 000 years ago (Broecker 1994).

Steadily accumulating evidence reveals that the climate of the globe changed to the metronome of whatever controlled Heinrich events, perhaps changes in oceanic circulation (Birchfield et al. 1994; Broecker 1994) or maybe fluctuations in tropical water vapor (Lowell et al. 1995). The short and sudden return to a glacial world during the Younger Dryas, the latest Heinrich event (Andrews et al. 1995), was globally synchronous (Denton and Hendy 1994; Gosse et al. 1995; Islebe et al. 1995; Kudrass et al. 1991; Wright 1989).

One indication that there has been a paradigm shift in Quaternary research is the wide variety of paleoclimatic records that have been correlated with Heinrich events, including: Greenland (Bond et al. 1993) and Antarctic (Bender et al. 1994) ice cores; sea-surface temperatures (Maslin et al. 1995); pollen in Florida (Grimm et al. 1993); rock magnetism in Europe (Thouveny et al. 1994); foraminifera off the coast of California (Thunell and Mortyn 1995); iceberg rafting in the North Pacific (Kotilainen and Shackleton 1995); spring deposits in southern Nevada (Quade 1994); glacial advances and paleolakes in western North America (Benson et al. 1995; Clark and Bartlein 1995; Gosse et al. 1995;

Phillips et al. 1994); glacial advances in South America (Lowell et al. 1995); monsoons (Sirocko *et al.* 1996); and even loess in China (Porter and Zhisheng 1995).

Heinrich events only record the major Wisconsinian iceberg armadas. There is growing evidence globally and regionally for higher-frequency millennial- and century-scale climate instability in the Pleistocene (e.g. Bond and Lotti 1995; Chappellaz et al. 1993; Fronval et al. 1995; Keigwin and Jones 1994; Kotilainen and Shackleton 1995) and Holocene (e.g. Blunier et al. 1995; Meese et al. 1994; Roberts et al. 1994; Scuderi 1994; Weisse et al. 1994). There may have been iceberg-related climate instabilities in the period from 70 000 to 13 000 years ago (Keigwin et al. 1994).

The aforementioned references represent a small fraction of the 'snowball' of publications in the last three years. Sudden and dramatic climatic changes have replaced orbital forcing as the main focus of Quaternary climate change research. Climatic changes coincident with millennial- and submillennial events hold far-reaching implications for our understanding of global climate change. Conventional *perceptions* of Quaternary climatic change are usually driven by, and correlated with, stages assigned to relatively gentle $\delta^{18}O$ curves of 'global' ice volume change (Imbrie et al. 1984, 1993; Martinson et al. 1987). There is comparatively little uncertainty that global ice-volume curves record the slow buildup and decay of continental ice, but ice-sheet volume fluctuates much more slowly than the sudden and dramatic climatic changes that appear to be characteristic of the Quaternary around the globe.

There are relatively few high-resolution records of climatic change in terrestrial settings, especially in the Death Valley region. Within the last few years, however, there has been a growing dataset indicating that century- and millennial-scale climatic changes did strongly influence hydrologic and geomorphic systems in the western USA (e.g. Allen and Anderson 1993; Benson et al. 1995; Clark and Bartlein 1995; Gosse et al. 1995; Phillips et al. 1994; Quade 1994; Smith and Bishoff 1993; Thunell and Mortyn 1995). I am convinced by the burgeoning database that ocean–atmosphere–terrestrial processes were strongly coupled in the Pleistocene – felt in the western USA by changes in atmospheric circulation (cf. Clark and Bartlein 1995). However, if the reader believes that there is still 'insufficient evidence' to conclude that sudden and dramatic, century- and millennial-scale climatic fluctuations influenced Death Valley and other terrestrial drylands, then the rest of the chapter becomes an exercise in the subjunctive.

The core issue in this chapter is the link between these sudden and dramatic climatic changes and fan evolution – through temporal correlations. The next section addresses whether techniques used to date alluvial-fan deposits (or hiatuses in deposition) are up to the task.

IMPRECISION IN CORRELATION TECHNIQUES

In order to relate dryland fans to climate, alluvial-fan researchers have been forced to turn to indirect chronometric correlations, because sedimentological characteristics cannot be tied to any particular climatic interval. Water-laid, debris-flow, and sieve-flow deposits all exist in a variety of climates. While climatic inferences are readily made for paraglacial fans that are physically tied to glacial moraines or fanglomerate that physically interdigitates with lacustrine sediment, in other circumstances chronometric correlations have been an important methodology.

At an extremely simplistic level, the following general approach is employed: a deposit X is dated to fall within climatic period Y. If there is a regional temporal pattern, and local lithotectonic or intrinsic factors are ruled out, a climatic signal is discerned. In this section, I evaluate different chronometric methods used to make correlations. If I appear too critical, however, it is because the only relevant issue in this section is whether available age-determination methods have the precision and accuracy to make a correlation between events on dryland fans and the century- to millennial-scale climatic changes that dominated the late Pleistocene.

A major problem in dryland-fan research is the paucity of age control in stratigraphic contexts. While accelerator mass spectrometry (AMS) ^{14}C (Linick et al. 1989) and uranium-series mass spectrometry (Edwards et al. 1986) do have sufficient precision to test correlations with millennial-scale climatic change, suitable materials for these techniques are extremely rare in dryland fanglomerate. For example, there are only two published Pleistocene ^{14}C measurements from within fan sediment in Death Valley (Hooke and Dorn 1992). Multiple ^{14}C ages do exist for fanglomerate elsewhere (e.g. Kale and Rajaguru 1987; Pohl 1995), for example in Holocene fans exiting ranges with conifers (e.g. Meyer et al. 1995; Slate 1991; Throckmorton and Reheis 1993). The issue, however, is the extreme paucity of stratigraphic age control for dryland fans before the Holocene.

Volcanic tephras diagnostic of a particular eruption have been used as isochronous units (Beaty 1970; Throckmorton and Reheis 1993). In effect, tephras provide upper and lower age limits. Volcanic ashes by themselves can be used to disprove a climatic correlation, for example if an investigator found a Holocene-age ash in a unit thought to be late Pleistocene. Tephras are particularly valuable when they can be directly linked to a climatic event, for example finding the same tephra in lacustrine sediment. Unfortunately, tephras have a limited spatial and temporal distribution in fanglomerate.

In light of the paucity of datable material in stratigraphic contexts, alluvial-fan researchers have turned to surface-exposure dating methods (cf. Dorn and Phillips 1991). Most surface chronometric methods produce a relative sequence. Morphostratigraphic relationships establish whether a fan segment is inset into or overlaps over another segment (Hooke 1972; Hunt and Mabey 1966). Soil development (Gile et al. 1981), changes in the degree of varnish or desert pavement development (Swadley and Hoover 1989), and changes in remotely sensed characteristics (White 1993) have been used to establish an ordering among deposits. The problem is simple: relative dating methods only provide information on order and cannot be used to correlate a fan unit with any particular time interval, let alone a climatic period. Correlations with discrete climatic intervals must rely on calibrated-, correlative-, and numerical-dating methods.

Calibrated dating methods regress a relative age signal against independently established numerical ages. For example, different soil properties are tabulated into a soil development index (Harden 1982) that is used to assign calibrated ages (Reheis et al. 1989; Switzer et al. 1988). Even if calibration points are valid, the uncertainties inherent in the method (Switzer et al. 1988) yield errors that are much larger than the length of millennial-scale climatic events. A similar problem in inadequate precision exists for cation-ratio dating of rock varnish (Dorn 1994). Soils and cation-ratio dating only have the precision to establish that dryland fan deposition occurred during the drier Holocene. Correlations with Pleistocene climatic changes are beyond the chronometric resolution of these techniques.

The inherent limitations of correlative-dating methods have not inhibited climatic interpretations. For example, visual differences in varnish appearance have been used to assign correlated ages to deposits, based on varnish characteristics at chronometrically constrained sites (McFadden et al. 1989). Varnish appearance has also been used to make climatic correlations (Harvey and Wells 1994). This is all despite serious uncertainties in using varnish appearance to estimate age, such as tremendous surface-to-surface variability in rates of varnish development (Bednarik 1979; Colman and Pierce 1981, p. 2; Dorn 1983; Dorn and Oberlander 1982; Dragovich 1984; Friedman et al. 1994; Grote and Krumbein 1992; Haberland 1975; Linck 1928; Lucas 1905; Rivard et al. 1992; Viereck 1964; Whitley et al. 1984) – issues that have been ignored by those who attempt to estimate exposure age in this manner.

Morphostratigraphic relationships can be used to establish correlative ages (Dorn 1988; Wells et al. 1987), where some units are older or younger than a given numerical age. In the case of dryland fans that spatially intersect paleolake shorelines, deposits resting over a terminal-Pleistocene shoreline would be Holocene (Gilbert 1890; Russell 1885), but fans cut by terminal Pleistocene shorelines could be correlated with any earlier Pleistocene climatic period (Hawley and Wilson 1965).

Much of the numerically dated material provides only minimum ages for sediment deposition. AMS ^{14}C ages on weathering rinds (Dorn 1994) tell when organic matter stopped exchanging CO_2 with the atmosphere – essentially when rock varnish encapsulated the weathering rinds. Although these ^{14}C ages postdate surface exposure by approximately 10% (Dorn et al. 1992b), even this uncertainty makes definitive correlations with millennial-scale climatic events impossible. Similarly, ^{36}Cl, uranium-series, and radiocarbon ages on pedogenic carbonate (Hooke and Dorn 1992; Liu et al. 1994; Peterson et al. 1995) must postdate fan deposition by an uncalibrated amount of time that it took the carbonate to form. In addition, pedogenic carbonates do not appear to be a closed system (Stadelman 1994).

Numerical ages have been assigned to fan units with the *in situ* buildup of cosmogenic $^{10}Be/^{26}Al$ (Bierman et al. 1995; Nishiizumi et al. 1993; Ritz et al. 1995) and ^{36}Cl (Liu et al. 1996). Claims of high-precision fan dating with cosmogenic nuclides being able to 'exploit these terrestrial archives of climate change' (Bierman et al. 1995, p. 449) ignore fundamental methodological limitations.

1. The 'tightest' datasets have a 1σ precision for 'apparent' exposure ages of 25–30%; this error alone invalidates Pleistocene climatic correlations.
2. Fire spalling is a serious problem for cosmogenic nuclides such as ^{10}Be and ^{26}Al that are only produced by spallation (Bierman and Gillespie 1991), but less so for ^{36}Cl that is also produced by neutron activation (Zreda et al. 1994); the only noncircular solution assesses boulder erosion with varnish microlaminations (Liu 1994).
3. Cosmogenic nuclides have uncertainties associated with 'inheritance' of nuclide buildup prior to clast emplacement in a fan (Dorn and Phillips 1991). Using measurements of cobbles in the most recent deposits in order to address issues of signal

inheritance (Bierman et al. 1995) assumes that late Holocene fluvial 'storage' of alluvium was similar to Pleistocene fluvial 'storage' – a very uncertain assumption (Church and Slaymaker 1989; Leece 1991; White 1991).

4. Boulder and cobble geometry can change over time, especially when sampling occurs on debris-flow deposits that erode or on desert pavements that are mobile (Mabbutt 1979).
5. The uncertainties associated with production rates are difficult to quantify at present, but these errors add at least another 20% to the uncertainty for $^{10}Be/^{26}Al$ ages. Cosmogenic nuclides have great potential to inform on rates of geomorphic processes, but these methods do not yield precise enough or accurate enough ages to make a definitive correlation between fan aggradation and Pleistocene climatic changes.

This entire discussion has assumed that dating techniques are employed flawlessly, and that no errors in accuracy are introduced. However, there are quite a number of technical issues that could affect accuracy. Consider a method whose results are often accepted uncritically, ^{14}C dating. There are serious uncertainties associated with sample pretreatment. Young organic molecules move with water and can adsorb to organics and clay-sized minerals in samples (Gu et al. 1995; Hedges et al. 1993; Heron et al. 1991; Österberg et al. 1993). Inaccurate ages may result when organics are not pretreated, or when conventional pretreatment does not remove these young organics (Gillespie 1991). My point is that even conventional dating methods such as radiocarbon are experimental, especially when they are used to date dryland alluvial fans. There are many uncertainties surrounding the history of the carbon atoms that are actually measured.

There is a more general concern, related to a systematic bias in the way that samples are collected for age determination. Traditionally, the first step is the genesis of morphostratigraphic maps – based on relative dating methods of characterizing fan surfaces. Then, samples are collected on these different morphologic units – with the assumption that the entire fan segment is temporally equivalent. If this assertion is erased, significant morphogenetic events may have occurred, but may not have been sampled. In other words, what is now recognized as a single fan unit may truly be composed of many time-transgressive elements – each of which occurred in response to a different forcing. This uncertainty amplifies concerns over the accuracy and precision of the dating results by an unknown amount.

In summary, I am not advocating a position that these new chronometric insights are unimportant. On the contrary, the aforementioned techniques provide valuable insight into rates of geomorphic processes and rates of landscape evolution in drylands. My only point in this section is that available chronometric methods do not have sufficient temporal resolution to correlate dryland Pleistocene alluvial-fan evolution with century- or millennial-scale climatic records. In the next section, I reassess research on the Death Valley fans in light of the new paradigm of Quaternary climatic change and in light of the above limitations in dating methods.

DEATH VALLEY FANS

Reevaluation of Prior Data

I have advocated three different climatic hypotheses to help explain the evolution of alluvial fans debouching from the Panamint Range (Figure 8.3) into Death Valley (Dorn

1994). Periglacial activity, dated in the upper Panamint Range to the last glacial period, could have supplied sediment in colder periods. Erosion of hillslopes likely generated sediment in the wetter period of the late Wisconsinian when Lake Manly occupied the floor of the valley and *Yucca* scrub and dwarf conifers grew on the lower hillslopes. Lastly, when the climate changed from the semiarid latest Pleistocene to the hyperarid Holocene, the vegetation could no longer hold the sediment in place – leading to fan aggradation. These hypotheses were supported by morphostratigraphic relationships, conventional ^{14}C measurements, weathering rind ^{14}C ages, ^{14}C ages on organics in pedogenic carbonate rinds, uranium-series ages, $^{10}Be/^{26}Al$ ages, calibrated- and correlative-varnish methods, and soil development (Dorn 1988, 1994; Dorn et al. 1987; Hooke and Dorn 1992; Nishiizumi et al. 1993; Stadelman 1994).

Climatic hypotheses to explain fan evolution in Death Valley may be true, but I now contend that it is not possible to test them at the present time. Consider the dataset for Hanaupah Canyon alluvial fan (Figure 8.4). The age range for the eroding Q1 unit is too long to correlate with even oxygen-isotope stages (Martinson et al. 1987). The age ranges for the Q2 and Q3 units are similarly too long to correlate with any global (Broecker 1994; Keigwin et al. 1994; Kotilainen and Shackleton 1994), regional (Phillips et al. 1990, 1994; Smith and Bischoff 1993; Thunell and Mortyn 1995), or locally derived (Ku et al. 1994; Lowenstein et al. 1995; Szabo et al. 1994; Winograd et al. 1992) climatic signal. A climatic correlation is not possible, even for the best constrained Pleistocene aggradational unit, an orange-colored tributary fan on the northwest side of Hanaupah Canyon fan – younger than 16 000 years, but older than 12 000 years (Dorn 1994). This period straddles Heinrich event 1, a wet event ~14 000 years ago that was felt throughout the western

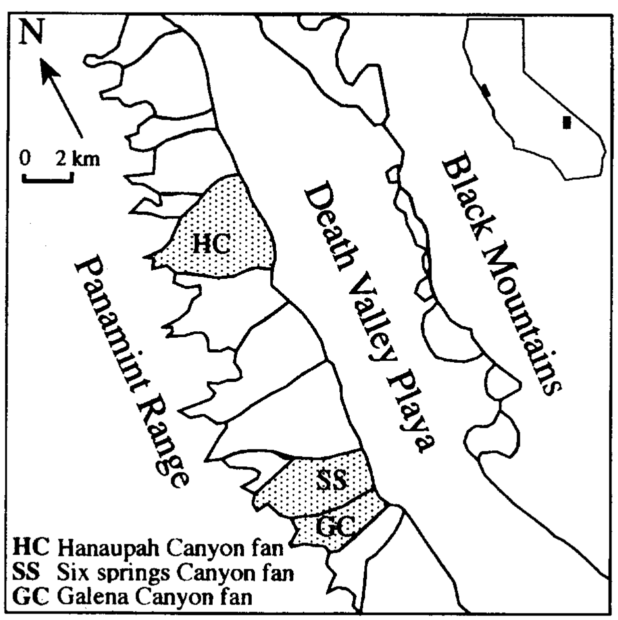

Figure 8.3 Alluvial fans in southern Death Valley, highlighting fans discussed in this chapter

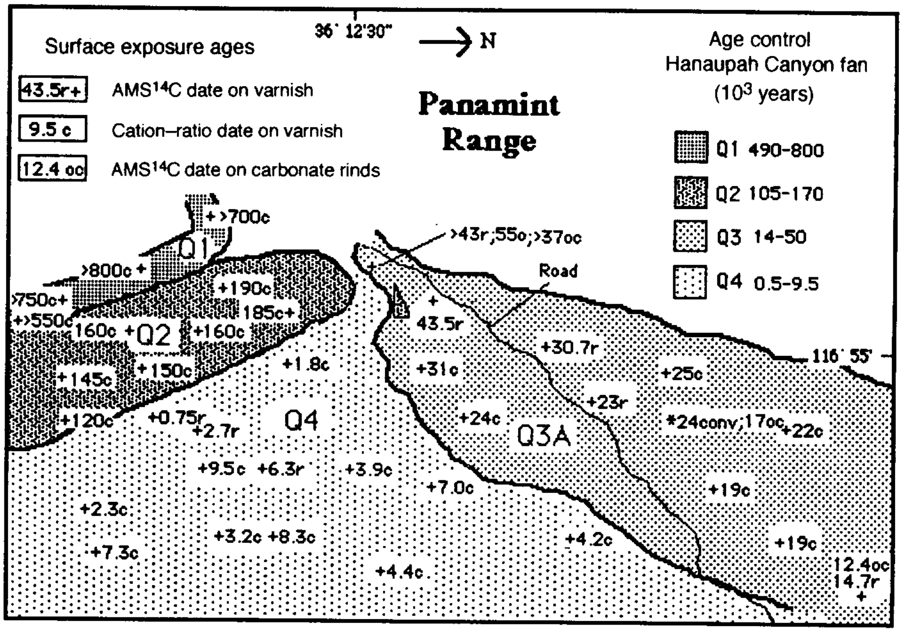

Figure 8.4 Oblique aerial photograph and corresponding map of Hanaupah Canyon alluvial fan, Death Valley. The symbol ' + ' identifies sampling sites for radiocarbon (r), cation-ratio (c), ^{14}C ages on organic matter from pedogenic carbonate rinds (oc), and a conventional ^{14}C measurement on a charcoal sample (conv). All ages are in 10^3 years. Fan segments correspond to those used by Hooke and Dorn (1992)

USA (Benson et al. 1995; Broecker 1994). It is not possible to correlate aggradation of the tributary fan to Heinrich event 1, drier periods on either side, or the climatic transitions between.

The only alluvial fan unit that correlates with a climate period is Q4. Although transgressive in space and time, deposition of Q4 occurred throughout the Holocene, a largely hyperarid climate interval (Lowenstein et al. 1995; Wells and Woodcock 1985). Climatic changes did occur in the Holocene (Blunier et al. 1995; Bryson, 1992; Meese et al. 1994; Roberts et al. 1994; Scuderi 1994; Weisse et al. 1994), but in Death Valley (Lowenstein et al. 1995; Wells and Woodcock 1985) and globally (Bryson 1992), the magnitude of Holocene climatic changes was far less than within the Pleistocene and between the Pleistocene and the Holocene. I think it reasonable, therefore, to acknowledge at least this correlation. As discussed in a later section, a singular temporal correlation is insufficient evidence to support a climatic interpretation. I note that the inability of these chronometric data to test climatic hypotheses, however, does not detract from or conflict with nonclimatic interpretations of fan evolution in Death Valley (e.g. Denny 1965; Hooke 1968, 1972; Hooke and Dorn 1992; Hunt and Mabey 1966; Jansson et al. 1993).

There is an entirely new way of linking alluvial fans to climatic changes in drylands. The next section explores, in the context of Death Valley, whether this higher-resolution approach can be used to test climatic hypotheses of fan evolution.

Evaluating Varnish Microlaminae as a Tool to Test Climatic Hypotheses

Optical varnish microlaminae (VML) exist in millimeter-scale depressions on rock surfaces. VML are analogous to lake and ocean sediment. They accumulate over time and yield climatic information. Orange (manganese-poor) and black (manganese-rich) varnish corresponds to dry and wet climates (Cremaschi, 1996; Jones 1991; Liu and Dorn 1996). In a study of some 2900 rock-surface depressions in 420 ultrathin sections from 360 rocks in Death Valley and the surrounding region, Liu (1994) determined that VML are organized into distinct layering units. Figure 8.5 illustrates the ^{14}C, uranium-series, and $^{10}Be/^{26}Al$ calibrated sequence for optical microlaminations for Death Valley, California.

VML have been applied to the study of alluvial-fan evolution in Death Valley (Liu 1994; Liu and Dorn 1996), where the basal layer of rock varnish provides a minimum age for the subaerial exposure of the underlying boulder. Details on sampling density, sampling procedures, and sample preparation are presented elsewhere (Liu 1994; Liu and Dorn 1996). However, I must clarify that the surface appearance of rock varnish in the field can be a misleading indicator of age. Time information is obtained by the oldest (bottom) microlamination of rock varnish, as seen with a light microscope in ultrathin sections obtained from different rock-surface depressions on a boulder. This oldest (bottom) layer provides a minimum age for the exposure of that particular boulder through correlation with the calibrated sequence (Figure 8.5).

A mappable pattern emerges when multiple boulders are sampled, side by side, and over a fan (Figure 8.6(a) and (b)). In these maps, the name of the alluvial-fan segment corresponds to the basal layer of the VML sequence in replicate samples. For example, those fan segments mapped as LU-3 all have varnishes where the oldest VML is LU-3. By mapping the basal varnish layers of the preceding and subsequent fan deposits, Liu (1994) and Liu and Dorn (1996) have determined that it is possible to obtain experimental,

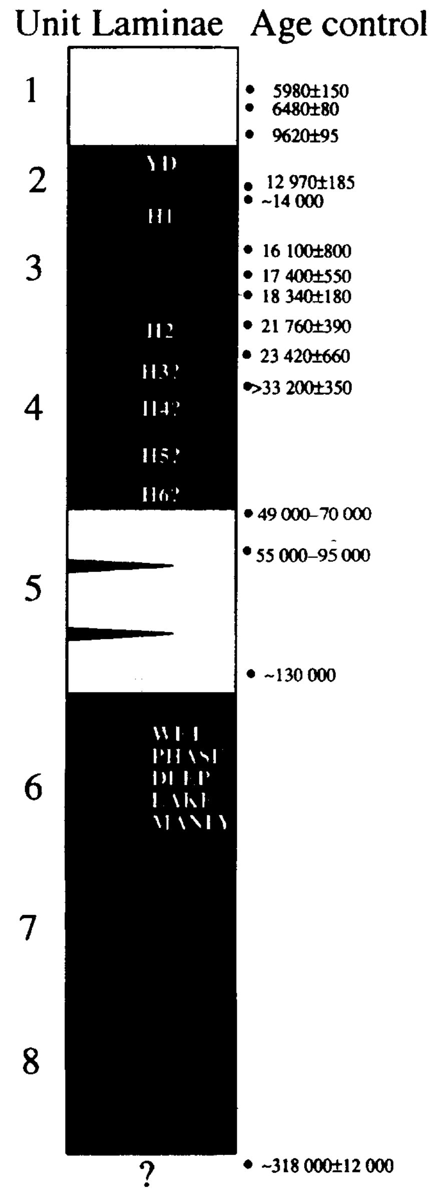

Figure 8.5 An idealized sequence of varnish layering units in Death Valley. Each varnish layering unit is on the order of tens of micrometers in thickness. Shading corresponds with what would be seen in an ultrathin section under a light microscope: light grey is yellow-orange and Mn-poor; dark grey is orange and Mn-intermediate; and black is dark and Mn-rich. YD and H1–H6 indicate possible correspondences between black layers and the Younger Dryas (YD) and Heinrich events H1 through H6. Age control, identified on the side of the sedimentary sequence, comes from radiocarbon ages (<35 000 years), uranium-series (49 000 to 130 000 years), and $^{10}Be/^{26}Al$ (318 000 years); the ages are tabulated in Liu and Dorn (1996). Each chronometric measurement, however, only provides a maximum age for the varnish stratigraphy on that boulder. Hence, the validity of the time scale exists within the limitations of the dating methods discussed in the text

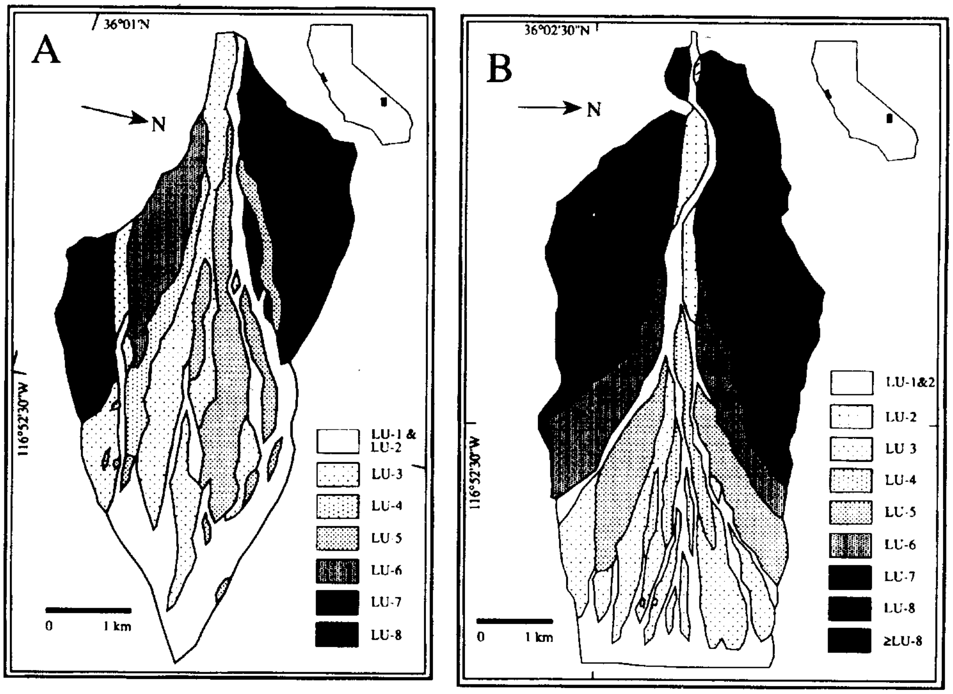

Figure 8.6 Maps of Galena fan (A) and Six Springs fan (B) (adapted from Liu and Dorn 1996). Geomorphic units on each fan deposit are correlated with the basal layering unit in replicate varnish samples (see Liu 1994; Liu and Dorn 1996)

minimum ages for fan segments in Death Valley for the past ~300 000 years (Figure 8.5). The calibration is firm, however, only for the last ~24 000 years (Liu and Dorn 1996). VML also make it possible to correlate fan aggradation with wet and dry intervals, because these intervals are recorded directly in sedimentary strata (rock varnish layers) that rest directly on top of the fan deposit.

Although I believe that the VML method, developed by Liu (1994), is the easiest to use and the most accurate varnish technique yet developed, and that VML provide millennial-scale correlations of spatially disjunct geomorphic surfaces for the last ~24 000 years, this technique cannot yet be used to test climatic interpretations of alluvial-fan development, for a couple of reasons. First, the rate of varnish formation is so slow that submillennial climatic changes are not necessarily recorded; it may be possible, however, in the future to systematically examine the fastest-growing varnishes. Second, available VML data do not indicate a clear correlation between fan aggradation and climatic change. Consider Figure 8.6, maps of two adjacent alluvial fans in southern Death Valley. Fan deposition occurred in all of the climatic intervals that are recognized in Death Valley varnishes, and in other paleoclimatic records (Lowenstein et al. 1995; Phillips et al. 1990, 1994; Smith and Bischoff 1993; Thunell and Mortyn 1995; Winograd et al. 1992). In other words, fan aggradation appears to have been continuous within the period of record, at least to the limit of the chronometric resolution of the VML method. Since deposition has been essentially 'nonstop' for the last $\sim$300 000 years on time scales of 10^3–10^5 years, and since information on the volume of this sediment is lacking, it is not possible to define the role of climate on fan formation in Death Valley through chronometric means.

EVALUATING CLIMATIC HYPOTHESES FOR DEATH VALLEY FANS

I contend here that all climatic models of alluvial-fan evolution that have been applied to Death Valley (periglacial, humid-period, transition to drier climate) fall short on key criteria developed by philosophers of science (Copi 1982; Farr 1983; Hempel 1966; Newton-Smith 1981; Popper 1966): (1) quantity of data explained; (2) ability to test the hypothesis; (3) consistency with established theoretical frameworks and accepted theories; (4) predictive capabilities; and (5) inability to falsify a competing hypothesis.

Quantity of Data Explained

The only clear match between a climatic interval (wet, transition, or dry) and dryland fan aggradation (or a hiatus in aggradation) in Death Valley is during the arid (Lowenstein et al. 1995; Wells and Woodcock 1985) Holocene (Dorn 1988, 1994; Hooke and Dorn 1992). Holocene aggradation also occurred in the Mojave Desert to the south (Dorn 1994; Wells et al. 1990), in southern Nevada to the east (Peterson et al. 1995), and western Nevada to the north (Slate 1992; Throckmorton and Reheis 1993).

The temporal correlation in Death Valley of fan aggradation during the drier Holocene, however, does not comprise an abundance of data in support of any of the climatic hypotheses. A basketball player who is able to make one shot may be a good shooter, but it is only one shot. (I do not mean to infer that the funds and labor spent on the corpus of 84 Holocene age determinations on Death Valley fans have been a waste, but the only issue here is the testability of climatic models.) More problematic is the realization that these data only falsify a model, not even proposed in the literature, that deposition only occurs in more humid periods.

Inability to Test Climatic Hypotheses

The inability of present-day techniques to match fan-segment age (or hiatuses in aggradation) with a climatic interval (with the exception of the Holocene) implies that it is not possible to test any of the three extant climatic hypotheses for Death Valley. It is impossible to test whether a dryland fan aggraded or stabilized in response to any of the century- to millennial-scale climatic changes in the Pleistocene. Even if a chronometric match occurred, the time-transgressive nature of dryland geomorphic systems would make temporal correlations ambiguous. In the context of Death Valley, different elevations in a single drainage basin in the Panamint Range would respond to climatic change differently and in a time-transgressive fashion (Melton 1965; Bull 1991). Certainly, chronometric information can be used to make sound and logical deductions. But the poor temporal resolution inherent in the time-transgressive nature of the hillslope–fan system, combined with uncertainties in precision and accuracy of dating methods, combined with increasingly precise paleoclimatic information, mean that available surface and subsurface chronometric data are not precise enough or accurate enough to test climatic hypotheses for Death Valley.

There is also a fundamental issue over correlation and causation. The correlation of alluvial-fan units with climatic periods can only suggest a climatic cause, not prove one. To illustrate this concern, consider Montgomery and Dietrich's (1992) model of the importance of the position of the channel head. In their discussion, a decrease in vegetation cover from either climatic- or land-use change moves the channel head up the slope – entraining hillslope debris into the fluvial system. A 50-year-long dry phase could cause an upslope movement in channel heads and excavate abundant hillslope debris in the midst of a 1000-year period of more effective moisture. The cause of any correlation could, therefore, be a temporal illusion based on an unstated assumption of climate stability during a given period. There is simply no way to test this complication in Death Valley with available chronometric techniques.

Consistency of Hypotheses with Established Theory

There are other complications that make it very difficult to test climatic hypotheses for fan evolution in Death Valley. A few of the more prominent issues, well recognized in the alluvial-fan literature, are sketched in this section.

Intrinsic geomorphic factors affecting fan evolution are difficult to separate from climatic factors (Field 1994). Intrinsic variables may force loci of deposition to switch (Beaty 1974; Hooke 1987), promote fan-head entrenchment (Germanoskiy and Miller 1995; Schumm et al. 1987; Weaver 1984), or redirect deposition through drainage piracy (Clarke 1989; Denny 1965). Some of the internal feedbacks include the role of tributary streams that empty at the fan head (Hawley and Wilson 1965, p. 22; Dorn 1994), in-basin storage (Lecce 1991; MacArthur et al. 1990; White 1991), and drainage-basin size (Melton 1965; Bull 1991; Wilcox et al. 1995).

Tectonic factors can be isolated from climate (Bull 1991; Ritter et al. 1995), but long-term rates of tectonic activity, as well as the timing of specific events, must be understood for each fan. In addition, tectonically altered spatial variability in stream power can influence the location of incision, aggradation, transportation, and depositional settings (Bull 1991; Bull and McFadden 1977; Hooke 1972; Jansson et al. 1993; Rockwell et al. 1984).

Volumes of aggradational units are an important missing link for climatic interpretations in Death Valley, because larger volumes imply more erosion. Volumes, however, are largely unknown. What evidence does exist suggests considerable spatial and temporal variability. For example, a <16 000 years to >12 000 years (Dorn 1994) orange-colored tributary fan, at the north side at the head of Hanaupah Canyon, is over 8 m thick against the hillslope; but it thins out completely a few hundred metres in the distal direction. The LU-4 unit (Figure 8.6) on Galena Canyon fan, resting on top of a petrocalcic paleosol, ranges from a thickness of $\geqslant$ 8 m to 2 m. There is also evidence, reconstructed from the partial erosion of pre-LU-4 fan units, that pedimentation occured before or during the time that LU-4 deposits aggraded; this can be seen, for example, at the wave-eroded outlier at the northeast corner of Hanaupah Canyon alluvial fan. Although the results of future, volumetrically based studies may indeed be fully consistent with climatic models, it is very difficult to test hypotheses of climatically driven sediment transfer when the volumes of sediment transfer are unknown.

Predictive Capabilities

A valid criterion for assessing scientific hypotheses is prediction, both success in prediction and ability to predict. Consider the failure of a climatic model in predicting fault hazards in Mongolia. Offset fan segments were formerly correlated with the last glacial/interglacial transition – leading to estimates of fault movement ~ 20 mm yr^{-1}. Yet, new ^{10}Be ages reveal that faulting rates have been >16 times slower (<1.2 mm yr^{-1}) than predicted using climatic models (Ritz et al. 1995).

In the case of Death Valley, ambiguous links between climatic changes and sediment erosion in drainage basins make predictions extremely difficult. The basic assumption of the transition-to-drier-climate model is that more vegetation holds sediment in place. This assumption is supported by regional analyses (cf. Knox 1983) and case studies of deforestation (Kesel and Lowe 1987; Meyer et al. 1995). Erosion rates are now highest in semiarid (cf. Bailey 1979) climates (Clayton 1983; Knox 1983; Langbein and Schumm 1958; Walling and Kleo 1979). Key spatial issues for Death Valley drainage basins are the starting position of erosion maxima and the direction of the climatic change. Yet, spatial positions of erosion maxima on hillslopes are not known in Death Valley at present, and certainly not for different times in the past.

Eventually, it may be possible to extrapolate erosion information from fossil plant assemblages (cf. Spaulding 1990; Wells and Woodcock 1985), but not at present. There are no quantitative links between vegetation-specific data and resistance of sediment to hillslope erosion (see discussion in Eybergen and Imeson 1989). Furthermore, vegetation changes can lag behind climatic changes (Bull 1991). Information is lacking in Death Valley to answer such basic site-specific questions as: was resistance to erosion greater on the lower slopes in the Pleistocene under a semiarid cover of *Yucca* scrub and dwarf conifers, or during the Holocene under a hyperarid regime of sparse *Larrea* coverage? This sort of ambiguity is heightened by clear warnings of the geomorphic impact of climatic change in other dryland contexts:

> ... when regional or local scales are considered, the relationship between climate and environmental conditions become problematic. Local factors such as topography, lithology and soils play a decisive role in the spatial redistribution of water resources ... The relationship between climate and environment in arid and semi-arid areas is even more problematic when climate change is considered ... The data presented show that the effect of a climate change in such areas is highly controlled by the surface conditions prevailing in the area prior to climatic change ... (Yair 1994, p. 223–224).

Inability to Falsify Competing Hypothesis

It is not possible in Death Valley to falsify the competing hypothesis that sediment transfer (hillslope erosion to fan deposition) in dryland alluvial fans is from high-magnitude (low-frequency) meteorological events – unrelated to any particular climatic condition. Extreme meteorological events (or short-term climatic fluctuations) within a longer climatic state are often responsible for geomorphic changes (Graf 1988; Kochel and Ritter 1990; Macklin et al. 1992; Meyer et al. 1995; Roberts et al. 1994; Shick 1974; Thomas and Thorp 1995). Furthermore, the 'impacts of extreme events within present-day climate regimes may mimic those of palaeoclimates ...' (Thomas and Thorp 1995, p. 195). Sediment mobilization may have even been tied to extreme drought followed by extreme rainfall, or in response to a fire followed by extreme rainfall (Germanoskiy and Miller 1995). There is abundant historic and prehistoric evidence to suggest the importance of extreme meteorological events in aggradation (Allen and Anderson 1993; Beaty 1974; Bowman 1988; Brookes et al. 1982; Dorn et al. 1992a; Eybergen and Imeson 1989; Field 1994; Grossman and Gerson 1987; Hooke 1987; Kesel and Lowe 1987; Williams and Guy 1973). In the case of Death Valley, it is simply not possible to falsify this relevant, plausible, and simple competing hypothesis to climatic models.

In summary, extant climatic hypotheses of alluvial-fan evolution in Death Valley do not fare well when they are evaluated with criteria suggested by philosophers of science. This does not mean that climatic explanations are incorrect, only that they are not testable at this time.

CONCLUDING REMARKS

Climatic hypotheses of alluvial-fan evolution in Death Valley have serious deficiencies, the most significant of which is they cannot be tested. Many of the difficulties in testing climatic models that I have isolated for Death Valley may also apply to research on other dryland fans. The fundamental question of temporal correlation is certainly applicable elsewhere: is it even possible to correlate, in time, climatic changes with fan aggradation or with hiatuses in deposition? The answer varies with the time scale of climate change. My answer would be 'probably' for the twentieth century where meteorological records are available; it would probably be possible to compile and map many historic aggradational events – and then to correlate them with meteorological data. My answer is 'possibly' for the orbital time scale of 10^4–10^5 years; correlations between alluvial-fan segments and broad climatic intervals are problematic under the old paradigm of gradual climatic changes (Figure 8.7), but still possible.

Correlations between sudden and dramatic, century- to millennial-scale Pleistocene climatic changes and dryland alluvial-fan events (aggradational or hiatus in deposition) are not possible within, and probably outside of, Death Valley. The best available chronometry in the southwestern USA, for example, places fan aggradation within any number of different climatic intervals (Figure 8.8). The very difficult problem is that the Pleistocene experienced high-frequency and high-magnitude oscillations in climate. The issue is not the worth of available chronometric information; the value of age determinations in providing insights into the rates of dryland geomorphic processes should be decoupled from their utility in testing climatic hypotheses. Chronometric methods available to measure the ages of Pleistocene dryland-fan deposits are simply not up to the task of correlation with century- or even millennial-scale climatic changes. To mix metaphors, the target has moved so far back that the light at the end of the tunnel is no longer visible.

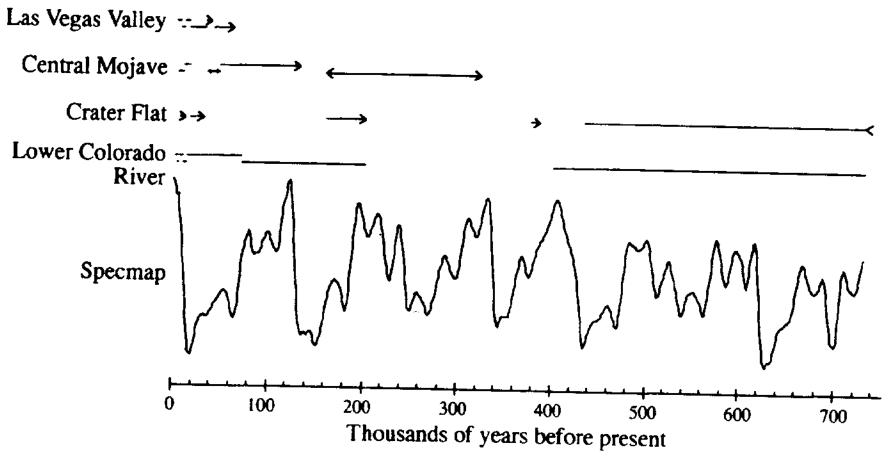

Figure 8.7 A visual comparison between the aggradation of alluvial-fan units in the southwestern USA and broad climatic intervals in the Pleistocene as portrayed by the Specmap record of global ice-volume change (Imbrie et al. 1993; Martinson et al. 1987). The Pleistocene alluvial-fan chronologies presented are those with the highest available chronometric resolution from: the lower Colorado River (Bull 1991); Crater Flat in southern Nevada (Peterson et al. 1995); the central Mojave Desert (Wells et al. 1990); and Las Vegas Valley (Quade 1986; Quade and Pratt 1989). Arrows indicate that ranges may be maximums or minimums. Aggradation units were placed lower and higher in any given record, giving the appearance of dashed lines, in order to clearly delineate truly separate deposits that would have otherwise 'run together'.

As in Death Valley, only one clear correlation can now be made in the southwestern USA between a climatic event and a fan unit: during the Holocene. Calibrated, correlative, and numerical ages are precise enough to constrain the ages of certain fan deposits to this drier-warmer climatic period (e.g. Bull 1991; Dorn 1994; Peterson et al. 1995; Reheis et al. 1989; Slate 1991; Throckmorton and Reheis 1993; Wells et al. 1987, 1990). I argue that, as in Death Valley, a singular correlation does not constitute an abundance of data in favor of a hypothesis. The issue here is not the value of these numerous Holocene datasets in answering important geomorphic questions, or their value for building process–response models, but in their ability to test climatic hypotheses. There are complications even in this single temporal correlation, because the response of fans to climatic change has been time-transgressive in the Holocene (Bull 1991), because smaller magnitude climatic changes did occur during the Holocene (Slate 1991; Bryson 1992), and because Holocene fan aggradation has occurred in a variety of climatic regions (e.g. Bull 1991; Church and Slaymaker 1989; Dorn 1994; Meyer et al. 1995; Peterson et al. 1995).

If my analysis for Death Valley can indeed be extended to other dryland alluvial-fan sites, the implication would be clear. Climatic hypotheses for fan evolution would have to be reevaluated: by geomorphologists developing theory; by the global change research community; by those assessing tectonic hazards; by remote sensing specialists who map fans with the assumption that certain units are diagnostic of a particular climate; by policy-makers deciding issues of flood insurance; by those looking for widespread proxy data in arid continental settings to test climate models; or by cognate disciplines such as biogeography or pedology interested in relating spatial data to landscape evolution in drylands.

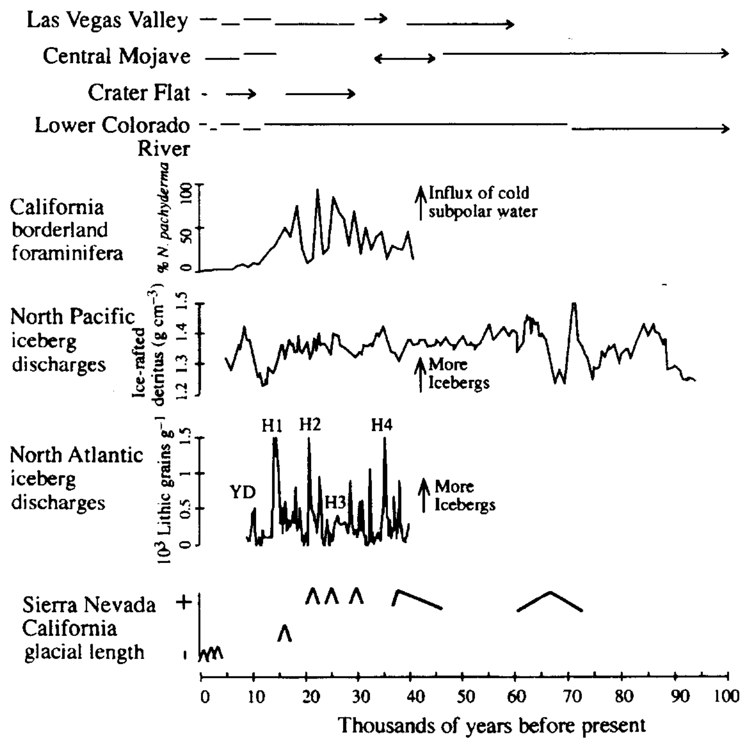

Figure 8.8 Comparison of the aggradation of alluvial-fan units in the southwestern USA (from Figure 8.7) with records of millennial-scale climatic change. This diagram focuses on the last 100 000 years, because this period has a higher chronometric resolution. The millennial-scale climate records are from: foraminifera in the Tanner Basin in the southern California borderlands (Thunell and Mortyn 1995); iceberg rafting events in the North Atlantic, with the Younger Dryas (YD) and Heinrich events (H1–H4) indicated (Bond and Lotti 1995); glacial advances in the Sierra Nevada (Bach and Elliott-Fisk 1996; Dorn 1996; Zreda and Phillips 1994; Zreda et al. 1994); and ice rafting in the North Pacific (Kotilainen and Shackleton 1995)

The discussion here has been limited to dryland fans, but similar issues may exist in the interpretation of evolutionary changes as a function of discrete climatic intervals in other morphoclimatic settings (Butzer 1980; Thomas and Thorp 1995). The paradigm shift toward sudden and dramatic climatic changes throws down a gauntlet for geomorphologists who attempt to relate past climatic events to landforms. There may be troubled times ahead for those who attempt to use chronometric techniques to correlate hillslope and fluvial systems with late Pleistocene climatic changes.

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