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SEGMENTATION OF ALLUVIAL FANS IN DEATH VALLEY, CALIFORNIA: NEW INSIGHTS FROM SURFACE EXPOSURE DATING AND LABORATORY MODELLING

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ABSTRACT

Laboratory experiments, recent paleoenvironmental analyses of rock varnish, and surface exposure dating of geomorphic units have led to new insights into the process of entrenchment and segmentation of alluvial fans, and into the history of Quaternary sedimentation in Death Valley. Entrenchment begins at the fanhead. As the trench deepens, its down-slope end migrates down-fan, taking several tens of thousands of years to reach lower parts of the fan. Laboratory experiments suggest, however, that a new segment begins to grow at the toe long before the trench reaches this part of the fan. Furthermore, the initial slope of the segment is not the equilibrium slope. Field evidence supports this model. The tectonic tilting that caused entrenchment and segmentation in Death Valley may have been triggered by loading of the valley with water.

Sedimentation on the salt pan in southern Death Valley is not, at present, in equilibrium with that on the fans. Rather, it seems to be adjusting to an increase in the amount of fine material reaching the playa, due in part to breaching of the outlet of Lake Tecopa somewhat after 600 ka BP, and in part to subsidence of different parts of the valley at different rates. Failure to recognize this disequilibrium resulted in errors in earlier estimates of the age of the segmentation events.

KEY WORDS Alluvial fans Rock varnish Surface exposure dating Death Valley Quaternary

INTRODUCTION

Six adjacent alluvial fans on the west side of south-central Death Valley, California, are segmented (Hooke, 1972); that is, geomorphic mapping and topographic map study have revealed that large areas of the fans have a remarkably uniform slope and are bounded up-fan, down-fan and laterally by surfaces with distinctly different slopes (Bull, 1964a). Following Bull (1964a), Hooke attributed this segmentation to episodic steepening of the fans by eastward tectonic tilting. Such tilting is believed to be responsible for entrenchment at the heads of the fans and deposition nearer the toes. Hooke inferred that this deposition occurred in down-fan thickening wedges as shown in Figure 1a, although only the up-fan edges of such wedges have been seen. Surfaces that have been entrenched are no longer reworked by flows from the source area; thus desert pavements and rudimentary soils develop on them, and they acquire a distinctive weathering character.

Hooke recognized three main episodes of segmentation, each represented by an abandoned surface with a different slope. These surfaces are designated Q1, Q2 and Q3 herein. They, and the presently active surface, Q4, are shown schematically in Figure 1b and more accurately in Figure 2. The weathering character and degree of soil and pavement development on the surfaces were comparable from fan to fan, suggesting that the segmentation events were contemporaneous on adjacent fans.

Recently, researchers have developed several new surface exposure dating techniques that provide

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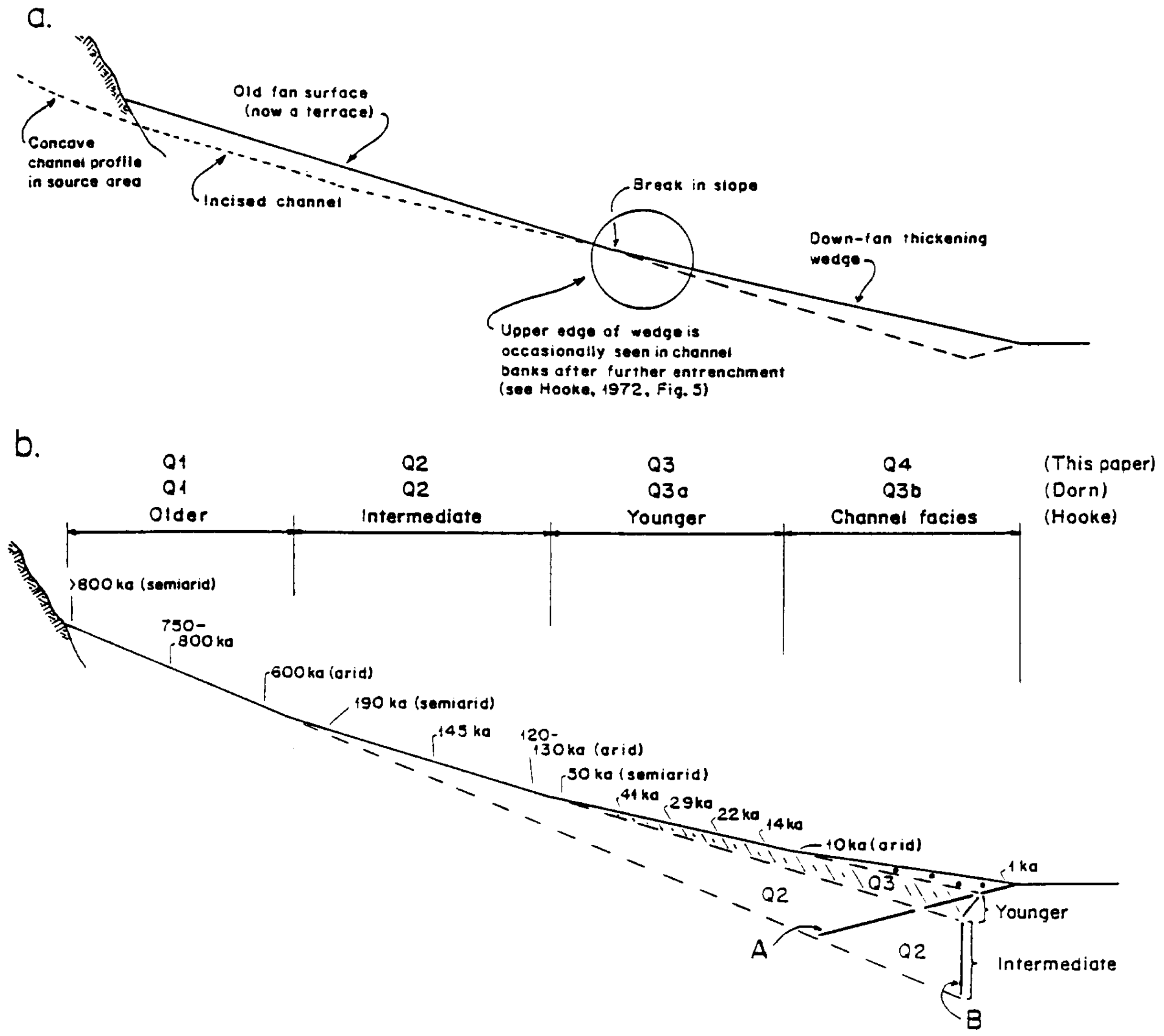


Figure 1. (a) Schematic longitudinal profile of a segmented fan on which the youngest segment is at the toe. Profile of channel is shown to be concave in source area and straight, with two segments, on upper half of fan on basis of profile of channel on Hanaupah fan in Death Valley taken from 15 min series topographic maps. Owing to the down-fan shift in locus of deposition, the toe of the fan is building out over the playa. (b) Schematic sketch of Hanaupah fan showing the breaks in slope resulting from the three earliest segmentation events recognized on most west-side fans studied. Stratigraphic unit names used by Dorn (1988), Hooke (1972), and in the present paper are shown at the top. Ages of basal varnish on the exposed surfaces of the units and climate at time of initiation of varnish formation are shown. Lines A and B are discussed in the text, near end of paper

numerical ages for the cessation of depositional geomorphic episodes. These techniques depend upon accumulation of cosmogenic isotopes (Phillips *et al.*, 1990; Kurz *et al.*, 1990; Cerling, 1990; Nishiizumi *et al.*, 1989; Jull *et al.*, 1989), dating rock varnish by radiocarbon (Dorn *et al.*, 1989) and cation ratio (Harrington and Whitney, 1987; Dorn, 1989) techniques, calibration of soil indices (Harden, 1987; Switzer *et al.*, 1988), and uranium series (Ku *et al.*, 1979) and uranium trend (Rosholt, 1985) dating of desert soils.

In addition, new techniques for studying the microstratigraphy of rock varnish have revealed characteristics with paleoclimatic significance. Variations in the Mn:Fe ratio (Dorn, 1990), in δ^{13}C (Dorn and DeNiro, 1985), and in micromorphology of rock varnish (Dorn, 1986) have proven to be useful.

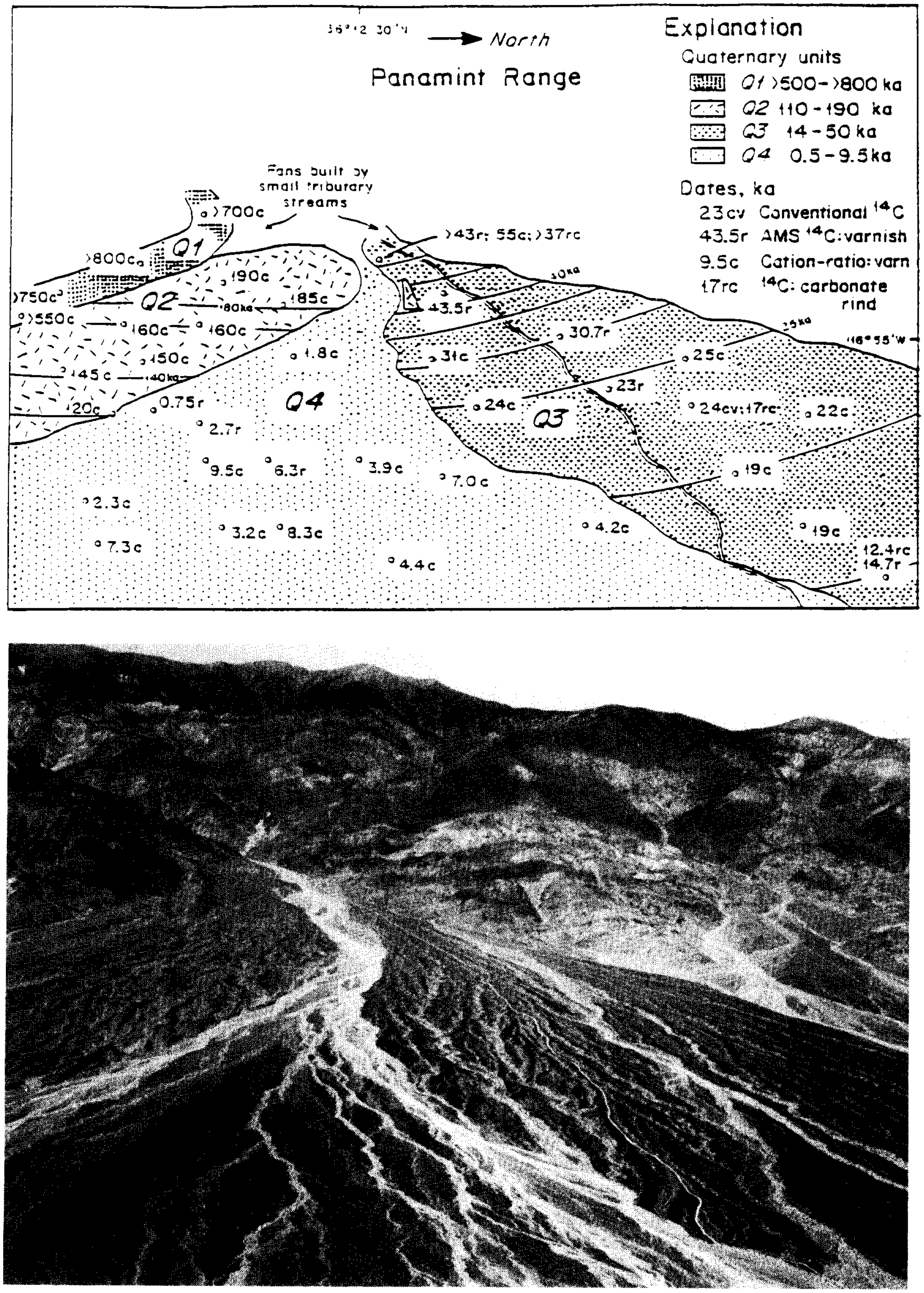


Figure 2. Oblique aerial photograph of Hanaupah fan, with corresponding map showing locations and ages of samples collected for surface exposure dating. For scale, road on Q3 surface is ~6 km long. Dates on surface Q4 do not show down-fan younging because this is the presently active surface. The three carbonate rind ages have not been published previously. They are >37 100 ETH 4291, 17 570 ± 145 ETH 4810 and 12 360 ± 150 ETH 3674

Application of some of these new techniques in Death Valley have led us to modify our earlier ideas on the two principal subjects discussed herein, the Quaternary history of these fans, and the process of segmentation.

Controversy continues regarding the precision of some of the dating techniques (Bierman *et al.*, 1991; Reneau *et al.*, 1991; Reneau and Raymond, 1991). We believe, however, that the criticisms have been adequately answered (Dorn and Krinsley, 1991; Dorn, 1992). In particular, consistent results have been obtained in other studies using combinations of cation ratio, conventional ^{14}C, AMS ^{14}C on rock varnish, uranium series, ^{36}Cl, ^{26}Al and ^{10}Be techniques (Dorn, 1992). (Only the first four of these were used in the present study.) Some of these comparisons were done independently by different investigators in different laboratories, and thus constitute 'blind' comparisons (Loendorf, 1991; Dorn, 1992). Furthermore, the internal consistency of dates obtained by four different methods in the present study provides convincing evidence for the reliability of the *relative* ages. Thus, even if numerical ages prove to be significantly and systematically in error, this would not alter the essential conclusions that we reach.

In the next two sections we summarize some recent results, a few of which may raise questions or appear to be inconsistent with the preceding discussion. Three problems are then stated and resolutions to them sought: (a) the explanation for the down-fan younging of the surface exposure ages; (2) the cause of the segmentation; and (3) the reason for a discrepancy with Hooke's (1972) earlier age estimates.

AGES OF SURFACES AND CLIMATE AT TIME OF DEPOSITION

Dorn (1988) investigated rock varnish on stones embedded in desert pavements on seven fans in south-central Death Valley. Six of these fans were those studied by Hooke (1972). Dorn determined the surface exposure age by conventional ^{14}C dating of a charcoal sample buried in one fan, by accelerator ^{14}C dating of organic material from the lowest layers of the varnish, and by cation ratio $[(K + Ca):Ti]$ analysis of the bulk varnish. Using accelerator ^{14}C methods, he has also dated organic matter that was extracted, using HF and HCl, from the innermost parts of carbonate rinds in soils. (Organics were used to avoid the inorganic carbonate system that may be open.) Figure 2 shows 39 of these surface exposure ages obtained on one of the fans that we have studied intensively (Hanaupah fan). The dates on carbonate rinds are systematically a few thousand years younger than dates on varnish in the same vicinity. While possibly due to contamination, such a discrepancy might also reflect a lag between the initiation of varnish and of carbonate accumulation.

The cation ratio technique is still being refined and the cation leaching curve for the Death Valley region has been revised recently to account for variables found to influence these ratios (Dorn, 1989, pp. 568–569; Krinsley *et al.*, 1990; Dorn *et al.*, 1990a). For these reasons, the 28 cation ratio ages shown in Figure 2 are 5–10 per cent older than ages reported previously, based on the same cation analyses (Dorn, 1988). In addition, we call attention to the fact that the >250 ka range in ages on the Q1 surface (Figure 2) is probably excessive. The uncertainty in these ages may well be >100 ka, both because they are near the limits of usefulness of the cation ratio technique, and because the Q1 surface is deeply eroded so the cation ratio clocks may have been reset.

The pattern of down-fan decrease in age on the Q1, Q2 and Q3 surfaces (Figures 1b and 2) suggests that the entrenchment resulting in abandonment of these surfaces began at the up-fan edge of the surface. The incision gradually progressed down-fan, so that material at the lower edge of the surface was still being reworked tens of thousand of years later.

Dorn's ages for these surfaces are about an order of magnitude older than Hooke (1972) originally proposed. However, Hooke and Lively (1979) later dated two samples of calcrete from unit Q2 on Johnson fan, using uranium series techniques. Their ages—178 ± 10 ka on a sample from the uppermost reaches of unit Q2 and 112 ± 4 ka about 0·5 km further down-fan—are consistent with Dorn's (1988) cation ratio dates, which suggest progressive abandonment of the Q2 surface between 190 and 120 ka BP (Figures 1b and 2).

The microstratigraphy of varnish layers has yielded insights into the changes in climate that occurred during the evolution of these fans (Dorn, 1988). Some examples are shown in Figure 3. Low on the Q3 surface on Hanaupah fan, there is a basal layer of varnish that is enriched in Mn (Figure 3a). This layer is capped by an Mn-poor layer. Further down-fan on the Q3 surface, only the Mn-poor layer is present, while at progressively higher elevations on this surface, the basal Mn-rich layer thickens (Figure 3b). Because the Mn:Fe ratio varies inversely with alkalinity (Dorn, 1990; Jones, 1991), which in turn varies inversely with humidity (Dorn, 1988), such Mn-rich layers represent periods when the climate was wetter than today. That the climate during deposition of the Mn-rich layer in Figures 3a and 3b, between ~45 and ~19 ka BP, was comparatively wet is supported by macrofossils in *Neotoma* middens of this age (Spaulding, 1985; Wells and Woodcock, 1985), and by evidence for a high lake stand (Hooke, 1972). The absence of the Mn-rich layer further down-fan on the Q3 surface indicates deposition under drier conditions. [Because Mn can be

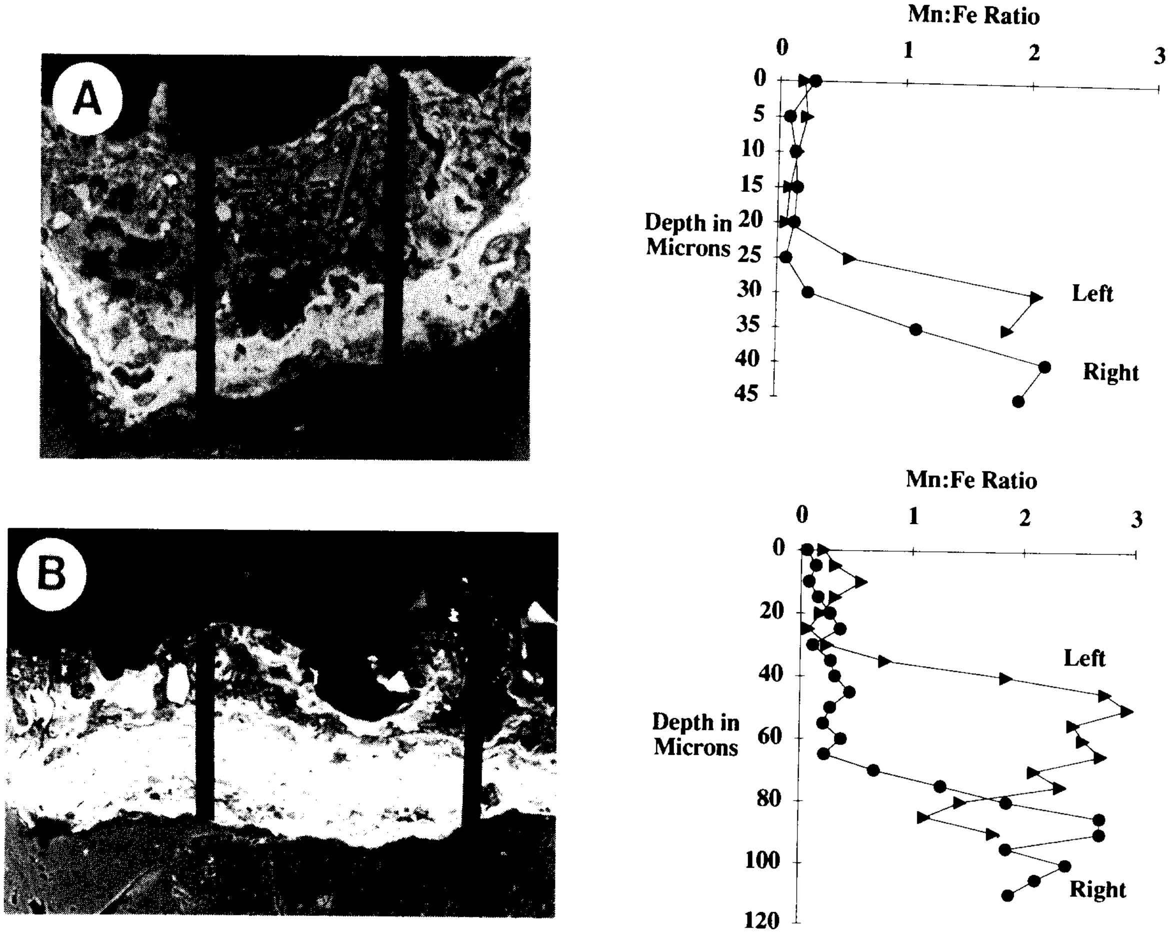
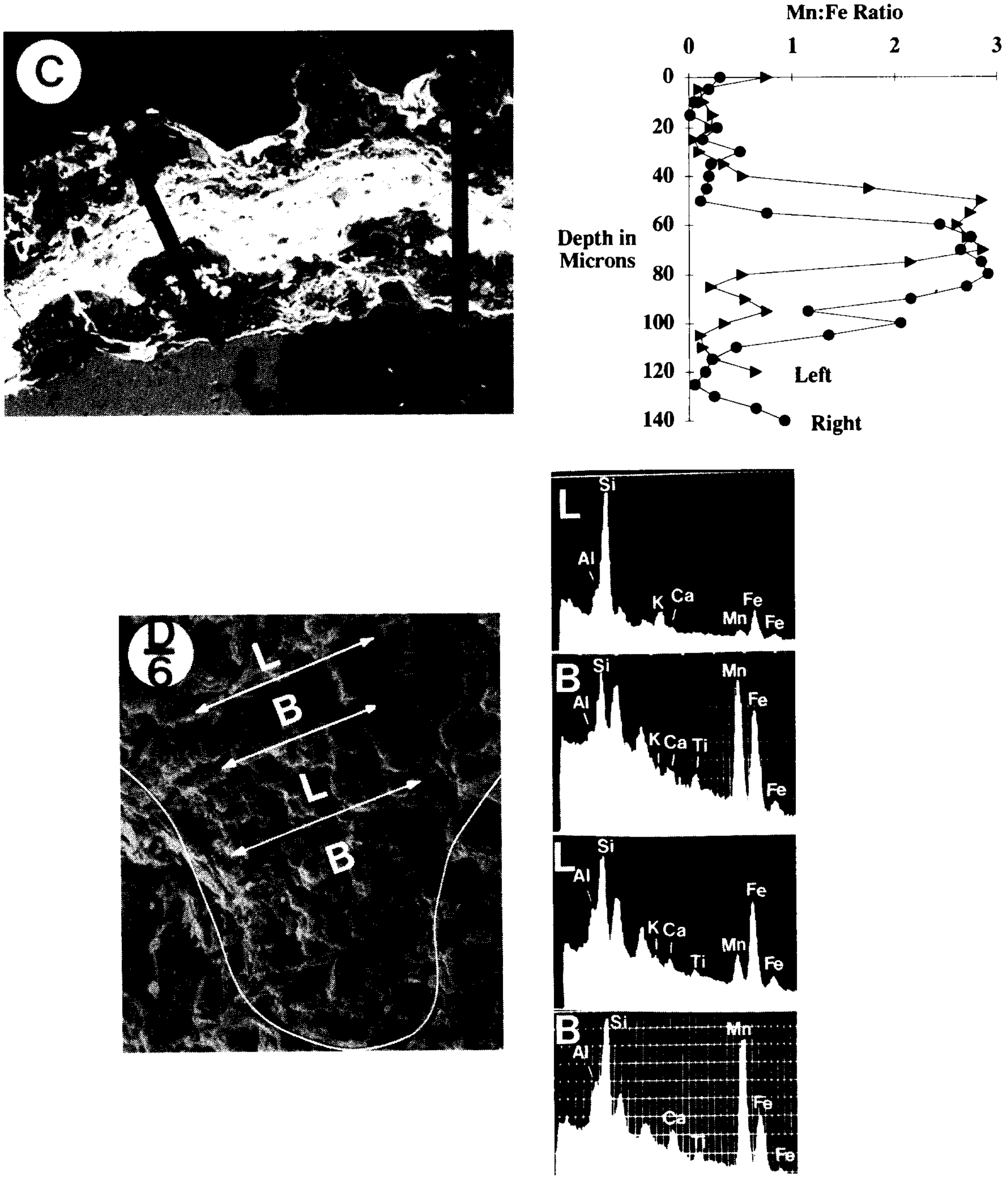


Figure 3. Representative cross sections of varnish from different localities on Hanaupah fan showing a progressive sequence of environmental change revealed by two different varnish paleoenvironmental tools: Mn:Fe microlaminations (Dorn, 1990; Jones, 1991) and micromorphology (Dorn, 1986). Scale is indicated by length of microprobe transects. Rock is at bottom in all micrographs. (a) Backscatter electron micrograph of varnish from Q3 unit (sampled from one of sites with 19 ka cation ratio age on Figure 2). The layer at the base of the varnish is brighter because it is enriched in Mn, reflecting a less arid climate. The corresponding left and right electron microprobe transects match the left and right transects on the micrograph. (b) Backscatter electron micrograph of varnish from Q3 unit (sampled from site with 43·5 ka radiocarbon age on Figure 2). Mn-rich (brighter) unit at the base is here thicker than in (a), suggesting a longer period of climate that was wetter than today's (Spaulding, 1985; Wells and Woodcock, 1985). Corresponding electron microprobe transects show Mn:Fe ratios. (c) Backscatter electron micrograph from Hooke's (1972) Blackwelder stand strandline at the base of unit Q2. Basal layer of varnish is not enriched in Mn. This is consistent with formation during the arid interval that led to dessication of Lake Manly. Corresponding electron microprobe transects show Mn:Fe ratios. (d) Secondary electron micrograph showing two cycles of lamellate (L) on botryoidal (B) varnish from Q2 surface (sampled from site with 185 ka cation ratio age on Figure 2). The corresponding energy dispersive X-ray analyses show chemistries of the different layers. The upper analysis corresponds to the upper lamellate layer, the second with the upper botryoidal layer, and so forth. Scale indicated by length of 6 μm bar



mobilized and reprecipitated as discontinuous threads and pockets within largely Mn-poor layers (Figures 3a–3c; Dorn, 1990), paleoenvironmental interpretations such as these must be based on replicate analyses of varnishes from multiple boulders at a site and on laminations that are laterally continuous (Dorn, 1988, 1990).]

Near the lower edge of the Q2 surface, three main layers are found in varnish: here the Mn-rich layer is sandwiched between two Mn-poor layers (Figure 3c). At the head of the fan on Q2, however, a second Mn-rich

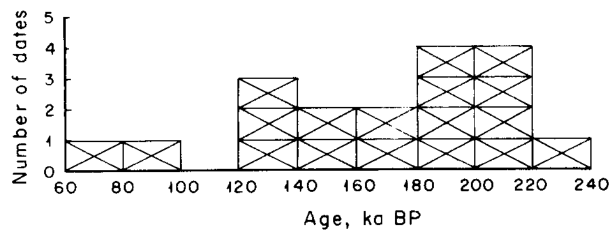


Figure 4. Histogram of U/Th dates on tufa formed during the Blackwelder stand of Lake Manly (data from Hooke and Lively, 1979). While the two youngest and several of the oldest dates may be in error owing to U migration, the concentration of dates between 120 and 200 ka suggests that the Blackwelder stand may have been roughly coincident with deep sea isotope stage 6, ~128 to 195 ka BP (Shackleton and Opdyke, 1973)

layer underlies this sandwich (Figure 3d). In this case, the climate signal is also revealed by varnish micromorphology. Mn-rich layers have a botryoidal texture, characteristic of less dusty, less alkaline periods and Mn-poor layers have a lamellate texture, characteristic of dustier, alkaline periods (Dorn, 1986, 1990).

These and similar microstratigraphic data, using $\delta^{13}C$ as well as Mn:Fe ratios and varnish micromorphology, led Dorn (1988) to conclude that the up-fan parts of the Q1, Q2 and Q3 units were abandoned as surfaces of active deposition during semiarid intervals, while the down-fan parts continued to be active until the climate had become drier, as it is today. Thus in each case the climate became more arid as entrenchment progressed. This is the basis for the climatic designations in Figure 1b.

DATING LACUSTRINE EVENTS

The lake that periodically flooded Death Valley, Lake Manly, cut strandlines on some of these alluvial fan surfaces. The most prominent strandlines are those left by the Blackwelder stand of Lake Manly at about 90 m above sea level (Hooke, 1972, p. 2086).

Hooke (1972) inferred that the Blackwelder stand was late Wisconsin in age, but subsequent U/Th dating of 18 samples of calcareous tufa formed in the lake (Hooke and Lively, 1979) suggested, instead, that it was Illinoian (Figure 4). While such dates must be viewed with caution, owing to the possibility of contamination and U migration, new cation ratio dates support an Illinoian age for the Blackwelder stand. Measurements of the cation ratios were made by inductively coupled plasma and wavelength dispersive microprobe, and the new cation leaching curve mentioned above was used. These measurements give an age for Hooke's (1972) Blackwelder stand shoreline cut into the Q2 surface on Hanaupah fan of 123 ± 20 ka BP, where the uncertainty is based on the standard deviation of measurements on nine different boulders. Cation ratio ages for shorelines cut into the Q2 surface at Hooke's (1972) Warm Spring and Anvil sites are 137 ± 22 ka BP (seven boulders) and 152 ± 27 ka BP (11 boulders). These sites are also on the west side of Death Valley, about 23 km south of Hanaupah fan. As these are surface exposure ages, they provide minimum dates for the withdrawal of Lake Manly from the Blackwelder stand.

Dorn (1988, p. 66) and Dorn *et al.* (1990b) identified another high stand of Lake Manly of late Wisconsin age. At this time the lake surface was approximately at sea level, and the lake was only ~90 m deep. Radiocarbon dates from cores (Hooke, 1972) suggest that this phase of Lake Manly lasted from >26 to ~10 ka. However, the highest stand of this lake was apparently abandoned before about 13 ka (Dorn *et al.*, 1990b).

THE PROBLEM

Dorn's data raise three questions: (i) how is a new segment formed at the toe, and how is it related to the down-fan migrating fanhead trench; (ii) what is the significance of the fact that entrenchment of up-fan parts of segments apparently coincided with a more humid climate; and (iii) why were Hooke's (1972) proposed ages for some of these events far too young? The next two sections address the first of the above questions, and the following two sections deal with the second and third.

FAN PROFILES

The profiles of the fans studied by Hooke (1972) in Death Valley undeniably consist of one to several *straight* segments. In the next paragraphs, processes that might lead to straight profiles are explored. We do not deny that some fans may have uniformly concave profiles, but do observe that data presented in support of such profiles normally do not permit one to distinguish between a uniformly concave profile and a segmented one (e.g. Figure 8 of Lattman, 1973).

The equilibrium profile of an alluvial fan is the profile at which flows transport and deposit sediment without any protracted tendency towards regrading. This is the profile that a fan attains after a period of stability that is long compared with the time necessary to regrade a fan to a new profile, but short compared with the time needed for appreciable changes in the fan source system that might change the profile, for example by changing the sediment yield. On fans that have been this stable, essentially the entire fan surface shows evidence of reworking within the past, say, 10 to 20 ka.

The slope at which material is transported and deposited at any location on an alluvial fan decreases with increasing mean discharge, and increases with increasing mean debris size and sediment concentration in the flows (Hooke, 1968; Hooke and Rohrer, 1979). In the down-fan direction, water flows are split into smaller and smaller channels. The discharge per channel thus decreases. This leads to a *tendency* towards a convex upward profile. However, deposition of coarser sediment in gravel bars is the cause of these bifurcations. Thus both mean debris size and sediment concentration decrease at bifurcations. This decreases the slope required to carry the remaining sediment load, countering the need for an increased slope (or convex profile).

These processes could reach a balance in such a way as to produce straight profiles if the effect of the decrease in sediment size and concentration at bifurcations does not quite offset the effect of the decrease in discharge per channel. A *tendency* towards development of a convex profile would thus remain. Convex profiles, however, cannot exist as stable profiles because in the limit they would result in a discontinuity in slope between the fan and the playa. Thus this tendency towards convexity is counteracted by deposition further down-fan, which eliminates the discontinuity.

Uniformly concave profiles, if they are shown to exist, can also be understood using this approach. Such profiles could reflect a situation, perhaps a particular grain size distribution, in which the effect on slope of the decrease in sediment size and concentration at bifurcations *more* than offsets the effect of the decrease in discharge per channel.

In the case of fans with straight profiles, the slope at which material is transported and deposited does not change in the down-fan direction. The term 'equilibrium profile' can then be replaced with *equilibrium slope.* If the slope of such a fan is changed tectonically or if the equilibrium slope is changed, as might occur following a change in climate, regrading of the fan is initiated and the fan becomes segmented. The profile of a fan that initially had a uniformly concave profile would also reflect such disturbances, of course, but the effects would be more difficult to detect and interpret.

THE PROCESS OF SEGMENTATION

Laboratory experiments

To better understand the processes by which a fan is regraded, resulting in a segmented profile, a laboratory experiment was run using a stream table similar in scale and operation to that employed previously by Hooke and Rohrer (1979). About 1000 cm^3 of loose fine sand and silt were placed in an inlet channel, and a discharge of $\sim 70\ \mathrm{cm}^3\,\mathrm{s}^{-1}$ was run through the channel for ~ 120 s. After 50 such episodes, a fan of about 0·8 m in radius had been built. Discussion of the procedure by which this fan was segmented is deferred for the moment.

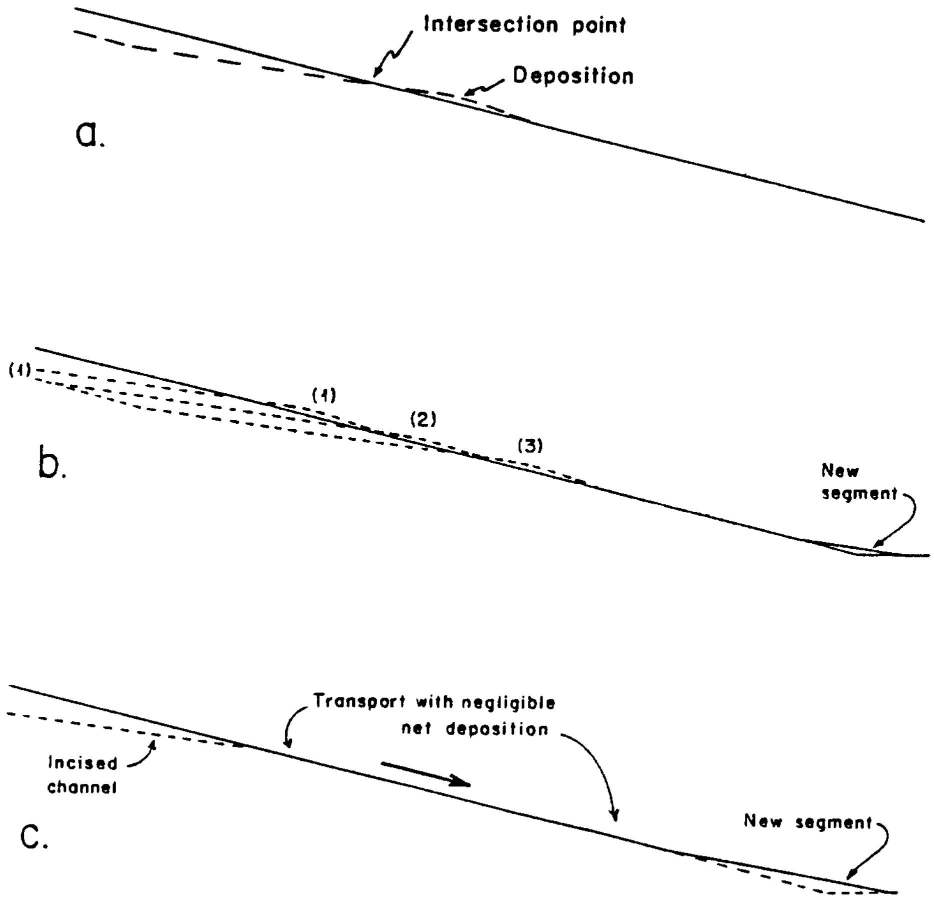


Figure 5. (a) Schematic sketch, based on both laboratory and field observations, showing intersection point and deposit immediately down-fan therefrom. (b) Schematic sketch showing successive stages, 1–3, in down-fan migration of an intersection point. Dashed lines below fan surface show channel downcutting into earlier fan deposits. (c) Initiation of deposition in a new segment by transport of sediment across a steeper surface between the intersection point and the new segment

Deposition on a fan prior to tilting

It is important to understand the changes that take place during a depositional episode on laboratory, and probably also on natural fans. The initial flow finds plenty of sediment, either added to the laboratory inlet channel just prior to the episode, or loosened by weathering and transported to the natural channel by slope processes between runoff events. (On a natural fan, this initial flow may take the form of a debris flow.) During this part of the laboratory episode, the water is heavily loaded with sediment, and a wave of sediment moves along the bed, causing appreciable local aggradation as it passes. The fan slope increases when this wave of aggradation reaches the fanhead. Later in the episode the water has a lower sediment load, having removed most of the readily transportable material from the source area (inlet channel). The fanhead is now downcut, deposition begins at the toe, and the slope begins to decrease. If the increase in slope during the initial phases of the episode equals the decrease during later phases, the average slope of the fan will not have changed; the slope may then be described as the equilibrium slope for that fan, given the experimental conditions imposed on the system in the laboratory, or the climatic and geologic conditions in the source area of a natural fan.

The processes on the lower part of the fan merit more detailed description. The downcutting at the fanhead and aggradation at the toe during later stages of a laboratory episode, or of a natural runoff event, result in a

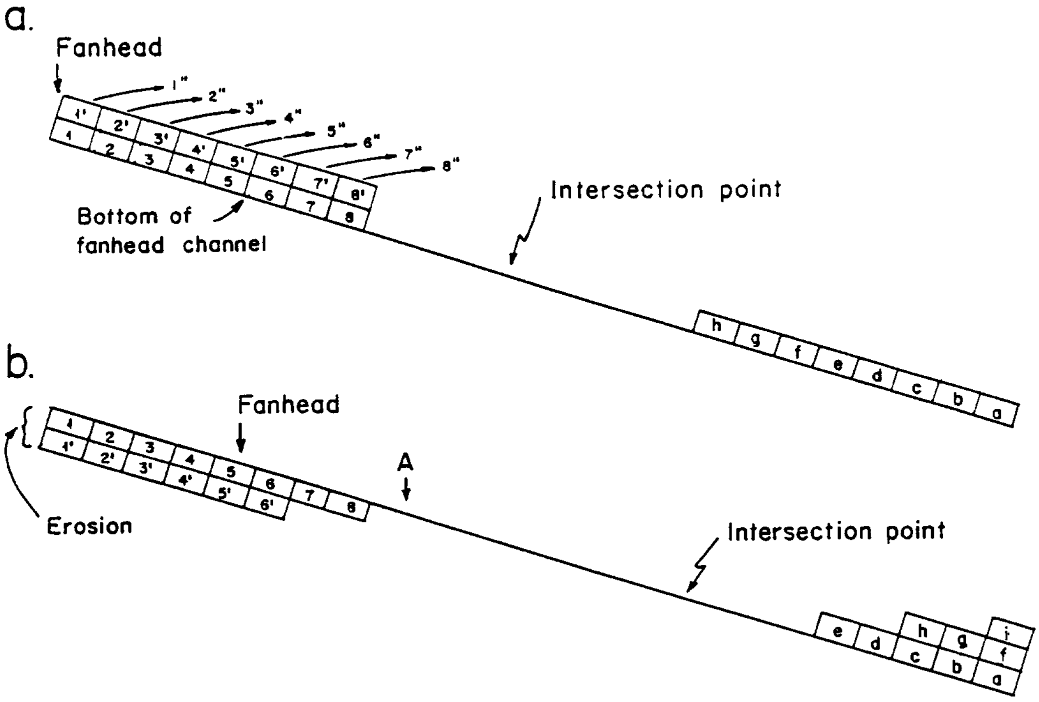


Figure 6. Model for erosion and deposition on a fan. See text for detailed discussion. (a) Fan surface during a runoff episode. Boxes at fanhead represent wave of deposition early in episode. Box 1 precedes 2 and so forth, and 1′ follows 1. At least the first part of this deposition occurs in a channel, not on the fan surface. Arrows and numbers with double primes represent subsequent erosion of this material later in episode. Boxes at toe represent deposition. Box a precedes b and so forth. The timing of this deposition relative to events at the fanhead is not specified. (b) Regrading of fan surface during segmentation. As in (a), erosion of box 1 precedes that of box 2, and deposition of box a precedes that of box b and so forth. Most of sediment deposited at toe comes from source area. Only a small fraction is from erosion of fanhead. Boxes are not intended to represent equal volumes or thicknesses of sediment

channel at the fanhead that decreases in depth down-fan. This channel merges with the fan surface in the midfan area in what has previously been called the ‘intersection point’ (Figure 5a; Hooke, 1967, p. 450). A depositional lobe is commonly present just below the intersection point. These lobes tend to build up until the flow, having been diverted down an oversteepened flank of one lobe, incises it rapidly and carries sediment well down towards the toe of the fan, a process observed both in the laboratory (Hooke, 1967, p. 457; Schumm *et al.*, 1987, pp. 335–336) and in nature (Eckis, 1928, pp. 234–235; Bull, 1964b, pp. 27–28). Deposition is then instigated at the toe by the break in slope there, and a wave of deposition migrates up-fan. When this wave reaches the intersection point, it may begin to bury it as a new intersection point lobe forms. The intersection point thus migrates up-fan. Eventually diversion down a new oversteepened flank occurs and the process is repeated.

This sequence is illustrated schematically in Figure 6a. The boxes in this figure represent incremental volumes of sediment, and the numbers or letters indicate the sequence in which individual increments are deposited or removed. At the fanhead, boxes 1–8 and 1′–8′ represent the initial wave of sediment. Depositional event 1′ followed event 1 by some unspecified length of time. Arrows 1″–7″ represent removal of the sediment in boxes 1′–7′ during the waning phases of the event. Boxes 1–7 are removed later; this phase is not shown in the figure. At the toe, boxes a–h represent deposition which, as noted, typically starts at the toe and migrates up-fan. Neither the timing of this deposition, relative to the events at the fanhead, nor the sequence of events in the vicinity of the intersection point are specified.

During the erosional phase that terminates episodes, fanheads become slightly incised, even if the fan has not been steepened by tilting or otherwise undergone a change in regime. Some of the fans along the foot of the Black Mountains on the east side of Death Valley are good examples. The active segment on these fans is

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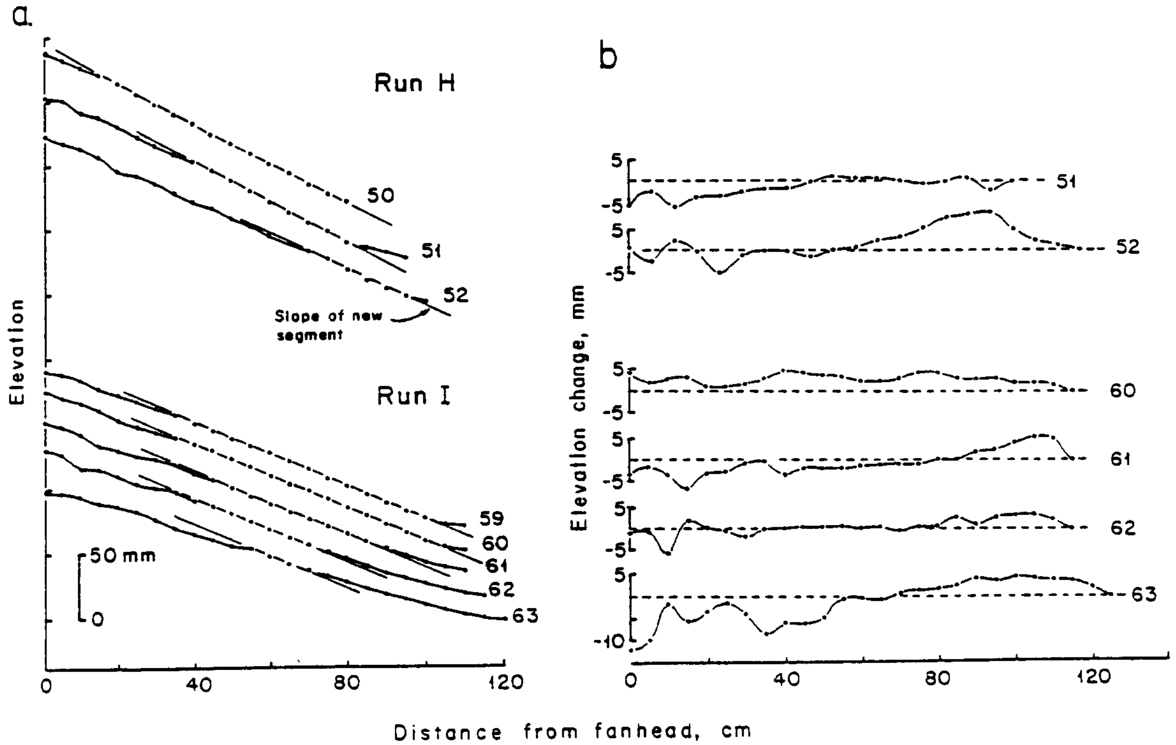

Figure 7. (a) Longitudinal profiles of laboratory fans. Dots are measurements; short fine lines between and extending beyond dots show slope and extent of presegmentation surface (except in episode 52). Depth and extent of incised channel at fanhead are shown by difference in elevation between dots and the headward projection of this presegmentation surface. (b) Changes in elevation between successive episodes. Curve labelled 52 represents change between episodes 51 and 52 and so forth. Incision at fanhead and deposition at toe are clearly shown

at their heads (Hooke, 1972). Fresh sediment on surfaces adjacent to the channel at the heads of these fans demonstrates that deposition has occurred relatively recently here, despite the fact that the channels are deep enough and wide enough to preclude the possibility that water-flows might have filled them to overflowing unless the channel first aggraded appreciably (Hooke, 1967), as just described. For this reason, at least the first wave of aggradation at the fanhead in Figure 6a should be understood to have occurred within this channel.

Segmentation of the laboratory fan

The fan described earlier was segmented by tilting the entire stream table ~2.5° and running seven additional episodes. At the end of these episodes, the fanhead had become incised somewhat more than 1 cm and the fan was clearly segmented. This is referred to as run H (Figure 7). Then, the sediment loading was reduced to 500 cm^3 per episode, and an additional seven episodes, run I, were run. Due to the reduction in sediment concentration, the latter procedure resulted in incision of the fanhead and deposition at the toe, much as did physical steepening of the stream table prior to run H. The lower segment from run H was buried during this run. Following each episode in runs H and I the elevation of the surface along the fan axis was measured to the nearest 0·1 mm at intervals of 0·05 m (Figure 7).

Deposition following tilting

Following tilting, the water can carry more sediment so the readily transported sediment is removed from the source area more quickly. This leaves a longer period of time later in the laboratory episode (or natural runoff event) when water can remove material that was deposited prior to tilting. Consequently, the increase in slope early in an episode is more than offset by the decrease later, and the overall slope decreases.

Upon initiation of this deep fanhead entrenchment on the laboratory fan, flows cut downwards, pushing the intersection point down-fan (Figures 5b and 7a). The deepening of the trench occurred in such a way that it was at the fanhead that the channel first became too deep to overflow. The abandonment of a surface as a locus of active deposition thus occurred progressively down-fan from the fanhead in a time-transgressive fashion. This is consistent with Dorn's (1988) age determinations on natural fans (Figures 1 and 2).

During the initial entrenchment of the fanhead in run H (Figure 7a, episode 51), the first sediment eroded from the deepening channel was deposited near the fanhead in a diffuse intersection point deposit (Figure 5b, stage 1), and a segment with a relatively low slope formed at the toe. (The low slope of this segment is attributed to the fact that the last 20–30 mm of the fan at the end of episode 50 was near the angle of repose, because the fan was building out into a lake ponded by downward deflection of the bottom of the stream table. This lake drained when the stream table was tilted, and the toe extended rapidly in episode 51.) During episode 60 in run I, a fairly uniform layer of sediment was deposited along the fan axis, where measurement were made, but the main flow was on the flank of the fan, out of reach of the point gauge. Thus any segment that began to form was not detected.

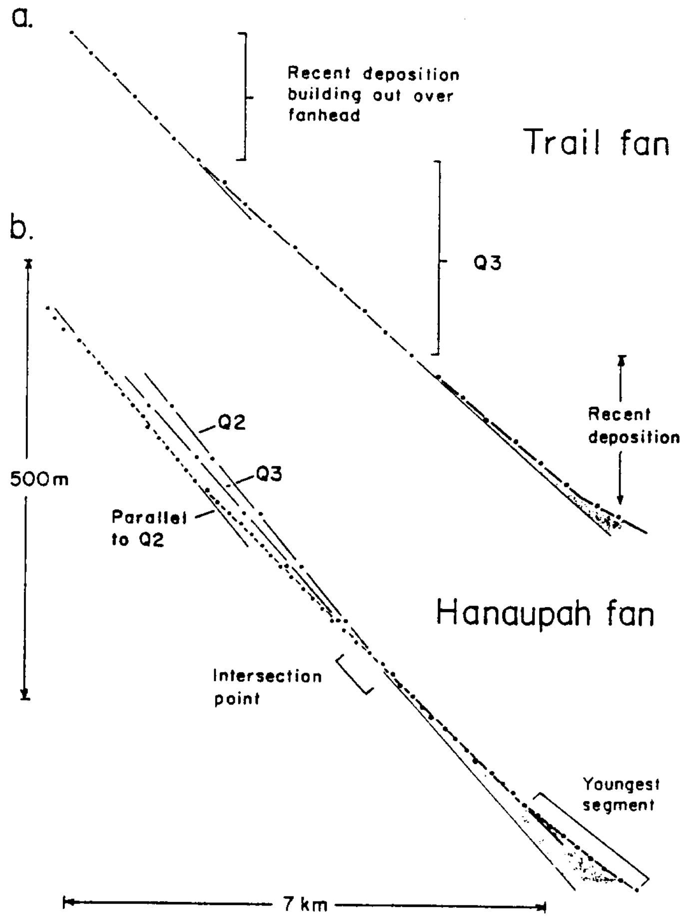

Figure 8. Longitudinal profiles of (a) Trail and (b) Hanaupah fans, Death Valley, from 7·5 min series topographic maps. Q2 and Q3 surfaces above intersection point on Hanaupah fan are projected from south and north of line of profile, respectively. Note significant difference in character of segmentation on these two fans indicated by the difference in the area (shaded) between present surface and projected Q3 surface and by recent sedimentation at the head of Trail fan. Such differences are consistent with a tectonic, but not a climatic explanation for segmentation

In episodes 52 and 61–63, downcutting continued at the fanhead, the intersection point moved down-fan and the new segment continued to grow thicker and headward. However, the surface elevation in the midfan area did not change. Due to the higher sediment loading during run H, this phase was recorded in only one episode during that experiment.

The model in Figure 6b is an attempt to explain these observations. In this figure, the initial aggradational phase of the runoff event at the fanhead is not shown. The starting point for the model is the situation once the recently added sediment has been removed from the inlet channel and redistributed over the fan, as in episode 60 (Figure 7b). Water is coursing down the steepened slope, which as yet has not begun to decrease. The water begins to entrain sediment. Sediment increment 1 (Figure 6b) is entrained first. The water now finds itself over sediment increment 2, but being loaded to capacity, with due consideration for the slope upon which it is flowing, we presume that it cannot entrain more sediment. This water enters a transport mode, moving its sediment load down-fan with no net change in sediment content. The next increment of water entrains sediment increment 2, and so forth. We infer that increment 1′ is not entrained at this time, perhaps because of an up-fan 'shadowing' by increment 2. That is, the slope from the bottom of the 'hole' left by increment 1 to the top of increment 2 may be too low to permit entrainment. After several increments of sediment have been removed from the surface layer, the shadowing is reduced and erosion of the next layer, 1′–6′, starts. In this way, the slope of the channel in the source area is not changed appreciably during erosion. This is consistent with the observation on natural fans (e.g. Figure 8b) that the channel near the fanhead may parallel one of the elevated and incised surfaces.

Throughout this process, water arriving at the down-fan end of the region of scour, for example at A in Figure 6b, is inferred to be fully charged with sediment. This water courses down the fan, neither depositing nor eroding, until it reaches the toe. Here, the break in slope instigates deposition, as in the pretilting model (Figure 6a). However, for reasons that are not completely clear, the wave of deposition that migrates up-fan, represented by boxes a–e at the toe in Figure 6b, apparently does not continue all the way to the intersection point. Rather, perhaps due to the high sediment load being carried on the steepened slope, some of the flow with its entrained sediment load manages to continue all the way to the toe again and increments f–h are deposited. Repetition of the process leads to deposition of increment i. In this way, a new segment is born. However, this segment does not achieve its final equilibrium slope until much later.

An important element of this model is that the new segment begins to form shortly after the tilting and well before the intersection point reaches the toe of the fan (Figure 5c). The up-fan edge of this segment is separated from the intersection point by a section of fan surface which has changed only minimally in slope and elevation. This is consistent with the observation that the upper edge of the youngest segment on fans along the west side of south-central Death Valley is well below the intersection point (Figure 8b).

During subsequent evolution of the laboratory fan, once the up-fan edge of the developing segment and the intersection point merge, a gradual regrading takes place. This may be a response to a decrease in available sediment in the inlet channel. Thus the final slope of the new segment is not attained until a significant time after the segment begins to form.

The rate of down-fan migration of the intersection point probably decreases as the length of the channel that must be eroded to produce an incremental down-fan shift of the intersection point increases. In the natural environment, such a decrease might, in addition, reflect a decrease in the rate of incision as the fanhead trench becomes armoured. Such a decrease in rate of migration is consistent with the down-fan spreading of the isochrons on the Q2 and Q3 surfaces in Figure 2. Left unexplained by such a model, however, is the remarkably uniform lateral reworking of the surface implied by the approximate parallelism between the isochrons and the topographic contours. Possibly this reflects the density of sampling.

This crude model seems consistent with observations on both laboratory and natural fans, and provides a partial explanation for the initial phase of the segmentation process. However, why sedimentation does not occur between point A and the up-fan edge of the new segment and why the sequence of deposition in the new segment is as illustrated in Figure 6b are not understood. To answer these and related questions may require a much larger laboratory model on which sediment and water fluxes can be measured at different points and times during an episode. A full understanding of this phase in the natural segmentation process is elusive, and constitutes one of the major unsolved problems of alluvial fan sedimentation.

During the final phase of the segmentation process in the laboratory, the average position of the intersection point was well down-fan from its 'pretilting' position. Its location varied through time, migrating down-fan when the flow shifted to an area that had not received sediment for a time, and then up-fan as sedimentation brought that area up to the level of other nearby areas. As the segment grew, the older steeper surface higher on the fan was progressively buried. The intersection point thus migrated up-fan during this 'burial' phase. (Note that dates on the currently active segment (e.g. Q4 in Figure 2) do not show any systematic pattern as deposition on this surface is, in effect, random in space and time.)

WHAT TRIGGERS THE TILTING?

As noted, paleoenvironmental data (δ^{13}C, Mn:Fe ratios, and micromorphology) suggest that incision of the upper parts of surfaces Q1, Q2 and Q3 began at times when the climate was semiarid rather than arid as at present (Figure 1b). The down-fan progression of the entrenchment coincided with a change towards aridity. We emphasize that this interpretation is based solely on the varnish microstratigraphy and is independent of the dating. The dating suggests, however, that entrenchment of a surface takes tens of thousands of years.

The time resolution for this process provided by surface exposure dating is best for surface Q3 because most of this surface is within the range of radiocarbon dating. Furthermore, the conventional ^{14}C date on charcoal from the middle of this unit is consistent with the AMS ^{14}C dating (Figure 2), which should assuage concerns about the reliability of the latter (Reneau *et al.*, 1991). The incision of surface Q3 began at ~ 50 ka BP under semiarid conditions, and ended under arid conditions ~ 40 ka later. However, the change towards

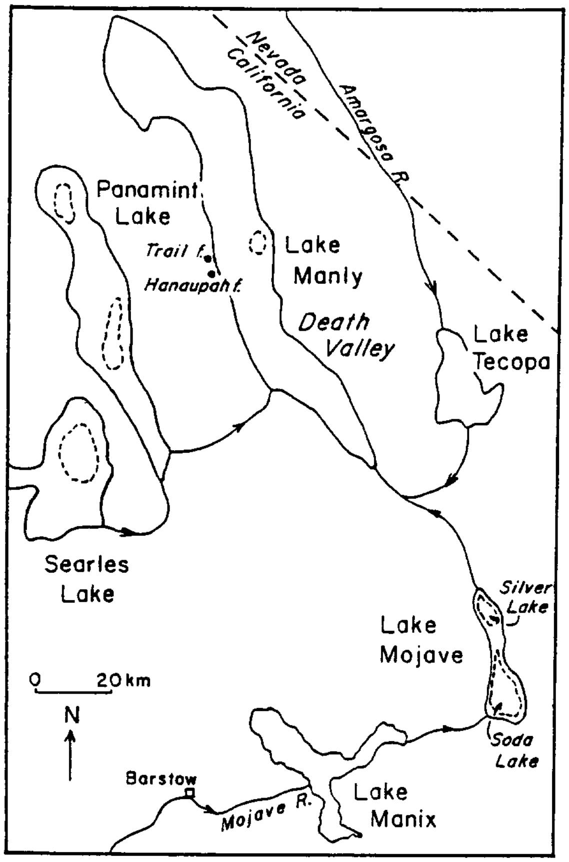

Figure 9. Map of southern Death Valley and vicinity showing former locations of pluvial lakes and of lakes Tecopa and Manix. Dashed lines delineate present-day playas

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aridity did not occur until ~ 13 to 10 ka BP; this is when the vegetation turned to desert scrub (Spaulding, 1985; Wells and Woodcock, 1985), Lake Manly dried up (Hooke, 1972), and the varnish paleoenvironmental signals turned arid (Dorn, 1988).

While climatic change can, by changing either the discharge or sediment concentration in flows, lead to a change in equilibrium slope and hence to segmentation, a strictly climatic model for the entrenchment and segmentation of fans on the west side of Death Valley encounters three problems. (1) In the case of unit Q3 on Hanaupah fan, the major change towards aridity did not occur until after ~ 13 ka BP, by which time the intersection point had moved well down-fan. (2) Trail fan, ~ 10 km north of Hanaupah fan (Figure 9), has a very different profile (Figure 8), a fact that is more easily explained by spatial variations in tectonism than by spatial variations in climate. The former are consistent with other evidence suggesting that the part of the Death Valley playa lying off of Trail fan has not been subsiding as rapidly as the part lying off of the segmented fans further south (Figure 3 of Hooke, 1972; Hunt and Mabey, 1966, pp. A101–A102). (3) The sense of segmentation on the east side of Death Valley is reversed, the youngest segments there being at the heads of the fans (Hooke, 1972).

As an alternative to a strictly climatic model, we suggest that entrenchment on the west side of Death Valley may have coincided with more humid conditions because the eastward tilting that led to entrenchment was triggered by loading of the valley with water when Lake Manly filled. During the late Wisconsin high stand of Lake Manly, the water was ~ 100 m deep, and during the Blackwelder stand it was over 200 m deep, allowing for subsequent valley fill. If isostatically compensated, such water bodies would depress the crust ~ 25 and 50 m, respectively. For comparison, the east side of Death Valley, has dropped a total of 45–50 m since the beginning of deposition of a gravel bar formed at the head of Goblet fan during the Blackwelder stand (Hooke, 1972, p. 2095).

Our thought is not that the water alone was responsible for the tilting. In fact, calculations suggest that this may be improbable (C. Chase, personal communication, 1989). Rather, we suggest that in an area of active extension such as Death Valley, accumulated strains on faults might be relieved rapidly as a result of the loading. In addition, subsequent desiccation of the lake would result in a *tendency* towards isostatic uplift of the valley, so a substantial amount of strain might accumulate before renewed tilting could occur. Thus tilting would tend to be more active during and immediately after filling of the valley with water. This could explain the initiation of entrenchment and down-fan migration of the locus of deposition at ~ 190 and again at ~ 50 ka (Figure 1).

That loading of such valleys in the Basin and Range province can result in adjustments of the crust is demonstrated by a 0·7 m depression in the 15 years following the filling of Lake Mead, which is actually somewhat narrower (~ 8 compared to 10 km) and shallower (100 compared to 180 m) than Lake Manly (Longwell, 1960). This filling was accompanied by a concentration of earthquake epicenters beneath the lake. Similarly, ~ 60 m of isostatic depression occurred beneath Lake Bonneville, which was ~ 160 km wide and 250 m deep (Crittendon, 1963). Thus the possibility of a tilting episode being triggered by a lake that was somewhat wider and deeper than Lake Mead, and that persisted for several thousand years in a more active tectonic environment, should not be dismissed.

SEGMENT VOLUMES

The present surface exposure dates suggest that the segmentation events that initiated entrenchment of the Q1, Q2 and Q3 surfaces occurred > 800, ~ 190 and ~ 50 ka BP, respectively, giving a ratio of roughly 16:4:1. Hooke's (1972) estimates of the volumes of the gravels deposited since these segmentation events are in the ratio 7:3:1. Thus, assuming that sediment yields have remained reasonably constant through time, Hooke's volume for unit Q2, deposited since initiation of entrenchment of unit Q1 (Figure 1), appears to be about a factor of two too small, and that for Q3 is also slightly low.

This discrepancy results from Hooke's assumption that the rate of deposition on the playa is equal to that on the fans, averaged over the entire fan surface. There is a tendency towards such an equilibrium in any bolson (Hooke, 1968, p. 616; Jansson *et al.*, submitted). However, based on Hooke's measurement of the volume of sediment deposited since abandonment of unit Q3 and Dorn's age for this event (50 ka), the sedimentation rate on fans on the west side of Death Valley is only $\sim 0{\cdot}1 \text{ m ka}^{-1}$, whereas Hooke's (1972, Table 3) radiocarbon dates give a mean sedimentation rate on the playa of $0{\cdot}7 \text{ m ka}^{-1}$ for the last 21 ka. Thus in Death Valley, some disturbance has resulted in a major increase in the rate deposition on the playa.

There are two possible sources for this additional sediment (Jansson *et al.*, submitted). The outlet from Lake Tecopa (Figure 9), a lake that once overflowed into Death Valley, has been breached, so that fine sediments carried by the Amargosa River and formerly deposited in Lake Tecopa now find their way ultimately to Death Valley. The drainage of Lake Tecopa occurred sometime shortly (?) after 600 ka BP (Smith, 1984, p. 7).

As the area drained by the Amargosa River is only about 60 per cent of the total now contributing fine sediment directly to Death Valley (without intervening lake basins), this change in drainage area alone could have been responsible for only part of the increase in sedimentation rate in Death Valley. Erosion of the Tecopa lacustrine units could account for some, but not all, of the discrepancy. Breaching of the outlet of Lake Manix about 14 ka BP (Meek, 1989) is probably not a major factor, as there are two shallow lake basins, Soda and Silver lakes (Figure 9), between Lake Mojave and Death Valley which would trap sediment, and there is no indication in Hooke's (1972, Table 3) radiocarbon dates that sedimentation rates in the playa increased at that time.

The remaining discrepancy is attributed to differential subsidence of the southern part of Death Valley relative to the northern part, so that fine sediments, formerly deposited further north, now find their way into the area under consideration herein. Such differential subsidence is evidenced by the difference in profiles of Trail and Hanaupah fans (Figure 8) and by the southerly increase in sedimentation rate reported by Hooke (1972, Figure 2 and Table 3).

Had the sedimentation rate on the playa during deposition of unit Q2 (Figure 1b) been $\sim 0{\cdot}1 \text{ m ka}^{-1}$, as on the fans, the down-fan shift in the locus of deposition associated with segmentation would have caused the fans to build out over the playa, as shown by line A in Figure 1b. As a result of the higher rate of input of fine material, however, the geometry of the playa–fan boundary at depth could have been closer to line B. Although not obvious from the schematic sketch in Figure 1b, calculations suggest that this could account for a factor of two error in Hooke's estimate of the volume of sediment in unit Q2. Furthermore, the calculations suggest that the sedimentation rate on the playa during deposition of unit Q2, between perhaps > 800 and 190 ka, while $> 0{\cdot}1$ m per year, must have been much lower than at present. Otherwise the rate of burial of the toes of the fans by the playa would have been so high that, extrapolating backwards in time, the fans would have to have extended all the way across the valley at one time, leaving no space for the playa.

CONCLUSIONS

Laboratory experiments suggest that when a fan source system is disturbed in such a way that the equilibrium slope of deposition is less than the fan slope, incision is initiated at the fanhead. The principal locus of deposition shifts to the toe shortly after the initiation of entrenchment, and flows apparently traverse the section of the fan between the down-fan end of the trench and the toe, without modifying its slope. As the depth of entrenchment increases, the intersection point migrates down-fan. Simultaneously the new segment grows and its up-fan edge migrates up-fan. Throughout this phase of the segmentation process the slope of the new segment is continuously adjusted. During the final phase, aggradation results in a gradual up-fan migration of the intersection point and burial of lower parts of older surfaces.

Varnish paleoenvironmental data suggest that entrenchment of older surfaces on the west side of Death Valley is systematically associated with more humid climatic conditions, which raises tantalizing questions about the role of climate in segmentation of these fans. Herein, however, we suggest that in an area of active tectonic extension, loading of the crust by filling of a lake basin with water may be sufficient to trigger an episode of more active tectonic tilting.

Finally, present data strongly suggest that sedimentation rates on the Death Valley playa have increased significantly in the past half million years, partly as a result of breaching of the outlet from Lake Tecopa, and partly due to differential subsidence of this part of the valley relative to that further north.

Because the validity of the surface exposure dating techniques used herein has been questioned, as noted earlier, it is worth emphasizing that the conclusions we have reached are not strongly dependent on the absolute precision of the dating, so long as relative ages are reasonably correct. The consistency of the ages provided by ^{14}C and U series on carbonate rinds, conventional ^{14}C on carbonized wood, accelerator ^{14}C on basal layers of varnish, as well as cation ratios from varnish, (e.g. Figure 2) argues strongly that the relative sequence is, indeed, valid. However, even if the numerical ages prove to be off systematically by a factor of even three, our inferences on the segmentation process and on the source of inconsistencies between these dates and Hooke's earlier ones would be substantially unchanged. Furthermore, our paleoenvironmental interpretations are based on comparisons of the stratigraphies of rock varnish on different surfaces that are known, on the basis of stratigraphy, position and weathering character, to be of different age, and recent work has substantiated the basis for this paleoenvironmental research (Jones, 1991). These interpretations are thus independent of the dating. Rather, the paleoenvironmental changes are dated by the surface exposure techniques employed. The dates thus obtained are consistent with other data on the gross timing of environmental changes, both in the American southwest and world wide. For example, dissection of the Q3 surface which probably started ~50 ka BP (Figure 1) coincided with high stands of Searles Lake from ~40 to ~10 ka BP (Figure 3 of Smith, 1984). Searles Lake contributed water to Death Valley when it and intervening Panamint Lake overflowed (Figure 9). This period also coincides with times of higher ice volume on land, represented by deep sea isotope stages 2 and the last part of 3. (However, other high stands of Searles Lake at times of lower ice volume during isotope stages 4 and 5 are not recognized in the Death Valley record.) Similarly, dissection of the Q2 surface, which appears to have started about 190 ka BP, coincided with isotope stage 6 which lasted from ~195 to ~128 ka BP (Shackleton and Opdyke, 1973). These comparisons further support the validity of the dating.

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