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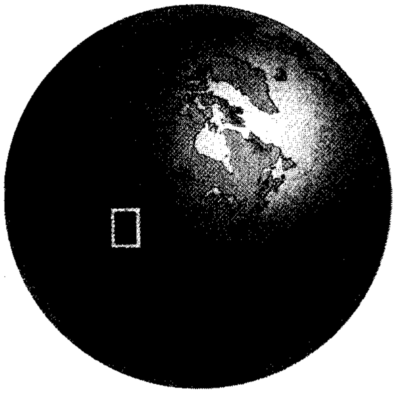
A Rock Varnish Interpretation of Alluvial-fan Development in Death Valley, California



Analyses of rock varnish on Quaternary alluvial fans in Death Valley, California, reveal that three cycles of fan development have been controlled by both climatic changes and tectonic activity. The most recent cycle of fan development, Q3, started before 50 000 B.P. *and has continued to the present. A previous cycle, Q2, originated before 170 000* B.P. *and ended after 105 000* B.P. *The earliest recorded cycle, Q1, started before about 800 000* B.P. *and ended after 500 000* B.P. *The first part of each cycle consisted of deposition during a climate more moist than today, associated with a stage of Lake Manly and a semiarid vegetation cover. During this period, deposition occurred from fanhead to fan toe. The latter part of each cycle followed a major glacial-to-interglacial climatic transition, when Lake Manly desiccated and the vegetation shifted to hot, dry desert scrub. During these climatic transitions and afterward during lengthy arid periods, aggradation shifted to the fan toes. The deposits of each cycle are preserved at the heads of the fans as tectonic faulting and tilting over tens to hundreds of thousands of years has caused enough downcutting of the stream system so that any aggradational pulses that followed did not bury the uplifted deposits.*

Death Valley National Monument is a landscape of contrasts, from the extreme aridity of the lowest elevation in the Western Hemisphere of −85 m at Badwater to the forested heights of the Panamint Range above 3300 m. These contrasts extend over time as well as elevation. Throughout the Quaternary, major shifts have occurred in vegetation, lake levels, the behavior of river systems, and hillslopes. In the midst of it all are the alluvial fans, conical deposits of water-laid and debris-flow material that accumulates where a canyon debouches from a mountain range. Deposition occurs when the sediment load from the source area is increased beyond the capacity of the stream system to transport it or when the flow is less confined (Bull 1977). Although alluvial fans are not limited to deserts, they dominate many piedmonts in arid and semiarid lands by coalescing into alluvial aprons or bajadas (Blackwelder 1931).

Alluvial fans, a dominant component of the desert landscape, have been the subject of intense scrutiny over the past century and for good reason. The controls and timing of the movement of sediment are topics of substantial concern to geomorphologists. Chronologies of alluvial-fan development permit comparisons with other environmental changes at the earth's surface, allow rates of faulting to be assessed, and facilitate a better understanding of archaeological events on alluvial fans. Uses of alluvial fans include roads, farming, groundwater extraction, grazing,

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housing (e.g., Bull 1977, Nilsen & Moore 1984), and access to a possible U. S. national, high-level nuclear-waste repository.

Previous alluvial-fan research (reviewed in Bull 1977, Nilsen & Moore 1984) has settled many questions as to why a stream deposits its load, sediment characteristics, and drainage basin and fan morphometric relationships. Progress has been comparatively minor, however, on what controls alluvial-fan development over time. Explaining this requires accurate and precise dating of the different fan deposits and data on past environments of deposition that has been achieved in only a few circumstances (e.g., Kale & Rajaguru 1987, Wells et al. 1987).

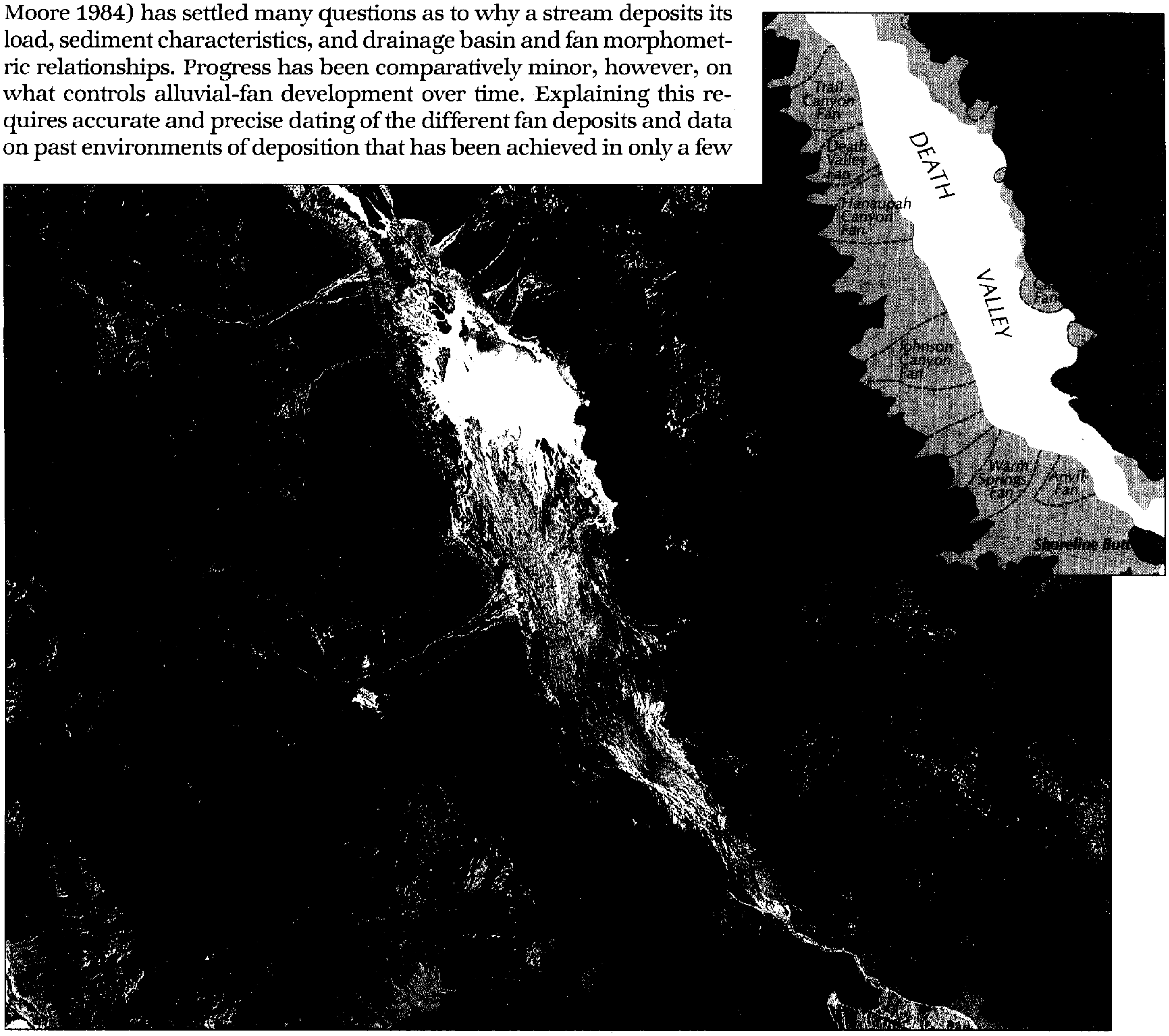

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Figure **1.** *SPOT satellite image of southern Death Valley. The image was acquired 17 June 1987 by SPOT Image Corporation.*

Many conceptual models have been proposed to explain alluvial-fan morphogenesis. These include the role of tectonics (e.g., Bull 1977, Hooke 1972), climatic changes (e.g., Bull 1986, Bull & Schick 1979, Lustig 1965, Ponti 1985, Wells et al. 1987), dynamic equilibrium (Denny 1965), steady states (Hooke 1968), complex responses (Weaver 1984), and a combination of theories (e.g., Bull 1979, Hunt & Mabey 1966). The basic question asked here is which of these conceptual models, or combination of models, best explains the development of alluvial fans in Death Valley, California.

In this study the author adds a new dimension to the study of alluvial fans by using the analysis of rock varnish that forms on different fan deposits. Rock varnish is a <0.5-mm coating on rocks that is composed of clay minerals, manganese and iron oxides, and trace elements (Potter &

Rossman 1977). It forms by the microbial concentration of manganese and iron and subsequent fixation to the rock surface by clay minerals (Dorn & Oberlander 1982). Minimum ages for alluvial-fan deposits are determined by radiocarbon (Dorn, Bamforth et al. 1986) and cation-ratio (Dorn 1983) analyses of rock varnish. Paleoenvironmental fluctuations since the deposition of a fan unit are determined by microchemical (Dorn 1984), isotopic (Dorn & DeNiro 1985), and micromorphologic (Dorn 1986a) analyses of rock varnishes. Conceptual models of fan development are tested for Death Valley by interpreting these rock-varnish dates and paleoenvironmental sequences from over 200 sites. The following paper summarizes the results of a five-year project.

Study Sites

Death Valley has become a "classic" locale for alluvial-fan research, and southern Death Valley was selected for study in part because the spectacular fans have prompted so much investigation (e.g., Beaumont & Oberlander 1971, Blackwelder 1933, Bull 1977, Davis & Maxson 1935, Denny 1965, Gillespie et al. 1984, Hooke 1972, Hooke & Lively 1979, Hunt 1975, Hunt & Mabey 1966, Maxson 1950, Troxel & Butler 1986). Death Valley also has one of the most arid and alkaline environments in North America, providing rock varnish a relatively safe haven from biogeochemical erosion. If erosion of rock varnish occurs, the dating and paleoenvironmental methods used here will not work.

Varnish was collected from over 200 sites on seven west-side alluvial fans of the Panamint bajada, five east-side fans exiting the Black Mountains, and prehistoric shorelines of Pleistocene Lake Manly (Figure 1). The fans of the Black Mountains are short, interfingered at the toe with playa sediments, and buried at the head by newer fan deposits. The fans of the Panamint Range are long, are divided into deposits of many ages, have fanhead trenches, and concentrate current deposition in the entrenched channels and near the toes (Hooke 1972, Hunt & Mabey 1966).

After the locus of aggradation on a fan shifts, the previous site of deposition becomes a new fan unit and starts to evolve, first by the development of a desert pavement and the onset of soil formation, and then by the creation of an internal drainage system that starts to incise into the deposit. These gradual changes over time lead to fan deposits with different geomorphic characteristics.

Eight fan units older than the active stream channels were sampled (Table 1) and compared with previous morphostratigraphic units used in mapping fans in Death Valley (Hooke 1972, Hunt & Mabey 1966).

Q3b is the youngest fan unit. It consists of deposits with a rough topography of alternating gravel bars and washes. On the upper and middle parts of the fans, it exists in an entrenched channel and is inset into older deposits. The bulk of Q3b, however, is deposited on the toes of the fans and can be seen burying older units there. Q3b is subdivided into three deposits. The youngest, Q3b3, has noticeable orange varnish on cobbles but black varnish is barely visible to the naked eye. The little older, Q3b2 has better varnish development with some dust accumulation in the soils of former washes (Figure 2, *top*). Still older, Q3b1 cobbles have a readily noticeable black varnish; soils typically have Av and Bk soil horizons, and the bar and wash topography has been subdued by some desert pavement development.

Q3a has the best-developed desert pavements of any fan unit; they run for kilometers from fanheads to fan toes (Figure 2, *middle*), but an

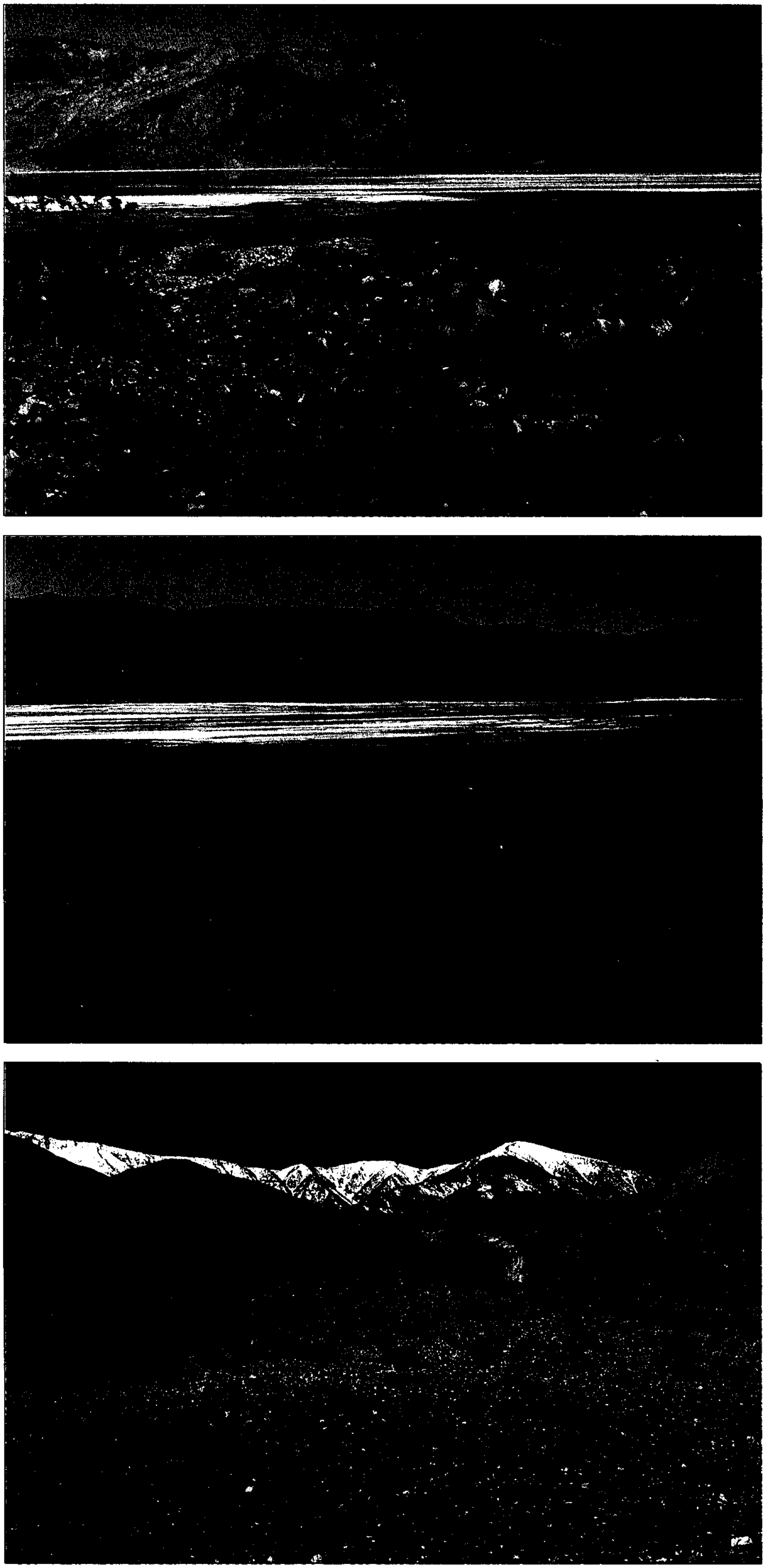

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Figure **2.** *Appearance of selected fan units:* **top,** *Q3b2, a mid-Holocene deposit of Hanaupah fan, consists of coarse bar deposits alternating with shallow washes;* **middle,** *Q3a, a latest-Pleistocene deposit of Hanaupah fan, is composed of smooth and well-varnished desert pavements;* **bottom,** *Q1a, a mid-Pleistocene deposit of Hanaupah fan, consists of highly dissected and rounded ridges covered with a calcrete rubble, with only a few locations of preserved desert pavement.*

incipient drainage system has started to develop. Soil development is restricted to cambic, argillic, and calcic horizons. Q3a is inset into still older units and is a terrace above Q3b. Although a complete determination of stratigraphic thickness was not possible in this study, as Hooke (1972) first recognized, Q3a is often visible in exposures as a veneer of gravels only a few meters thick burying a much older petrocalcic soil horizon.

Q2a and Q2b rest above Q3a and retain desert pavements on areas not dissected by gullies. Well-developed argillic and some petrocalcic horizons lie beneath the patches of desert pavement. The induration provided by the petrocalcic horizon probably helps protect the fan surface from erosion. Some calcrete rubble has been incorporated into the pavements. There is no clear topographic break between Q2a and Q2b, as Q2b buries the lower portions of Q2a. Buried varnished pavement cobbles of Q2a have been found in some places still preserved under Q2b.

Table *1*. Minimum Age-estimates for Alluvial-fan Deposits in Southern Death Valley

Author	**Mapping Unit**							
Hunt & Mabey (1966)	**Qg2**	**Qg2**	**Qg2**	**Qg2**	**Qg2**	**Qg3**	**Qg3**	**Qg4**
Hooke (1972)	**Older**	**Older**	**Intermediate**		**Younger**	**Transitional**		**Inactive**
Dorn (this study)	**Q1a**	**Q1b**	**Q2a**	**Q2b**	**Q3a**	**Q3b1**	**Q3b2**	**Q3b3**
Alluvial Fan	**Millennia B.P.**							
Hanaupah	800–650	600–490	170–140	130–105	50–14	9.5–7.0	4.5–3.0	2.5–0.5
Trail Canyon	n.o.*	n.o.	165–135	120–110	38–13	11.0–7.0	4.0–3.0	2.5–1.0
Johnson	770–660	610–500	170–140	125–110	42–13	9.0–6.0	4.0–2.5	2.0–0.5
Death Valley	n.s.†	n.s.	n.s.	n.s.	55–15	10.0–6.0	4.5–2.5	2.0–0.5
Galena	750–670	620–520	165–135	120–105	40–14	9.5–7.0	4.0–2.0	2.0–1.0
Warm Springs	n.s.	n.s.	n.s.	n.s.	42–14	9.0–6.0	3.5–2.0	1.5–0.5
Anvil	n.s.	n.s.	n.s.	n.s.	42–15	9.0–6.5	n.s.	n.s.

**n.o. = deposit not observed*
†n.s. = deposit not sampled

Q1a and Q1b lie well above the Q2 units. The deposits consist mostly of rounded ridge crests that are incised by deep gullies. As the original surface erodes, the petrocalcic horizon breaks up into a rubble of calcrete that rests on much of the surface. Only isolated patches of flat desert pavement remain (Figure 2, *bottom*). The boundary between Q1a and Q1b can only be mapped by using pavement remnants, hence precise mapping of Q1 was not possible in this study. The progressive decay of desert pavement from Q3a to the Q2 units and then to the Q1 units gives the older deposits a lighter appearance in visible and near-infrared light, even though they are far older.

Methods and Results

Mapping of these fan units is based on the above soil and geomorphic criteria and the interpretation of rock varnish. Mapping was completed mostly by field surveys, but assisted by vertical and oblique aerial photography and the previous mapping by Hooke (1972) and Hunt & Mabey (1966). Figure 3 illustrates the relationships among fan units for the head of Hanaupah Canyon fan.

Rock varnish must be sampled with great care. Varnish was collected from rocks that: have not been exposed to eolian abrasion or breakup by salt weathering; come from a flat interfluve that has not been gullied; are large enough not to have been turned over during the development of a desert pavement; and have not been exposed to agents of biochemical erosion. Agents of biochemical erosion include lichens, abundant microcolonial or filamentous fungi, and abundant organic detritus. Specific microsites were avoided during collection: where runoff collects; traps of large eolian detritus; and near sources of anomalous concentrations of calcium, potassium, and titanium, such as calcrete rubble and weathered rocks with a high titanium content.

Age Determinations

Table 1 presents minimum age-estimates for alluvial-fan deposits in Death Valley. The age-ranges for each unit show the variations among the average dates assigned to each unit. Each age-range for each unit is based on a minimum of five determinations and in some cases as many as 12. (Since the publication of preliminary results in Dorn [1986b], important new analyses have been completed.)

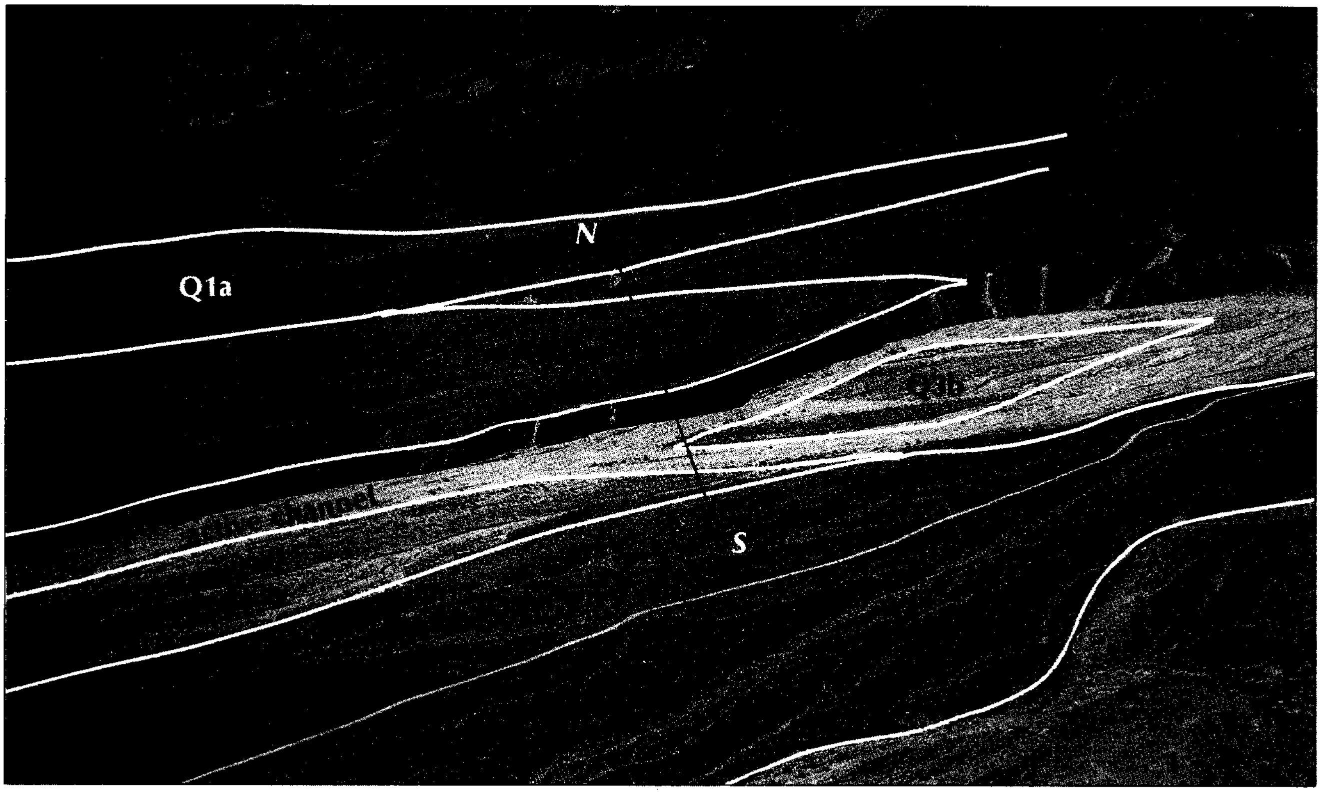

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Figure **3.** *Photogeomorphic map of deposits at the head of Hanaupah Canyon fan. The S–N line is where amounts of fanhead entrenchment were measured.*

The age-determinations of units Q3a, Q3b1, Q3b2, and Q3b3 are based on accelerator mass spectrometry (AMS) radiocarbon dating of organic matter extracted from the very lowest layer in varnish. The details and limitations of this method are presented in Dorn, Bamforth et al. (1986) and Dorn, Turrin et al. (1987). Although radiocarbon dating of rock varnish is still experimental, tests using radiocarbon dates obtained from different material (such as charcoal) at controlled sites have shown that the radiocarbon dates obtained from varnish underestimates the independently obtained ages of the deposits by about 10% (Dorn, Turrin et al. 1987). The age-ranges reported in Table 1 are corrected for this effect by the preliminary estimate of 10%, but the final correction amount will be based on the results of ongoing tests conducted by the author with the Accelerator Research Group at the University of Arizona.

The age-determinations of Q1a, Q1b, Q2a, Q2b, and the oldest sections of Q3a are based on cation-ratio dating (Dorn 1983, Harrington 1986). In cation-ratio dating the elemental ratio (K + Ca)/Ti in rock varnish is correlated with the previously established ages of several sur-

Figure **4.** *Stable carbon isotope fluctuations on fan units of Johnson Canyon fan. Q1a, Q2a, and Q3a were sampled from the head of the fan. Q1b, Q2b, and Q3b1 were sampled toward the fan toe. More arid conditions are represented by less negative values, and semiarid conditions by more negative values. Each data point represents a stable carbon isotope value at 10-μm intervals, starting with 5 μm. The spatial uncertainty of each point is estimated to be about 10 μm (Dorn, DeNiro et al. 1987).*

Figure **5.** *Electron microprobe profiles from the surface to the base of varnishes on different fan units of Hanaupah Canyon fan. Each of these transects is representative of multiple profiles of varnishes from each deposit. Higher ratios reflect less alkaline (more humid) conditions, while lower ratios indicate a more arid, alkaline environment. As varnish accretion rates are irregular, and diagenetic compression occurs, especially upon burial of a surface layer, the thickness of a paleoenvironmental signal should not be interpreted as an indication of relative time (Dorn 1984).*

faces. In the case of Death Valley, the calibrations come from AMS radiocarbon dates on varnishes within Death Valley and from K–Ar dated volcanics in the surrounding regions. These calibrations are then used to establish a cation-leaching curve to estimate ages of varnishes. A complication for Death Valley is that the closest K–Ar dated volcanics are tens of kilometers away, too distant to use as calibration points without having a firm basis of comparison (Dorn 1983). Adjustments can be made by using radiocarbon calibrations that have been obtained in Death Valley and comparing them with radiocarbon calibrations in adjacent regions where there are K–Ar dated volcanics.

These data establish a local basis of comparison, along with data on microenvironmental effects and initial varnish cation-ratios. Until a complete biogeochemical model of cation-ratio change in varnish has been thoroughly tested, however, age-determinations presented here beyond about 45 000 B.P. (the approximate limit of AMS radiocarbon dating) can only be viewed as tentative. But they can be compared with Hooke & Lively's (1979) uranium-series dates of about 112 000 B.P. and 178 000 B.P. on caliche on the Q2 unit of Johnson Canyon fan; these results are similar to the varnish age-range of 110 000 B.P. to 170 000 B.P.

A rock varnish date should be viewed as a minimum-limiting age for the deposition of the underlying fan unit. Uncertainties, including the following, are always present: the sampled rock may have weathered since deposition; the sampled rock may have eroded out of the deposit; the varnish may have eroded and reformed since the fan unit was deposited. These potential problems could result in progressive underestimation of the ages of fan deposits as the fan units become older. Sampling was conducted so as to avoid these circumstances. To further safeguard against these potential difficulties, multiple samples were taken from different positions on a given place on a fan unit, repeated for different sites on that unit, and repeated again on equivalent units on the same fan. This sampling was repeated from fan to fan in Death Valley and is the best way of ensuring reliability of results.

For a rock-varnish analysis to be useful in interpreting events on an alluvial fan, there should only be a small time-lag between the deposition of the cobble and the onset of varnishing. Historic structures built in the Death Valley region were studied by scanning electron microscopy; results indicate that it takes about 100 years for a varnish to start to grow. However, a few thousand years may be necessary before varnish can be seen readily with the naked eye in the Death Valley region.

Several factors suggest that dating varnish on rocks in a preserved desert pavement might closely reflect the cessation of fan deposition. First, using K–Ar dated basalt flows in the Cima volcanic field of southeastern California, McFadden et al. (1987) and Wells et al. (1985) argue that desert pavements can remain stable for very long periods of time. Second, it is unlikely that many of the large and rounded rocks sampled here were disturbed by rock weathering or pavement development. Third, the age determinations and paleoenvironmental data are consistent from the same units within a given fan and the same units on different fans. The disturbance of a fan unit is probably not so systematic as to have compressed all the paleoenvironmental sequences and age determinations in the same fashion.

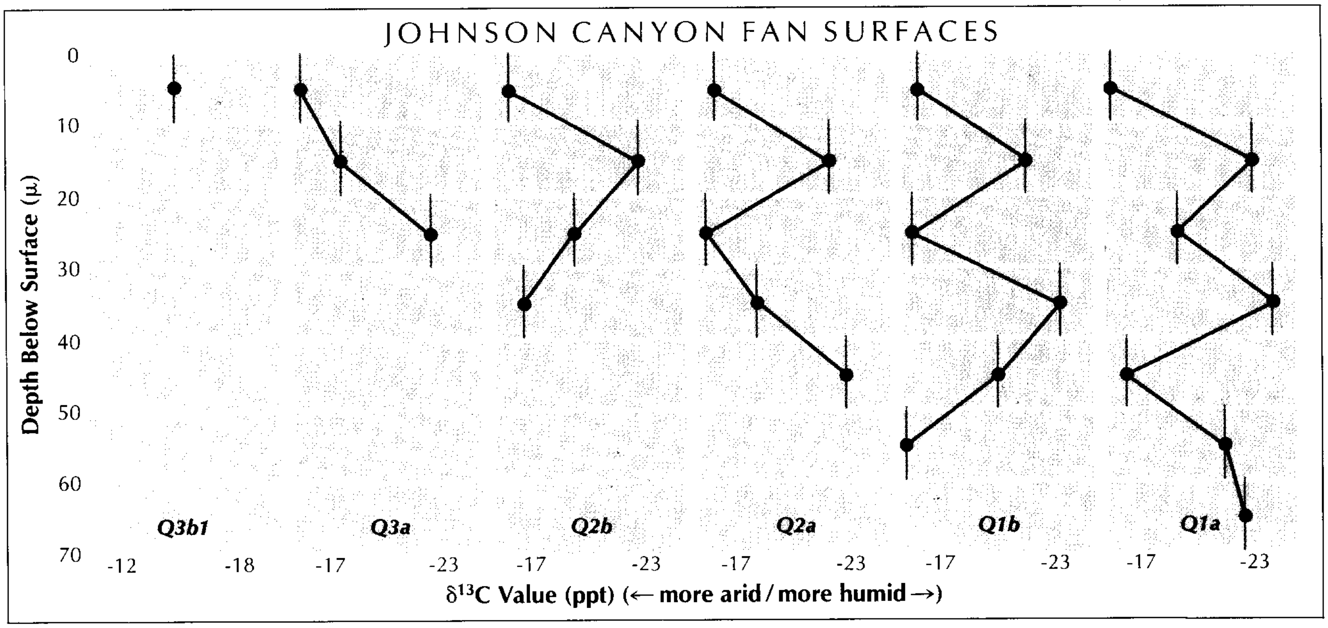
Paleoenvironmental Signals

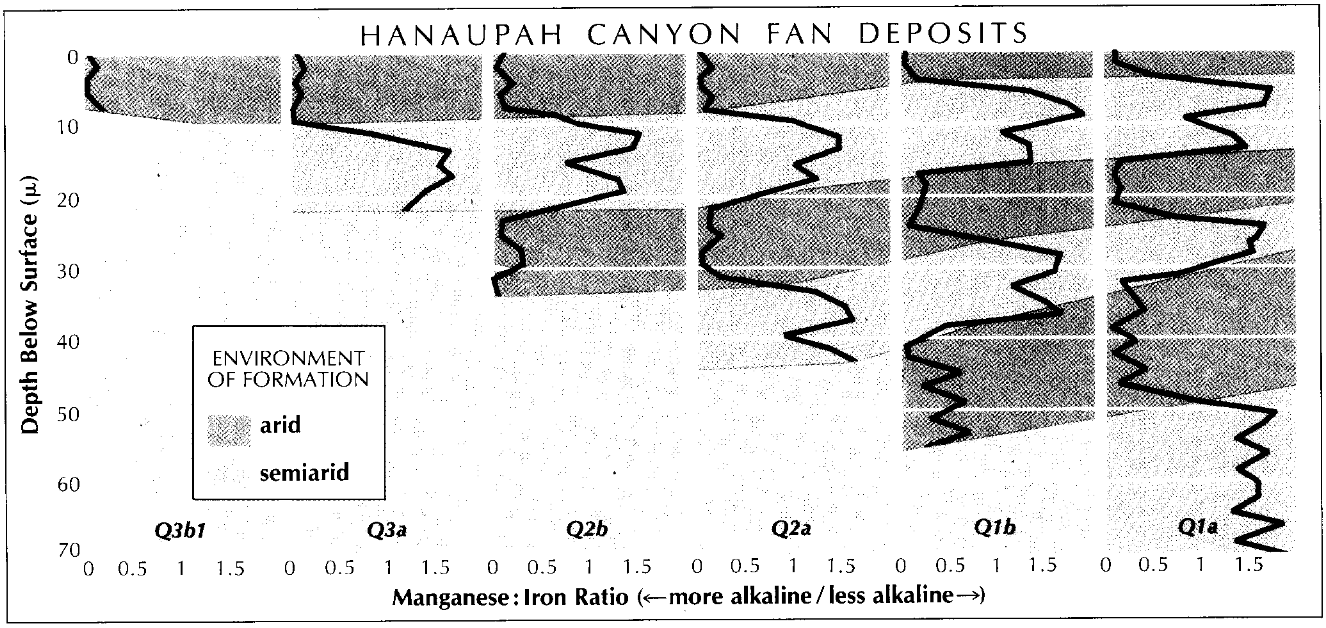
Rock varnish is a fairly robust method of determining environmental fluctuations because each of the three paleoenvironmental signals recorded in its fossil layers provides a separate signal of climatic change.

Stable Carbon Isotopes

The $\delta^{13}C$ value of rock varnish yields information on whether adjacent plants tend toward more humid or more arid mechanisms of photosynthesis. Dorn & DeNiro (1985) found that the surface layer of varnishes collected from semiarid and humid regions have $\delta^{13}C$ values of around −22 parts per thousand (ppt). Varnishes sampled from hot, arid areas, in contrast, have more positive values of around −15 ppt.

Results of $\delta^{13}C$ fluctuations in fossil layers of varnishes on Johnson Canyon fan can be found in Figure 4. The varnishes sampled from units near the fanhead (Q1a, Q2a, Q3a) all have a basal layer reflecting a more humid paleoenvironment (more negative values). A sequence of three semiarid-to-arid cycles is recorded in varnish on Q1a. Two such cycles are found on varnishes on Q2a, and only one on Q3a. In contrast, samples collected toward the fan toe (Q1b, Q2b, Q3b1) all have a basal layer reflecting a more arid paleoenvironment. The only Q3b deposit





sampled was the oldest, Q3b1, because varnishing on the younger units was limited. Dorn, DeNiro et al. (1987) present a similar record for Hanaupah Canyon fan.

Microchemical Laminations

The manganese-to-iron ratio in rock varnish reflects the alkalinity of the adjacent environment. Higher manganese-to-iron ratios develop in less alkaline (more humid) conditions, while lower manganese-to-iron ratios develop in more alkaline, arid environments (Dorn 1984). Figure 5 presents variations in this ratio with depth in varnishes on deposits of Hanaupah Canyon fan. These results are representative of microchemical laminations from more than 100 collection sites from different fans. Changes in the area of Lake Manly, the prehistoric lake in Death Valley (Blackwelder 1933), are the likely cause of these fluctuations. Probably when a stage of Lake Manly was present, fewer alkaline aerosols were deflated. This contrasts with the present arid environment, where alkaline particles are frequently lifted off the dry Death Valley playa surface.

The alkalinity changes on Hanaupah Canyon fan in Figure 5 are similar to the isotopic fluctuations on Johnson Canyon fan in Figure 4. Varnish on Q1a, Q2a, and Q3a sampled near the head of Hanaupah fan record a basal layer with a high manganese-to-iron ratio indicative of more humid, less alkaline conditions just after the cobble was deposited. Although the microchemical signal has a finer spatial resolution than the carbon isotope record and is therefore more detailed, three distinct semiarid-to-arid cycles are recorded in Q1a varnishes, two in Q2a, and one in Q3a. Varnishes on Q1b, Q2b, and Q3b1 all have a basal layer with a lower ratio reflecting greater alkalinity and aridity.

Micromorphological Stratigraphy

The micromorphology of varnish structures as viewed by scanning electron microscopy can reveal whether a past eolian environment was dusty and arid or less dusty and semiarid. Studies of varnishes in contemporary environments have shown that where vegetation is abundant (surface cover >40%) and dust fallout is minimal, varnishes develop a botryoidal structure. In contrast, varnishes sampled in dusty and relatively unvegetated areas have a lamellate or layered structure. Alternating layers of lamellate and botryoidal micromorphologies in varnish cross-sections, therefore, indicate fluctuations in abundance of dust (Dorn 1986a, Dorn & Oberlander 1982). The likely controls on abundance of dust in Death Valley are the fluctuations of Lake Manly and of changes in vegetation cover. When Lake Manly existed and the vegetation cover was more abundant, a botryoidal micromorphology developed. When Lake Manly dried up and the vegetation cover decreased, a lamellate micromorphology formed.

Sequences of dust fluctuations revealed by micromorphological analyses of varnish are similar to the other varnish records. Q3b1 varnishes are only lamellate, indicating an arid signal in the Holocene (Figure 6A). The microstratigraphy of varnishes of Q3a reveals a surficial lamellate (arid) layer on a botryoidal (more humid) layer (Figure 6B). Two such semiarid-to-arid cycles are found in varnishes on Q2a (Figure 6C). Toward the fan toes on Q2b, however, the basal layer is lamellate, reflecting dusty, arid conditions (Figure 6D).

The study of micromorphological changes in varnishes in Death Valley is confused by the poor preservation of fossil botryoids where varnishes do not contain enough manganese (cf. Dorn 1986b). The author has not found a preserved microstratigraphy for varnish on any Q1a or

Q1b deposit, despite examining over two dozen sampling sites on each Q1 unit. However, where micromorphological stratigraphy is present in varnishes in Death Valley, it is consistent.

In sum, the three cycles of fan development (Q1a–b, Q2a–b, Q3a–b) match three paleoenvironmental cycles of semiarid-to-arid conditions. Although it is not possible to date the internal layers in varnish at this time, the upper two paleoenvironmental cycles in Q1a may correspond to the development of Q2a–b and Q3a–b; and the upper semiarid-to-arid cycle in Q2a may correspond to the development of Q3a–b.

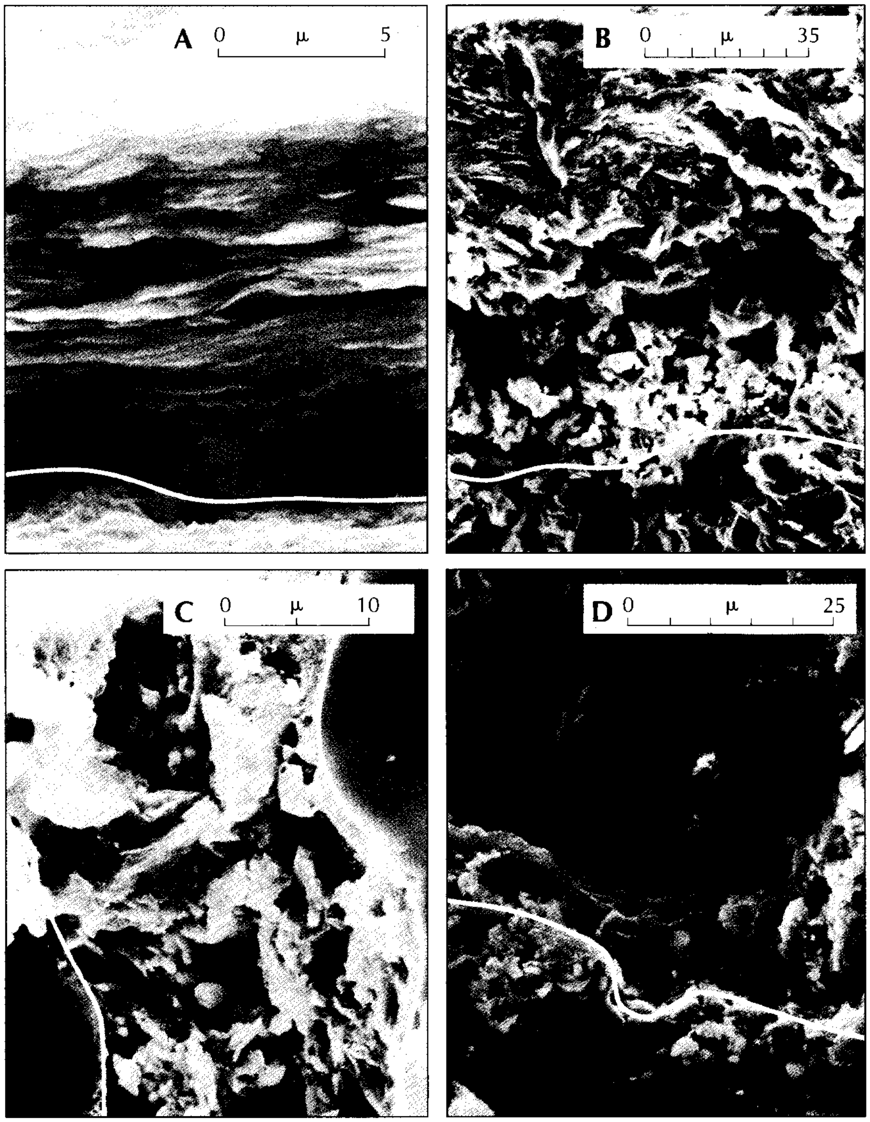


Figure **6.** *Micromorphological stratigraphies of varnishes in Death Valley. Lines indicate the varnish–rock contact. The relative thickness of the layers does not imply a relative length of time, only a sequence of environmental changes between more humid (botryoidal micromorphology) and more arid and dusty (lamellate micromorphology) conditions (Dorn 1986a).* **A.** *Lamellate varnish on a Q3b1 surface of Trail Canyon fan, indicating dusty eolian conditions throughout the time of varnish formation, in this case the last 7900 ± 1500 years B.P.* **B.** *Varnish on late-Wisconsin Q3a surface (28 500 ± 1800 B.P.) of Natural Bridge fan on the east side of Death Valley, illustrating lamellate varnish (dusty, arid conditions) overlying botryoidal varnish (less dusty, semiarid conditions).* **C.** *Varnish in microdepression on quartz, on Q2a on Galena Canyon fan (143 000 ± 12 000 B.P.). The basal layer is botryoidal, followed by lamellate, botryoidal, and then a surface lamellate layer.* **D.** *Varnish on Q2b surface of Johnson Canyon fan (113 000 ± 7000 B.P.). The varnish micromorphological sequence is a basal layer of lamellate, then a botryoidal, and lastly a surface lamellate layer.*

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Discussion

The Last Cycle: Q3a and Q3b

In interpreting the history of alluvial fans in Death Valley, the near past may be the key to understanding the more distant past. The most accurate and precise evidence of fan development is from the last 45 000 years. The deposits are best preserved, and the time range is datable by radiocarbon analysis. For these reasons the Q3a and Q3b units will serve as a type sequence to interpret the older fan deposits.

Q3a is the latest-Pleistocene fan unit in Death Valley. Radiocarbon and cation-ratio analyses of varnishes indicate a clear trend in age for Q3a on all west-side fans: the dates at the fanheads are oldest and age decreases regularly down the fans. At Hanaupah Canyon fan, for example, varnish sampled near the fanhead yielded a "dead" radiocarbon date of > 43 000 B.P. (AA-1416); cation-ratio analyses suggest an age of about 50 000 B.P. About three fourths of the way up, Q3a varnishes date to 41 430 ± 1070 (Beta 20566; ETH 2938). About halfway up, the radiocarbon date is 29 190 ± 370 (Beta 20567; ETH 2939). About one fourth of the way up, the date is 21 740 ± 390 (AA-1419). At the toe of Q3a, near the bottom of the fan, the date is 13 990 ± 145 (AA-1300). (These dates are reported in radiocarbon years before present, without a 10% correction.) Cation-ratio dates from varnishes sampled between these radiocarbon sites indicate a gradual downfan shift in age.

Paleoenvironmental records from varnish in Figures 4, 5, and 6B show that after cobbles were deposited at the fanheads, as Q3a deposition moved down the fans, conditions were more humid than today. Further evidence is provided by $\delta^{13}C$ values of basal organic matter from the same sites analyzed for radiocarbon dating at Hanaupah fan. A more humid paleoenvironmental signal is found from the fanhead to the toe: −21.6, −23.2, −24.1, −23.1, and −18.2 ppt. Only at the toe of Q3a at about 14 000 B.P. to 15 000 B.P. does the isotopic signal start to become more arid. Methods of analyzing varnish cannot assess whether the lower stratigraphic section of Q3a was deposited during an arid or a more humid period. What is evident from varnish analyses is that the period from about 50 000 B.P. to about 14 000 B.P. was significantly more humid than today, and that this period coincided with the deposition of at least the surface section of Q3a.

The paleoenvironmental fluctuations in Death Valley varnishes are similar to the *Neotoma* plant macrofossil record in the area. Wells & Woodcock (1985) established that the full-glacial (19 000 to 13 000 B.P.) climate in Death Valley was much less arid than at present. A semidesert of chaparral yucca *(Yucca whipplei)* with a minor component of Joshua tree *(Y. brevifolia)* lived at about 425 m, while a juniper woodland occupied slopes from 1130 to 1280 m that are now occupied by creosote bush scrub *(Larrea tridentata)*. From approximately 13 000 to 10 000 B.P., the full-glacial vegetation shifted to a hot-desert scrub similar to today's. A longer *Neotoma* macrofossil record is presented by Spaulding (1985) for the desert just east of Death Valley; a juniper woodland *(Juniperus osteosperma)* was widespread below 1800 m from at least 45 000 to about 10 000 B.P. in what are now desert lowlands.

The history of Lake Manly during this time corresponds with the varnish and plant macrofossil evidence. Hooke's (1972:2087) coring results demonstrated the presence of a perennial lake that "probably existed in Death Valley from some time prior to 26 000 years . . . up to about 10 000 years" ago. As originally suggested by Blackwelder (1933) and again by Hooke & Lively (1979), this latest-Pleistocene stage of Lake Manly was probably shallow. In this study radiocarbon and cation-ratio dates of rock varnish on shorelines throughout Death Valley indicate that this latest-Pleistocene lake existed as high as about 15 m. The oldest varnish date for the high shoreline of this lake is 12 630 ± 110 (AA-1299) at Mormon Point, indicating that the lake started to decline about 13 000 B.P. It is clear from the varnish, vegetation, and lake history data that the entire upper stratigraphic part of Q3a, and perhaps the entire deposit, aggraded during a period that was significantly more humid than today.

The idea of a gradual downfan shift of deposition is not new to the literature on alluvial fans (Ku et al. 1979), but the seemingly continuous deposition of Q3a from around 50 000 B.P. to around 14 000 B.P. is new. It is conceivable that the aggradation to Q3a was not continuous, but episodic on a time-scale not yet resolved by the varnish sampling. Arguments can be made that global (Chappell & Shackleton 1986) and regional (e.g., Benson & Thompson 1987) records indicate climatic fluctuations during this time that possibly could have forced pulses of aggradation, for example, by changes in the intensity of periglacial activity at higher elevations in the Panamint Range. However, given the hazardous nature of long-distance correlations of climatic changes, the existence of woodland in the area from at least 45 000 B.P. to about 10 000 B.P., and the occurrence of a lake from before 26 000 B.P. to about 10 000 B.P., it is difficult to hypothesize a significant climatic change causing the deposition of Q3a or its gradual downfan shift. Instead, tectonic uplift and tilting of the Panamint Range (cf. Hooke 1972) may have promulgated a shallow fanhead trench that, with continued uplift, slowly deepened and shifted deposition toward the fan toes.

The Pleistocene–Holocene climatic transition is centered in Death Valley around 13 000 to 10 000 B.P. when hot-desert vegetation became dominant (Wells & Woodcock 1985), Lake Manly desiccated (Hooke 1972), and a new fan unit was deposited. The aggradation of Q3b1 is the result of deep fanhead entrenchment of stream systems' shifting deposition of sediment to fan toes. The earliest maximum-limiting age of Q3b1 is from the top layer of Q3a varnish that is buried by a Q3b1 deposit at Trail Canyon fan; this upper layer has an AMS radiocarbon date of 11 810 ± 150 (Beta 20570; ETH 2942). The earliest varnish date for the surface of Q3b1 is about 9500 B.P. and the latest about 6000 B.P.

A climatic change best explains the deposition of Q3b1. The age-determinations are too similar from fan to fan to call on a purely intrinsic mechanism of geomorphic change such as dynamic equilibrium (Denny 1965) or complex response (Weaver 1984). An external mechanism that affects all the fans at the same time is needed. Others have argued persuasively that a climatic change from more moist to more arid conditions results in movement of sediment from hillslopes to the lower parts of alluvial fans (e.g., Bull & Schick 1979, Lustig 1965, Wells et al. 1987). Bull (1979:460) explains the mechanism: "reduction of vegetation density decreased infiltration rates [into hillslopes] and exposed more soil to erosion, resulting in increases . . . of sediment load and size [that] greatly increased the critical power" of the streams. This sequence, combined with a drop in the base level as Lake Manly desiccated, likely led to fanhead entrenchment, transport of this eroded hillslope material, and deposition of Q3b1 toward the toes of the alluvial fans in Death Valley.

Alternative hypotheses to explain the fanhead trenching and deposition of Q3b1 at the start of the Holocene emphasize a tectonic rather than a climatic cause. If tilting is episodic and occurs, for example, along with a change from a wetter to a drier climate, the effect would have been as the varnish data indicate: an initial incision during the transition from semiarid to arid and downfan deposition into the drier period (R. Hooke personal communication). Alternatively, if tectonic activity has been fairly continuous, steady tilting during a change to a drier period could have increased the critical stream power to the point where a threshold of fan incision was reached (Weaver 1984). These hypotheses are difficult to test; nevertheless the timing of the trenching event at the Pleistocene–Holocene transition, the timing of Q2b at a similar climatic transition approximately 130 000 B.P., and similar occurrences of early Holocene deposition on fans not so tectonically active as those in Death

Figure **7.** *Simplified model of three cycles of alluvial-fan development in southern Death Valley.*
A and B, the Q1 cycle: *before 650 000 B.P., deposition of Q1a occurred at all locations on the fans during a climatic period more humid than today. The deposits may have interfingered with the lake sediments of an early stage of Lake Manly in Death Valley. With the onset of drier conditions ~600 000 B.P., the stream system cut down into the Q1a deposit, making a trench at the fanhead, and shifted the loci of deposition to the fan toe, resulting in the aggradation of Q1b. The downfan deposits of Q1a were buried by Q1b.*
C and D, the Q2 cycle: *Q2a was deposited from before 170 000 B.P. to ~135 000 B.P. in a climate more humid than today during a stage of Lake Manly. The previous Q1a and Q1b units that were not lifted high enough by tectonic faulting and tilting were buried by the aggradation of Q2a. The preserved Q1a and Q1b units are at the fanheads. Deposition of Q2a ceased first at the top of the fans and last at the bottom of the fans. Accompanying the desiccation of Lake Manly ~130 000 B.P. was the development of a fanhead trench and the subsequent deposition of Q2b at the fan toes during an arid climate, starting ~130 000 B.P. and continuing after 105 000 B.P. Q2b buried the downfan deposits of Q2a.*
E and F, the Q3 cycle: *Q3a aggraded from before 50 000 B.P. to ~14 000 B.P. during a climate more humid than today with a stage of Lake Manly and a semiarid vegetation cover. Deposition of Q3a ceased first at the top of the fans and last at the bottom of the fans. Q3a buried Q2a and Q2b deposits that were not uplifted high enough by tectonic activity. With the drying of Lake Manly and the change to a desert-scrub vegetation ~13 000 B.P., a fanhead trench developed and shifted the loci of deposition to the fan toes forming Q3b. Q3b buried the downfan deposits of Q3a. Because the deposition of Q3b was so recent, it is possible to distinguish different aggradational pulses. Q3b1 has the largest area and volume and was deposited from ~11 000 B.P. to 6000 B.P. Q3b2 and Q3b3 are of a smaller area and volume and date from ~4500 to 2000 B.P. and 2000 to 500 B.P., respectively.*

Valley (e.g., Wells et al. 1987) argue for a climatic trigger.

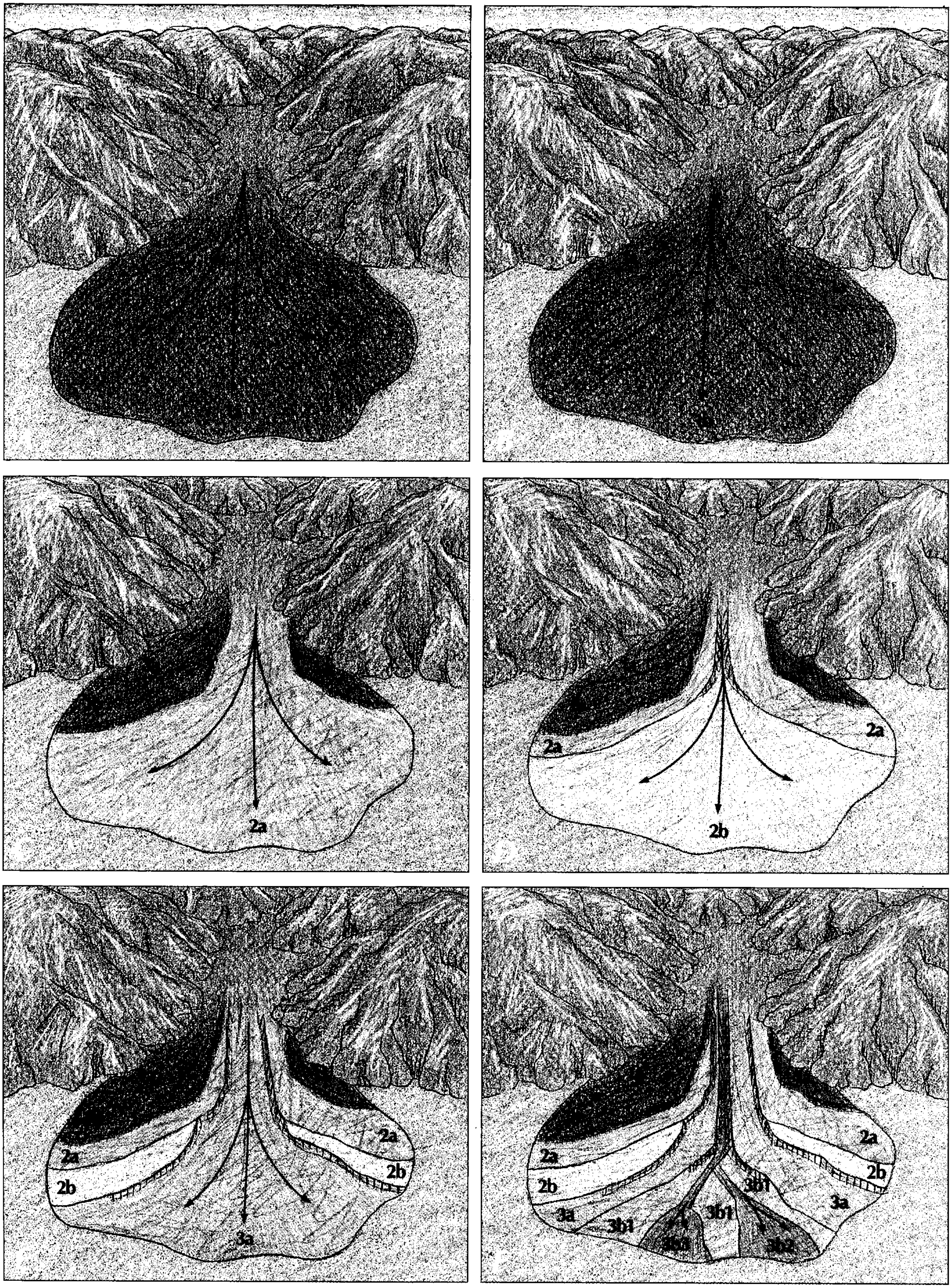
An explanation proposed by Bull (1979), involving both external climatic and intrinsic geomorphic causes, fits both the fan-to-fan similarity and episodic timing of the mid to late Holocene Q3b2 and Q3b3 units. After the deposition of Q3b1, the entrenched trunk stream was filled up to the point where the stream gradient was greatly steepened. Climatic changes that occurred during the mid to late Holocene (cf. Hunt 1975, Spaulding 1985) could have then triggered a new and smaller phase of aggradation, represented by Q3b2, by transporting this temporary channel fill in the downfan direction. The deposition of Q3b2 resulted in the backfilling of the fanhead trench again and steepened the stream gradient once more. With another climatic event in the late Holocene, incision of this accumulated sediment resulted in another deposit toward the fan toe as Q3b3. Hunt & Mabey (1966) observed earlier that the limited volume of Q3b3 (their Qg4 deposit) probably derived from accumulations of debris higher up on the fans.

Previous Cycles of Fan Deposition: Q2 and Q1.

The older fan units in Death Valley appear to mirror the above Q3a–Q3b cycle, but the evidence is clouded by the progressive erosion of the flat interfluves that preserve desert pavements. Q1a and Q2a appear to be equivalent to Q3a in that the basal layer of varnish contains a more humid signal and the dates get younger in the downfan direction. Q1b and Q2b bury the downfan parts of Q1a and Q2a, like Q3b overlaps Q3a toward the fan toes. Q1b and Q2b units are undoubtedly composed of separate episodes of aggradation, like Q3b, but time has blurred morphostratigraphic distinctions.

The Q2a–Q2b cycle appears similar to the development of Q3a and Q3b. The 65 000 years of deposition of Q2a and Q2b recorded by varnish is close to the 40 000 to 50 000 years of Q3a and Q3b deposition that is still ongoing. The shift from Q2a to Q2b was likely the result of a major climatic change, like the change from Q3a to Q3b. Cation-ratio dating in combination with paleoenvironmental analyses in Figures 4, 5, 6C, and 6D indicate that a semiarid period occurred during the deposition of Q2a, but an arid phase occurred during the deposition of Q2b. The timing of Q2b from about 130 000 B.P. to after 105 000 B.P. indicates deposition after a major climatic change that dried up the Blackwelder stand of Lake Manly at about 85 to 90 m (Hooke 1972), dated by uranium-series analyses to between 135 000 and 225 000 (Hooke & Lively 1979). Cation-ratio dating of rock varnishes in this study indicates shorelines of the Blackwelder stand at Shoreline Butte, Mormon Point, and elsewhere were last abandoned about 130 000 B.P. to 120000 B.P.

An important issue is how the different stages of Lake Manly interacted with the alluvial fan deposits and why there is so little clear evidence of shorelines in Death Valley, except at such sites as Shoreline Butte and Mormon Point (Blackwelder 1933). The latest-Pleistocene stage of Lake Manly (highstands at 0 to 15 m) that ended about 13 000 to 10 000 B.P. and the deeper Blackwelder stand (at 85 to 90 m) that ended about 125 000 B.P. should have eroded strandlines into fan units deposited at an earlier time. As noted by Hunt & Mabey (1966), the minimal evidence for the latest-Pleistocene lake can be attributed to the more recent deposition of Holocene gravels in the elevational range of the latest-Pleistocene lake. Similarly, as Hooke (1972) observed, the Blackwelder stand is at an elevation where the post-Blackwelder units of Q2b and Q3a were deposited. Other factors that could explain the paucity of evidence of the existence of a shoreline are the shallow depth of the latest-Pleistocene



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lake and, as Blackwelder (1933) anticipated, the greater age of the deep lake in Death Valley. Hooke (1972) identified a possible Blackwelder strandline cut into Hanaupah fan deposits. Five carbon-ratio dates of varnish on this possible shoreline yielded an average of 105 000 ± 15 000 B.P. (±2 standard errors). These dates suggest that the identified slope break may not be related to the Blackwelder stand of Lake Manly, but may be a small fault scarp.

The sequence of events for Q1a and Q1b is similar to that for Q2a–b and Q3a–b, but with much less precision and accuracy in dating. Varnishes on Q1a maintain a basal paleoenvironmental signal that is more humid and tends to decrease in age from the fanhead to the fan toe. Q1b units are downfan from Q1a, probably buried the toe of Q1a deposits, and are younger than Q1a; paleoenvironmental data indicate that the basal layer of Q1b is composed of an arid signal. It is possible that an earlier stage of Lake Manly may have existed during the development of Q1a, but no clear records of such a lake were found in this study.

A major difference between the Q1 units and the Q2 or Q3 units is the much longer period of deposition recorded by varnish, around 300 000 years. Three explanations for the greater length of this cycle are possible, none being mutually exclusive. The greater age-range likely could be from problems in dating older varnishes. Cation-ratio dating is based on a semilog regression; the effect of this is that only a very small change in a varnish cation-ratio results in a very large change in the age-determination of varnishes older than about 300 000 years (Dorn, Tanner et al. 1987; Dorn, Turrin et al. 1987). Another very likely possibility is that several distinct episodes of aggradation were combined in Q1 without enough tectonic tilting and uplift to clearly isolate different units. A third possible explanation is that the length of the climatic periods was greater during this time. Smith (1984) notes an "intermediate" depth for Searles Lake from about 1 million to about 570 000 B.P. that may correspond to Q1a. This was followed by a "dry" lake starting about 570 000 B.P. that may correspond to Q1b. A proper comparison with Searles Lake, however, must wait for an improved chronology based on C1-36 analysis (Jannik et al. 1986).

Model of Fan Development

Figure 7 summarizes fan development in Death Valley by combining cyclic climatic changes, progressive tectonic uplift, and eastward tilting of the Panamint Range fans. Aspects of Figure 7 can be found in the earlier work of Bull (1977, 1979), Hooke (1972), Hunt & Mabey (1966), and Lustig (1965). Some detail is lost in Figure 7 to better portray the general sequence of events.

Tectonic influence can be distinguished from climatic change by comparing units deposited under similar paleoclimatic conditions. At the head of Hanaupah fan, for example, about 24 m of permanent incision occurred between Q1a and Q2a and about 12 m of incision occurred between Q2a and Q3a (Figure 3). All these units aggraded during a more humid period. Deposition at progressively lower levels, therefore, represents entrenchment due to tectonic activity, not climatic changes.

The importance of tectonic activity is highlighted by the asymmetry of Death Valley fans, from the short east-side to the lengthy west-side fans, as pointed out by Davis & Maxson (1935) and Hooke (1972) (also seen in Figure 1). A trunk stream can become permanently entrenched without tectonics by the gradual reduction of relief between the range and the basin. However, this is not the case in Death Valley. By using varnish dates as minimum age-estimates of fan units that are offset by faults, maximum rates of faulting can be obtained by measuring the height of the fault scarps. On Hanaupah Canyon fan, for example, maximum rates of faulting along the major scarps at the fanhead have averaged about 3 cm/1000 years since the time of Q1a. This rate has increased to about 9 cm/1000 years in the mid-fan scarps since the time of Q2a, increasing again to a rough average of about 20 to 30 cm/1000 years along the more complex scarps on Q3a and Q3b at the fan toe. These faulting rates are almost enough to explain the observed rates of entrenchment from Q1a to Q2a of about 4 cm/1000 years and from Q2a to Q3a of about 10 cm/1000 years. Some additional tectonic tilting (cf. Hooke 1972, Hooke & Lively 1979), however, is required to explain the missing ~1 cm/1000 years of entrenchment at Hanaupah Canyon.

Conclusions

This first application of rock-varnish dating and paleoenvironmental methods to a suite of alluvial fans has illustrated that both tectonic activity and climatic changes influence alluvial-fan development in southern Death Valley. During semiarid climates aggradation occurs from the heads to the toes of the fans. At the major glacial-to-interglacial transitions, the drying of the Death Valley climate affected the vegetation, lake levels, and the soil–hydrologic balance on the hillslopes. This caused stream entrenchment at the fanheads and resulted in aggradation that was limited to the fan toes. Three such semiarid-to-arid cycles of fan development are recorded by the fans in the Panamint Range in Death Valley. The older cycles are preserved because the climatically induced entrenchment lasted tens to hundreds of thousands of years. This allowed progressive tectonic activity to lift the deposits at the fanheads out of the reach of the next wave of semiarid aggradation.

Additional issues that should be at least introduced here are the implications of these results for the study of other earth-surface processes in Death Valley. As explained earlier, minimum age-determinations for fan units offset by faults provide a way to obtain rates of tectonic uplift. The varnish age-estimates in this study are also being used to model drainage development and morphologic changes on units of different ages with different relief and gradients. McFadden et al. (1987) and Wells et al. (1985) used K–Ar dates in the Cima volcanic field, Mojave Desert in California, to model pavement evolution on basalt flows. These varnish dates are similarly being used to examine pavement evolution on alluvial deposits, from the pristine late-Holocene deposits to the heavily degraded mid-Pleistocene fan units. These and other implications of this study will be elaborated in a subsequent monograph.

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